IPIC 2023 Conference papers and posters Contributions
Proceedings
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Asset capability, transparency, and governance - fundamental to PI Proliferation.

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Physical Internet Roadmap (Link): Select the most relevant area(s) for your paper:☐ PI Nodes, ☐ PI Networks, ☒ System of Logistics Networks, ☒ Access and Adoption, ☒ Governance.

Abstract

This research focuses on identifying and overcoming potential organisational obstacles that may hinder the acceptance and adoption of the Physical Internet. While information and technology systems are well-defined, the physical system is not. Therefore, it is necessary to thoroughly describe the physical system regarding asset utility, functionality, and operational structure. A qualitative approach investigated physical assets' hierarchy, capability requirements, and organisation based ontheir significance and interdependence. These fundamental aspects are critical for synchronising assets, the flow of freight, and accessing real-time data. The literature review concluded that: 1) infrastructure and interface architecture may pose potential barriers to Physical Internet progress; 2) asset characteristics, hierarchy, and freight system orientation are essential in functional design, accurate routing, and matching capacity; and 3) a global system and standards are required for multi-user governance (See Australian Coal Chain example). The paper aims to provide practical approaches to the organisation and asset categorisation, mitigating potential obstacles to PI progression. The research will make theoretical and practical contributions to achieve this goal. Theoretical contributions include adapting the Theory of Complexity to extend its boundaries into the Service Industry by developing a physical system framework. Valuable contributions include contributing to the PI 2030 objectives of optimising network flows and nodes interconnecting across the Physical Internet.

Introduction

Battles over online information control are often fought at the level of the Internet infrastructure (DeNardis 2012). These arrangements of technical architecture and physical transmission are also arrangements of power. Internet Infrastructure has become a significant factor in access, control, and transparency battlelines. Even before the internet, the telegraph changed human history by separating communications from transportation over vast distances. The physical Internet has the potential to reunite communication and transportation like never before, though it may also be susceptible to similar acceptance and access barriers of the past. For this reason, the paper argues that the evolution of the Physical Internet requires an aligned emphasis on critical assets (intelligent physical assets) and key assets (operating systems). The paper focuses on the assets' hierarchy, operational orientation, and governance structure. The paper sets out to 1. Define the relative hierarchy of assets, 2. Describe PI assets and routing descriptors, 3. Delineate the semantic orientation of assets, and 4. Discuss governance examples. In this regard, the main contributions of this piece are summarised as follows.

1. Establishing a method for determining asset hierarchy,
2. Categorising and orientating the freight system; and
3. Representing governance systems in practice.

The following diagram 1.0 describes the physical vs. digital traits to provide context. However, the paper focuses on the physical asset framework described in the second diagram, 2.0. In the second diagram, the first circle groups the hierarchy of assets, which is discussed in further detail in the following section. The middle-interrelated circle is the global network of networks and governance. The third circle identifies the primary actor groups as 1. beneficial freight owners, 2. service providers and 3. network managers. All three groups are underpinned by their systems. Some actors will affiliate with all three groups, though most will only align with one. The framework establishes an asset hierarchy, descriptors, categories, orientation, and governance. These sections will be described in further detail throughout the paper.

The Relativity and Hierarchy of Assets

The internet offers transmission over the airways and lines to hosts and routers. In contrast, freight is transported via critical assets, supported by complementary, key, and residual assets. These assets have relative scarcity and utility in transactions between buyers and suppliers (Cox, Ireland et al. 2001). Utility and scarcity are related to the asset's indispensable capability, availability, and substitutability. These assets are of operational and commercial importance; therefore, these key determinants must be carefully navigated in the evolution of the physical internet. Specifically, the characteristics of the physical product as these become Smart, Connected Product Systems (SCPS or a Physical Twin) need to be defined and described (Grieves 2019). The following diagram illustrates a method for determining the relativity of asset utility and scarcity.

Figure 1.0   Asset Relativity and Hierarchy

	Complimentary Assets	**Critical Assets**
High Primary activity	π-containers- international & domestic, π-handlers - RTGs, forklifts, reach stackers, tugs, rail vehicle placers, support assets - provisioning, maintenance facility, empty park facility, etc **Low-Medium Utility**	π-nodes - port gateway, terminals, hubs, DCs, fulfillment centres, warehouses, airports, etc; π-links - railways, roadways, seaways, airways, π-movers - ships, planes, trains, trucks, etc **High Utility**
Degree of commercial importance	**Residual Assets**	**Key Assets**
Low Support activity	Office buildings, car parks, loading and securing equipment and materials, packaging, etc **Low Utility**	π-protocols - rules, data structure, etc, web & systems - booking and operating systems, Vehicle Booking System, EDI links, data hubs, descriptive and predicative software, etc **Medium-High Utility**
	Low Readily substitutable	**High Non- substitutable**

Degree of operational importance

Note: Example content added to asset sections

Figure 1.0 describes the relativity of assets and sets out a method for establishing an asset hierarchy. Whilst this approach is universal, examples of assets within a corridor are used in this context. This is particularly important, as it may only be viable to describe some digital assets in a freight system, and the ones that are, will be interdependent upon other smart assets and systems. Freight is transported via critical assets, which carry out primary activities and are difficult to substitute or physically imitate. Therefore, it is contended that these assets would be the first to evolve into intelligent assets, i.e., the physical asset to be twinned. Whilst complimentary assets are also a primary activity, they are generally easier to substitute in their current design, though challenging from an intelligent π-container perspective. Therefore, current asset designs may have to evolve as

the first step to intelligent tagging systems before hardware and modular software design. Key assets (systems) are becoming more significant in support of field assets and are challenging to substitute due to their path-dependent innovation; this is often the case with operating systems. A potential solution to these barriers is the PI management system (PIMS) concept, which aims to exchange relevant information, such as identifiers, dimensions, and destinations (Tran-Dang, Krommenacker et al. 2020). PI management systems will be vital to transmitting and ingesting relevant data to and from actors operating systems and logistic webs.

Significant global conglomerates own or control enormous physical asset portfolios. These service companies have considerable operational and commercial risks associated with their assets, e.g., international/domestic containers, ships, trains, trucks, planes, terminals, distribution precincts, railways, and roadways, etc. Companies may choose to exploit the utility and scarcity of assets in pursuing higher rents or greater efficiency through innovation (Cox, Ireland et al. 2001). At the core of this position of power is information asymmetry. Whilst open-source data is unavailable and assets are not interconnected, the barriers to entry remain expansive to overcome. These are challenging isolating mechanisms, as interconnected assets and access to open-source data potentially reduce market power. For PI to be successful, it's essential that critical assets can be synchronised across handover points (actor interfaces), so the that the seamless momentum of freight is maintained. This means there must be digital transparency of interconnected assets, whether linked to actors operating systems or open-source systems.

According to Porter (Porter 2008), the Internet has significantly impacted industries that previously struggled with high costs for communication, information gathering, and transactions. In contrast, transporting goods physically is still considered too expensive and harmful to the environment. There are many digital barriers and implementation obstacles, such as the need for more openness, interconnectivity and interoperability (Cichosz, Wallenburg et al. 2020). To address obstacles surrounding proprietary technology and access, three areas of further research are proposed: Firstly, standardising open-source data and access licensing through regulatory influence. Secondly, obtaining non-commercial coordination data (including critical and key assets) from third and fourth-party operators through beneficial freight owner influence. Lastly, developing business models that promote collaboration among industry players and enhance economies of scale by synchronising critical assets, using industry influence.

PI Assets and Routing s

Whilst the asset is tangible in physicality, like a smartphone, it must be able to receive, acquire, process, perform actions, and transmit data from various types of RFID, sensors, and computing systems. The 'physical asset' would preferably have a power source, cyber security, computing, and remote transmission capability. Once remote visibility is achieved, data is ingested into descriptive software, which overlays the data onto a digital schematic of the assets' design. The structured data from assets is transformed into viable information describing its state and traits. The operating systems must then make sense of data for virtual planning, controlling, coordinating, and monitoring, as well as running diagnostics to validate the asset's current state against the plan or allowable parameters. These data sources are merged to form the digital description of the asset, e.g., ship, container, crane, truck, train, stacker, terminal, warehouse, roadway, railway etc. This intelligent asset emulation is the imitation of the asset and its behaviour. It visually represents or reproduces the intellectual assets' real-time functionality, i.e., location, dimensions, the status of vital systems and provisions. Accurately describing a given asset's state and trait is the basis for precise prediction of freight momentum.

Within the core system, simulation of the physical assets' operation (origin, destination, condition sets) could determine the asset's future behaviour and respond to physical and process constraints with given inputs, e.g., capacity, capability statements, or spatial characteristics. Predictive analytics could also identify physical limitations and potential mission threats that impede the asset's momentum. Once constraints are identified, optimisation and validation modelling can be used as

findings for recommended actions in a specific situation. Both methods have their place in planning asset and infrastructure capacity requirements, geographical configuration, and process capability in response to external changes. Influenced by: (Redelinghuys, Basson et al. 2020).

In PI, there are four primary components: π-containers, π-nodes, π-movers, and π-protocols describing their characteristics and state. The PI network is constructed as a network of logistics based on the interconnection and interoperation of π-nodes following the standardised π-protocols for handling, transporting, and storing π-containers. The globally standardised π-containers conform to physical specifications, with informational features (e.g., identity), and in the digital network transmit data packets. In parallel, the π-nodes represent facilities such as transit centres, distribution centres, and warehouses, which are innovated to enable the smooth flow of freight (Tran-Dang and Kim 2021). Implied rather than formalised are π-links between nodes that are particularly important to π-movers. That is, π-protocols may have rules to route π-movers from the origin to the intermediate location to the destination based on average time or speed over the distance between π-nodes. However, π-movers that spend most of their time on 'links' (e.g., roadway, railway) are constrained by many infrastructure restrictions, such as axle load, length, and kinematic parameters.

Shaikh and Montreuil's introduction to Services and Protocols for Inter-Hub Transportation in the Physical Internet opens up many research avenues for defining more setting-based parameters to improve the algorithm performance, more extensive simulation-based assessments with scenarios varying notably in terms of demand mix, patterns, and uncertainty; vehicle mix; package size mix; transit time stochasticity; hub availability, capability, and capacity; and tightness of promised delivery times (Shaikh, Montreuil et al. 2021). Generally, the parameters for roadways and railways are not included in the calling conventions and limitations of an actor's operating system. To gain a better understanding of the duty cycle and constraints that impact the level of certainty and responsiveness needed in service design, it is important to delve deeper into potential π-link characteristics. Without including these characteristics as part of the network, distance becomes a crude method for determining the time between nodes.

Whilst most agent operating systems have electronic data interchange, the origin of the data is often a hybrid between human-entered information and data ingestion. In many cases, what is shared is controlled by company policy rather than open source. Therefore, intelligent physical assets will require greater autonomy and utility to interact with various networks via APIs, programmatic applications, operating systems, and other intellectual assets for greater routing accuracy and open-source data. Greater asset capability will also reduce barriers to PI proliferation by providing a potential direct data feed of asset characteristics, spatiotemporal visibility, and diagnostic status. This, in turn, will offer greater transparency for modal synchronisation, emulation, simulation, and optimisation.

Semantic orientation of assets

Once assets can be defined in terms of criticality, and inputs defined for routing, the next logical step is to understand their orientation and categorisation within a network. The following conceptual design has been developed to categorise assets, services, and their primary orientation. Whilst this simplified approach could be universal, a national logistics context is taken for this paper. This contribution supports the ALICE goal of "standard service definitions and information sharing across actors enabling higher efficiency in the use of nodes, services and resources". The logic behind the framework is: that products are generally packaged and encapsulated within assets for handling, transportation, and storage. Beneficial freight owners (BFOs) typically place orders within a 4PL or 3PL booking system to move encapsulated goods onto a service. Critical assets perform transport services, and complimentary assets carry out handling and support activities. These configured assets that perform such services traverse nodes and links within network corridors. This simplified view in diagram 3.0 classifies their dimensional orientation.

Diagram 3.0 Orientation layers
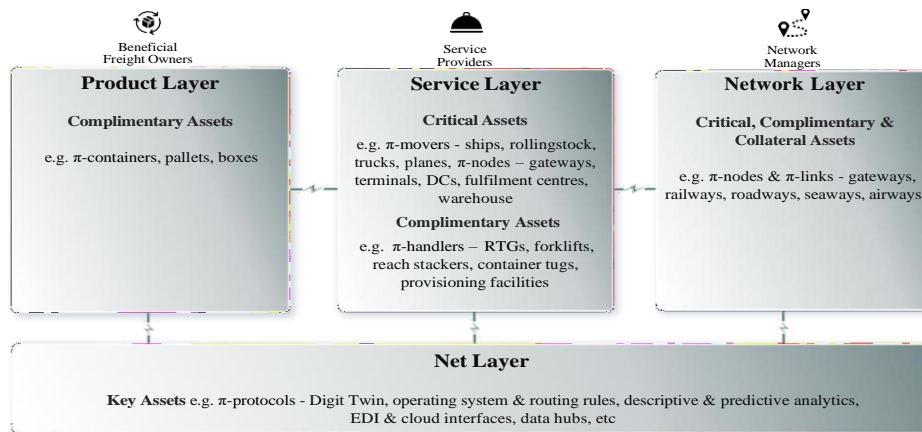
Since the development of the physical internet is of a physical dimension, the asset orientation proposes four distinctive layers or categories of this dimension; the diagram starts at the smallest physical unit, linking to the largest unit, the system network, and the digital network. The approach provides vertical and horizontal synergies in four distinct functional domains to create intra-dimensional and inter-dimensional visibility across different supply chain dimensions.

1. **Product layer:** Product layers include π-containers, pallets, and boxes, which encapsulate 'Goods.' Products are digitally described (weight, cubic size, type - dangerous goods, priority etc.). The consignment information includes priority, DGs, sender, receiver and associated locations that link the container to track and trace systems. Products (within π-containers) traverse networks (node-link routes) within a digital service packet (within π-movers capacity) from origins to destinations, including intermediate locations. Products are amassed at π-nodes, transferred, and atomised via critical π-movers and complimentary π-handlers. A parent model convention could be used to relate the π-containers to the π-movers, i.e., the π-container child is linked to the wagon or trailer, which is linked to the parent asset, the loco or truck, which is linked to the grandparent π-movers, the Train or B-Double. Therefore, at a more granular level, boxes are subservient to the pallets, which are subservient to their parent π-container. The term 'Product layer' is purposeful as it distinguishes its orientation and relationship with 'Service Assets'; this provides a layer directly linked to the *actors of goods* rather than the *actors of services*.

2. **Service layer:** Services (E-services) have a Master ID with subservient IDs, all of which have a Network identifier within a naming convention. The Master IDs identify the π-movers origin, intermediate hub, destination, weekday, time sequence, priority, and network. The subservient IDs are linked to parent IDs, identifying π-container consignments within the service. These consignments can have unique identifiers related to the π-mover, π-node, π-handler, service, and network. Consignments within π-containers are at a pallet size and are digitally linked to the π-container, linked to a π-mover, linked to a service and a network. Services are essentially a naming convention describing modal (π-mover) capacity and infrastructure usage (π-node & π-link pathing) within corridors, encompassing the logistical distance across a network. Critical assets (π-movers) perform services across π-nodes and π-links, with complimentary assets that either support the critical asset or π-handle the π-containers. The term 'Service layer' is purposeful as it distinguishes its orientation and relationship with 'Products and Networks'; this provides a layer directly linked to the *actors of services* rather than the *actors of the goods or networks*.

3. **Network layer:** The layer is separated as this layer is generally a common user layer. That is, private actors are multi-users of the central infrastructure. Vertically or horizontally structured major infrastructure is usually subject to network access legislation. Master networks generally consist of gateway nodes, general nodes, and links within an infrastructure corridor, e.g., transcontinental, or land-based penetration lines. These networks could have a unique Master ID,

with subservient IDs for complimentary networks. Critical networks are digitally mapped via nodes and links to complimentary networks at nodal point boundaries (Interception or Tran scalar). The point of nodal interface (spatial) describes relationships between critical and complimentary networks. Each describes the infrastructure's intermodal gateway, corridor, adjoining trans-modal hubs, capacity, and capability characteristics. Services can be digitally linked to critical and complimentary networks for logistically pathing (π-routing) from origin to destination, including intermediate destinations. They include headway time, kilometres between nodes (distance), capacity (volume/load/length), and constraints (effort). The term 'Network layer' is purposeful as it distinguishes its orientation and relationship with 'Services'; this provides a layer directly linked to the *actors of networks* rather than the *actors of services*.

4. **Net layer:** Key assets are interfacing, booking, operating, diagnostic and billing systems. Depending upon their operational and commercial importance, these systems could also be categorised at a critical and complimentary level. The network, E-services, and associated critical field π-assets can all be digitally linked to key assets. Systems can route services either by nodes or geofenced blocks within links. Data transmitted from π-nodes, π-links, and π-movers could be emulated, simulated, and optimised via descriptive and predictive software, e.g., spatiotemporal tracking and tracing, asset condition, capacity, and process capability. The term 'Net layer' is purposeful as it distinguishes its orientation and relationship with 'physical field assets' within the service layer. The net layer is directly linked to external *systems, internet, and transmission networks*; the systems encapsulate software that can emulate, simulate, and optimise the product, service, and networks 'physical field' layers and their interrelationship.

Conventions within Layers

Within the orientation layers, actors develop service conventions that provide granular information such as the operator, nodal pairing, service type, load type, service allocation, deployment weekday, sequence of the day, and direction. A train number reporting system in railway operations provides the service description within the network. These services are mapped on train line diagrams across a network to describe the paths between nodal pairs and where services will cross or dwell against a given schedule. The following figure provides an insight into rail conventions.

Figure 2.0   *Rail Convention System*
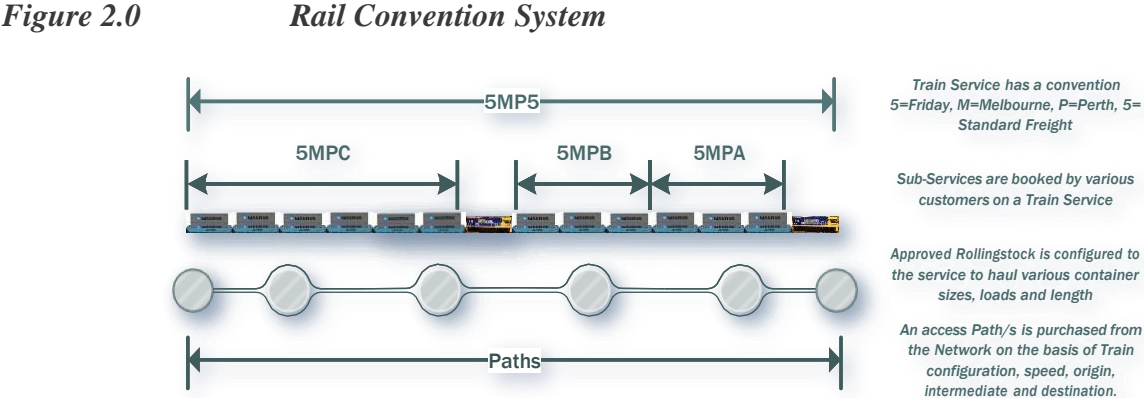
Figure 2.0 represents an Australian Intermodal rail network convention, where customers book services, which are sub-sets of capacity allocation within the overall train service. The train service has Rollingstock configured within a train for a particular path from origin to destination. The point of the Illustration is that π-movers (the train) can have various configurations to match the requirements of a service and associated access requirements. Services are routed via train paths with varying capacities (nodes & links) across a rail corridor. Therefore, the system in PI terms has π-containers, π-movers, π-handlers, π-nodes, π-links, and system π-protocols within a π-network. Links being railway sections between nodes that have various constraints, such as axle loading, asset length, and kinematic dimensions.

A node is either a connection point, a redistribution point, a passing point, or a communication point in the rail network. Similarly, in the digital network, computers or devices are modems, hubs, bridges, switches, etc., which are part of a network[1]. In an Internet sense, data is transmitted from nodes that define the bi-directional flow of information packages streaming wirelessly between two communication devices. In the physical world, frictionless (digital) and friction-intense (physical) activities exist in parallel. That is, contained goods are electronically booked to services. Services are electronically booked on critical assets (π-mover), and complimentary assets (π-containers) are electronically routed from nodal origins to traverse links to nodal destinations. In contrast, the physical activity system is friction-intense with loading (π-handlers) at nodal points (π-node), crossing via seaway, railway, roadway, or airway links, to arrive for freight unloading amassment or goods atomisation at the nodal points. The distinctive difference between electronic transmission to physical transportation is that π-movers undertake the physical effort of hauling volume over distance. Routing the physical may be more challenging than routing the data packet, as the activity system has many varying functions. Kaup and Ludwig's paper proposes π-transporters as routing entities whose software representatives negotiate freight handover points in a cloud-based marketplace. They further argue that implementing such a marketplace also allows the integration of software representatives for stationary π-nodes, which contribute to their location and capacity utilisation levels for the market (Kaup, Ludwig et al. 2020). Alternatively, a straightforward method more widely adopted in routing is via nodes or potentially geofenced link-node blocks, which may be more logical regarding fixed geographic locations.

Defining asset criticality, determining inputs for routing, and establishing layering/category conventions will pave the way to more granular inputs, focus, and associated transparency. This is important, as coordination and collaboration can significantly improve effectiveness and sustainability in transitioning from individually managed supply chains to open supply networks[2].

Supply Chain Governance Case

As discussed, understanding the criticality of assets, their role, route requirements, and how they are categorised and layered within an overall network is necessary to achieve greater system granularity. However, without good governance, supply chain cooperation and collaboration are somewhat limited to contractual requirements that do not exist between all actors across the network.

Coal Chain Governance has significantly matured over the last 25 years in Australia. The same cannot be said for Intermodal and Bulk freight movement. These sectors do not generally have central coordination across multiple actors and, in most cases, have minimal system protocols. The global adoption of PI will require enormous cooperation and collaboration. It will require layers of development to calibrate the current state, explore directional and transitional options, then create a future state. Addressing members requirements, navigating stakeholder collaboration, and associated business models will eventuate in significant governance layers at a product, service, network, and digital system level. The Alliance for Logistics Innovation through Collaboration in Europe is leading collaborative efforts. ALICE is based on recognising the need for an overarching view of logistics, supply chain planning and control, in which shippers and logistics service providers collaborate closely to reach efficient logistics and supply chain operations[3]. The following insights on 'governance precedents' are included to contribute to the 'ownership and governance' initiative within the Systems and Technologies for Interconnected Logistics stream.

An overarching view on logistics, supply chain planning and coordination was recognised as a need in Australian Coal chains in the 90s. However, it was not fully realised until Industry and the Australian Competition and Consumers Commission intervened in breaking crucial impasses that the industry faced. Collaborative efforts generally broke down over gaining consensus on capacity and

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[1]   https://afteracademy.com/blog/What-is-a-network-and-what-are-the-nodes-present-in-a-network
[2] https://www.etp-logistics.eu/roadmaps-3-2/global-supply-network-coordination-and-collaboration-2/
[3] https://www.etp-logistics.eu/

associated commercial compensation. Capacity alignment of the critical asset was at the centre of disagreement in all cases. As a result, several reports were commissioned, and recommendations were implemented. The following extracts provide insight into the legislative change that occurred to coordinate physical assets better logistically and across supply chains.

1. Recommendation from O'Donnell Review 29th July 2007, Australian Competition Authority.

   *A **central coordinator role is created** to oversee and, if necessary, coordinate all activities that span the whole supply chain. The position would oversee master plans to ensure that future capacity is in line with forecasts, facilitate industry consideration of ...investment, and oversee short-term planning and the establishment of business rules for daily optimisation of system capacity. A co-located workgroup containing resources from the rail providers and DBCT port would facilitate optimising the application of resources to service DBCT port[4].*

2. Australian Competition and Consumers Commission (ACCC) determination on "a queue management system designed to address the imbalance between the demand for coal loading services at the Dalrymple Bay Coal Terminal and the capacity of the Goonyella coal chain". 29th February 2008.

   *The ACCC notes that some progress has been made towards implementing the recommendations in the O'Donnell Review, including the commencement of a business improvement program across the supply chain, the procurement of locomotives, the **appointment of people to coordination roles**, and a rail contract renewal process.*

3. CEDA Queensland Export Infrastructure Conference. The ACCC's role in coal chain logistics. Dr Stephen King, Commissioner. 15th July 2008, Brisbane.

   "There is significant complexity in managing the supply chain from both strategic and operational viewpoints. This complexity is primarily a function of the number of entities directly associated with it. Eight coal producers are operating across the 13 mines...In addition, there are regulatory, commercial and shareholder interfaces with the Queensland Competition Authority (QCA), ACCC, Port Corporation of Queensland (PCQ) and the State Government"[5].

4. Coal Network Capacity Co. CENTRAL QLD COAL NETWORK Initial Capacity Assessment Report. 27th October 2021 Version: 2021 ICAR

   *Requirements of 2017 Access Undertaking (UT5), as approved by the Queensland Competition Authority (QCA), requires Capacity Assessments of each of the Central Queensland Coal Networks to be performed, ... UT5 specifies two types of Capacity Assessments...1. Definition of Deliverable Network Capacity, and 2. System Capacity. For the **Independent Expert** Initial Capacity Assessment, only the Deliverable Network Capacity is required to be assessed.*

Following the Governments intervention, coordination groups were established with clear expectations, roles, and resourcing. They include:

1. Integrated Logistics Company (ILC). The Central coordinator will oversee and, if necessary, coordinate all activities spanning the entire coal chain. The ILC would operate under the core principles of remaining independent and encouraging cooperation between participants for the betterment of the supply chain. The ILC has an appointed board made of industry stakeholders, has a Memorandum of Understanding (MOU), and has appointed an independent coordinator.; it has a leadership team and an Integrated Logistics Centre in Mackay, QLD, and has also incorporated Integrated Logistics Company Pty Ltd[6].

2. Hunter Valley Coal Chain Coordinator is an independent body overseeing activity along the world's largest and most complex coal chain. HVCCC's purpose and vision reflect a focus and role within the evolving circumstances of the Hunter Valley Coal Chain Members.

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[4] https://ncc.gov.au/images/uploads/DeRaRrSu-008.pdf
[5] https://www.accc.gov.au/system/files/The%20ACCC%27s%20role%20in%20coal%20chain%20logistics.pdf
[6] https://www.ilco.com.au/background-of-the-ilc

HVCCCs' objectives are to plan and coordinate the cooperative operation and alignment of the Coal Chain to maximise the volume of coal transported through the Coal Chain at minimum total logistics cost by the agreed collective needs and contractual obligations of Producers and Service Providers. Accordingly, HVCCC's purpose is to Independently optimise the end-to-end coal chain to serve Members' collective needs best[7].

3. The appointment of an Independent Expert Coal Network Capacity Co by the Queensland Competition Authority. Independent Expert (IE) undertakes dynamic Deliverable Network Capacity Analysis based on a dynamic model, sets out the System Operating Parameters (SOP) for each Coal System having regard to how each Coal System operates in practice and develops an Initial Capacity Assessment Report (ICAR) that sets out Deliverable Network Capacity (DNC), assumptions, constraints, and Existing Capacity Deficits (ECDs). The IE conducts Dynamic Simulation Modelling using the AnyLogic modelling software to determine the DNC of the CQCN and each Coal System[8].

In summary, the Coal Chain coordination companies 1. Coordinate operational planning, 2. Independently report on SC performance, 3. Declare critical asset availability, 4. Model system capacity, 5. Lead investment reviews across supply chains, 6. Establish and maintain system goals, processes, and rules; and 7. Resource these functions via industry contributions. The coordination companies have no jurisdiction over commercial contracting between actors and must comply with all relevant federal and state competition laws and regulations. However, the coordination company structure significantly influences transparency of declared capacity, operating parameters, performance accountability, and clarity of where investment across the chain is required.

Across these Governance regimes, collaboration models vary from arms-length to prescriptive collaboration requiring significant digital transparency, interconnection, system rules, capacity declaration, and performance data. The fine line is determinations about the greater system good vs exposure of marketplace commerciality. A greater focus on factors required for synchronisation, rather than factors of commerciality, may be better suited to lowering barriers to PI entry and proliferation.

With transformational change comes disruption. This disruption could come in the form of 1. intelligent physical assets capable of providing direct computing and data transmission to open-source systems, 2. Business models that improve the economies of scale across multiple actors, 3. Greater asset and corridor transparency and accessibility to open-source networks.

Conclusion

Observations from the research indicate that the solutions to potential PI impediments include: 1. The interoperable and interconnected capability of intelligent physical assets to compute and transmit open-source data to systems that encapsulate digital twin software; this will result in greater asset utility (use-value) and avoid manual input into operating systems; asset data will remain a source of scarcity without this capability, 2. Definitions of asset categories and classes will establish a standard system and industry language and better define a hierarchical focus for collaboration and interconnection of actors, 3. The demarcation of orientation layers will provide clarity for different industry sectors and developers and simplify overarching governance, 4. An *arms-length* governance approach simplifies the path to industry acceptance whilst avoiding the commercialisation of the central elements of the PI model. At the core of effective logistics and supply chain operations is the ability to synchronise the momentum of freight movements to reduce dwell and unnecessary exchanges; at the core of the Physical Internet are Intelligent Physical Assets, which must remain central to this goal.

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[8] http://qcaprod.australiaeast.cloudapp.azure.com/wp-content/uploads/2021/11/coal-network-capacity-co-initial-capacity-assessment-report-redacted.pdf

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PI Data Sharing Infrastructure

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Abstract: Data sharing is key to realizing the Physical Internet (PI) as its roadmap illustrates. Examples are for full visibility of nodes and their business services, adjustment and assignment of routing to reduce empty miles, and protocols and services for operational efficiency of logistics networks. These examples and many more existing ones are use cases for a PI Data Sharing Infrastructure that can support current and future data sharing requirements. One aspect of the PI is its organizational structure as a network, where logistics is a common resource used dynamically. These imply that any data sharing infrastructure must be open, flexible, and extendible for innovative use cases. Semantics and data sharing functionality is the core for such an infrastructure. By applying semantic web standard and – technology, the objectives can be reached, and a large variety of use cases can be supported. A set of agreements, or protocol stack, is proposed including an approach for governance.

Keywords: *data sharing, data spaces, Physical Internet, federation, open and neutral data sharing infrastructure.*

Physical Internet Roadmap: PI Networks, System of Logistics Networks, Governance.

1   Introduction

The Physical Internet roadmap (Alice, 2022) proposes five phases for constructing the Physical Internet where each of the phases has its own roadmap. Seamless, interconnected transport networks adaptive to change need to be constructed, including governance. One of the main aspects is full visibility, accessibility, use of business services for optimization, and situational awareness for optimal routing (De Juncker, 2023). Data sharing is a prerequisite to realize the Physical Internet, where data is not always public available but needs to be validated against certain criteria (Eckartz, Hofman, & Veenstra, 2014) to address data sovereignty (Dalmolen, et al., 2019). An open, neutral data sharing infrastructure is required where all logistics stakeholders can share data in a controlled way, without prior (bilateral) agreements (Digital Transport and Logistics Forum (DTLF) Subgroup 2: Corridor Information Systems, 2018). It must be flexible and extendible to support current and future data sharing requirements.
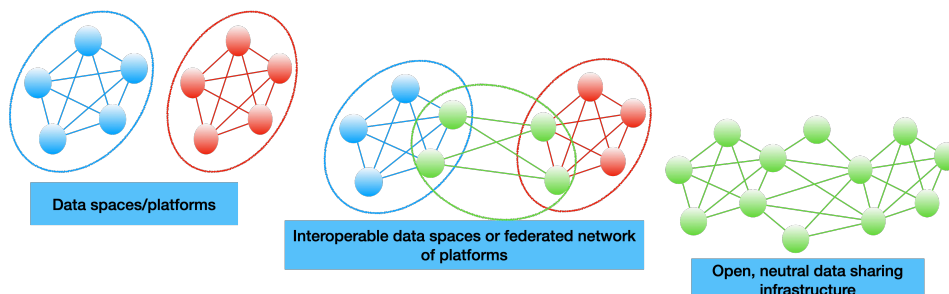
Figure 1 – From data spaces/platforms towards an open, neutral data sharing infrastructure

A so-called mobility data space needs to be constructed, according to agreed principles (Nagel & Lycklama, April 2021). Such principles result in functionality that must be supported, where this functionality is data agnostic (Nagel & Lycklama, April 2021). So-called Data Domain Standards can be implemented by a data space, leading to data spaces that are not necessarily

interoperable as argued by the Digital Transport and Logistics Forum (The Digital Transport and Logistics Forum (DTLF), 2017). The Physical Internet however requires preferably a global data space with potentially local and/or mode specific sub-spaces (Figure 1). A data sharing infrastructure like the Internet, energy network, or road network is required, where this infrastructure can take different technical appearances, but still be open.

To achieve the objective shown in the previous figure, we consider interoperability models (Wang, Tolk, & Wang, 2009), (European Commission, Belgium) that can be related as shown below. The figure shows a requirement for a legal basis across different national domains and governance of the results as part of the EIF (European Interoperability Framework) that is lacking in the other model, whereas the latter one takes a more detailed approach by addressing conceptual interoperability. The latter is required for constructing a PI Data Sharing Infrastructure.
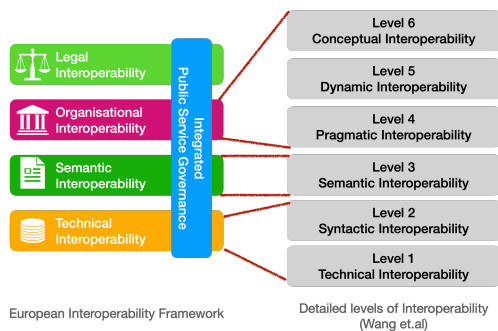
Figure 2 – Interoperability models

The core of this paper is a proposal for a protocol stack to achieve conceptual interoperability and addresses legal aspects and governance as indicated by the EIF. First, the protocol stack will be discussed, secondly governance and legal aspects are presented. The proposed protocol stack supports business collaboration and compliance, but can also be applied for other types of use cases.

2 Protocol stack

To meet the objective, a set of agreements must be constructed. This is called the 'protocol stack'. This section presents the protocol stacks and focusses on gaps that are not addressed by other initiatives.
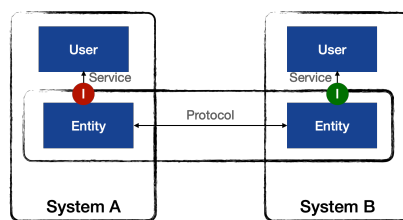
Figure 3 protocol, service, and interface

2.1 Protocol, service, interface

The concepts of protocol, service, and interface date back to the Open Systems Interconnection model that is the basis for the Internet (Tanenbaum, 1996). A **protocol** is a structured sequencing of interactions between two peer entities by different systems (or organizations). These 'entities' that are software components implementing a protocol, provide a **service** via an **interface** to a user. Protocol and service must be identical for any two implementations; each implementation can have a different interface.

Protocol specifications must be concise, consistent, coherent, and complete to enable implementations of a protocol by different providers. Separation of concerns is crucial for modularization. A protocol uses a lower layer service. Any software component must at least implement one protocol layer but can implement more. For instance, an endpoint of an openAPI is an interface of a service that uses Internet protocols for lower layer protocols. A messaging client implements the messaging protocol over Internet protocols.

2.2 Protocol stack

The protocol stack (Figure 4) consists of protocol layers specifying behavior implemented by two roles as defined by the EU Data Act: 'data holder' and 'data user'.
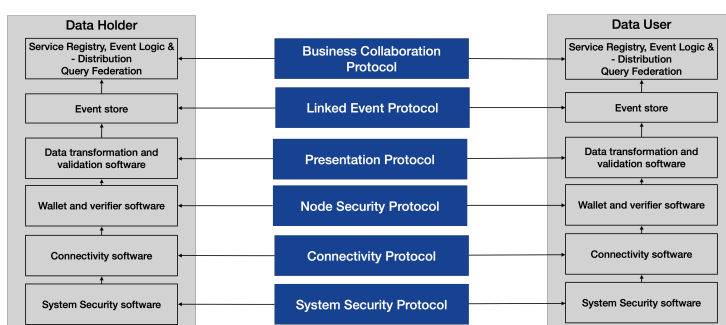
Figure 4 PI protocol stack

The protocol layers are:

- **Business collaboration protocol** – the capability to discover business services and assess organizational profiles of peers with their data capabilities and – requirements and share data for a business activity. Each peer entity of this protocol must implement at least a business activity and its interaction patterns as specified by the design and its configuration of that activity. These will be elaborated in this paper.
- **Linked Event protocol (pull)** – each interaction in a business collaboration protocol is implemented by sharing only links to additional data as specified by subtypes of 'event' in a design. Each link can be evaluated by a (standardized) query. Additionally, each user of the service of this protocol can formulate its own queries according to the multimodal ontology.
- **Presentation protocol(s)** – the syntax and technology (messaging, (open/webhook) APIs (Application Programming Interfaces) with JSON(-LD) (Java Script Object Notation – Linked Data), semantic web protocols (SPARQL (Standard Protocol and RDF Query Language), RDF (Resource Description Framework))) used for sharing data. These are technical aspects of the implementation of the upper layer protocols.
- **Node Security protocol** – it is about identification and authentication: the capability of nodes to verify each other's credentials applying open standards like OAUTH2.1, JWT (JSON Web Tokens), and/or Verifiable Credentials (VCs) and Decentralized Identifiers (DIDs).
- **Connectivity protocol(s)** – the technical capability for reliable, safe, and secure data sharing using a System Security Protocol. Current list of connectivity protocols: FENIX connector protocol, IDSA connector protocol, EDS (Eclipse Data Space) connector of GAIA-X, a large variety of blockchain protocols (e.g. Corda, Hyperledger Fabric, and Baseline protocol), and AS4 implemented by CEF eDelivery.

- **System Security protocol(s)** – the safe and secure sharing of data with PKI certificates, utilizing standard protocols (e.g. https, TLS).

These layers can be mapped against the interoperability models as follows:
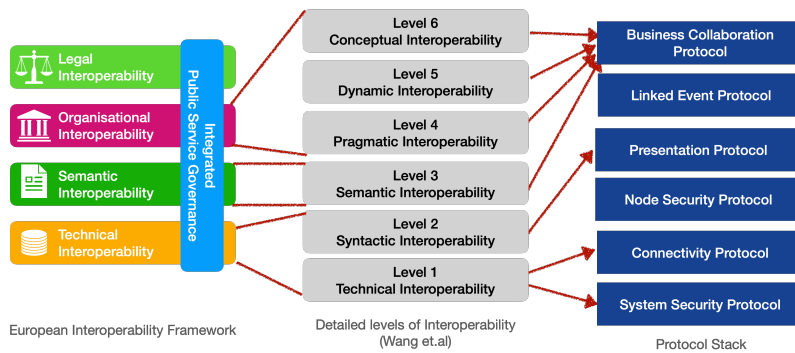
Figure 5 protocol stack and interoperability layers

Note that two protocol layers are additional to the interoperability layers. The Node Security Protocol is required in an open, neutral data sharing infrastructure providing identity and authentication. Some implementations of the connectivity protocol implement their proprietary node security protocol, e.g. Corda. Other implementations support combinations of the various protocols, but data agnostic and potential in a different manner (e.g. IDSA – or Eclipse Data Space connectors). Differences in implementation could give an indication of the quality of a protocol design: there are too many degrees of freedom. The Linked Event Protocol is about optimizing data storage and contributes to data quality. There is always a single source of truth.

2.3 Business collaboration protocol

As the previous figure shows, this protocol implements four interoperability levels as identified by (Wang, Tolk, & Wang, 2009) and two of the EIF (European Commission, Belgium). This is achieved by modeling interaction patterns for business activities as constraints to a multimodal data sharing model. The latter is an alignment of existing mode and/or cargo specific models as specified by for instance industry associations and regulators.

The multimodal data sharing model is a so-called upper ontology. Mode -, cargo -, and/or infrastructure specific ontologies are lower ontologies. Alignment between those lower ontologies is via the upper ontology. Of course, individual lower ontologies can also be aligned (Euzenat & Shvaiko, 2010). Having a single upper ontology for alignment allows individual users to select required functionality of one or more lower ontologies.

Alignment is on concepts representing the physical world, like a taxonomy of Digital Twins with subtypes like container, truck, and vessel, and infrastructural aspects like locations, hubs, and road infrastructure, complemented with actors like a legal entity or a person. These all have associations in place and time, represented by event. Other concepts are the data sharing concepts: business activity their interaction patterns. A pattern reflects a Business Process Modelling (BPMn2.0) choreography (Object Management Group, 2011) that consists of states and state transitions triggered by interactions. These concepts are all represented as subtype of 'event'. An interaction or a business document is for instance a subtype of event associating Digital Twins, locations, and organizations for a business activity. The data sharing concepts are a separate module of the ontology. A choreography is represented by states and state transitions triggered by events with links to data. States specify access policies, implying that a minimal and maximal data set can be retrieved given a state for interactions. Events are actually shared between a data holder and -user to synchronize their states.

The following figure visualizes the multimodal data sharing ontology (data sharing concepts represented as blue circles; physical and administrative concepts represented as yellow circles). Not only each interaction pattern has a start and end state, also a business activity must have these states. In case of a sequence of interaction patterns, like booking, ordering, and visibility, each interaction patterns adds state data to a business activity start state resulting in its end state.
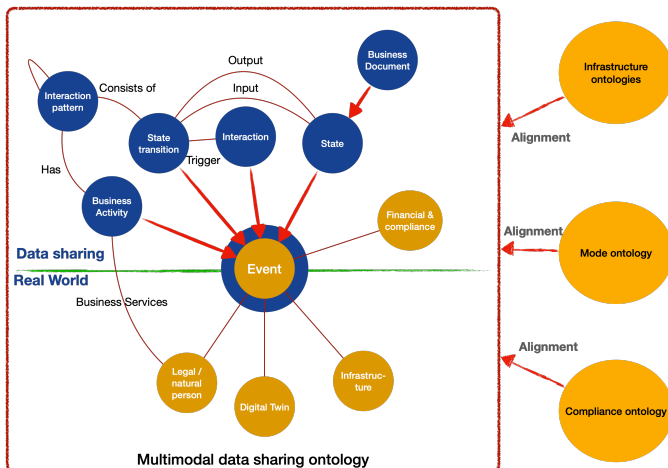
Figure 6 – the multimodal ontology with details of business data sharing concepts

Semantics itself must be machine-readable with open standards. Those are the semantic web standards like Ontology Web Language (OWL), Resource Description Framework (RDF), and SHApe Constraint Language (SHACL) (Berners-Lee, 2006). Modelling data sharing concepts representing process aspects (i.e. business process collaboration) allows the specification of minimal data requirements for states and events represented by SHACL for data quality validation (correctness and completeness); state transitions must be modelled by pre- and post-conditions and firing rules (Hee, 1994) resulting in executable event logic.

2.4   Configuring the business collaboration protocol – Service Registry

Each logistics stakeholder and authority will have its own data capabilities and requirements. These are based on the concepts of the multimodal ontology, for instance a regulation for risk assessment and taxation of incoming goods (transport) into the EU by customs or the transport of cargo by a shipping line. These specific capabilities and requirements must be specified, published, and discoverable. This is supported by a distributed Service Registry. Each organization thus has its own Service Registry. A Service Registry enables any organization:

- to specify its data requirements and
- to define and publish its business services for discoverability.

The data structure of the Service Registry enables a user to formulate interaction patterns for business activities; the blue circles shown in Figure 6. The Service Registry can be applied in two ways:

- **Design** – to specify business activities and their interaction patterns. Industry associations, communities, and regulators can do design. Subtypes of business activities and interaction patterns can be provided as an ad hoc standard and be applied for design to improve alignment.
- **Configuration** – to specify an organizational profile by searching and:
  - selecting those parts of a design that are relevant to an organization,

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        o   specifying its business services and electing the various lower layer protocols it supports (including endpoints). Business activities and their interaction patterns define constraints to the multimodal ontology.

    In addition, a user selects the constraints applicable for its organization i.e., selecting the relevant logistic Digital Twins applicable to its organization.

Additionally, Industry Associations, and regulators can align their ontology with the upper ontology, applying standard alignment tools. Alignment requires using the same open standards for representing data schemes, which is not always the case. Alignment is also on all concepts of the upper ontology; for instance, a data scheme for an electronic business document only aligns with that concept of the upper ontology and potentially a business activity (e.g. transport for an eCMR).

The configurations also specify access control: each organization is only able to provide access to data that is stored. Access can of course only be given to data of which links are shared by events.

Discoverability is implemented at technical - and business level, based on known SPARQL endpoints of Service Registries. Technical level is about re-use of a design to construct a configuration with business services, resulting in an organizational profile.

Any two stakeholders can share data for those parts of their organizational profile that are common. They can do business digitally (and be compliant) if goals and business services can be matched, which is established as part of the business collaboration protocol. The more stakeholders implement of a maximal design for a business activity in terms of interaction patterns, the more their business can be supported digital and seamless data sharing is achieved.

To enable migration, the business collaboration protocol can be implemented by both APIs and semantic technology. Therefore, the Service Registry will produce openAPIs and SHACL for implementation by an index. First examples of such generated APIs and SHACL are available.

2.5   Index functionality

The business collaboration protocol utilizes the Service Registry for configuring peer-to-peer data sharing; index functionality is about the events with links to data that are shared between a data holder and -user. An index of an organization contains all events (with links to data) send as data holder with other organizations and received as data user from data holders.

The functionality consists of the following components:

- data quality validation (correctness and completeness of event data and query (results)),
- event logic (validating the sequence of events),
- event storage (storing shared events)
- event distribution (sharing an event with the proper data holder(s)),
- enable access for replying to data users queries (link-based access control), and
- query federation (data provenance).

Having an event with a link to additional data implies that a data user is authorized by a data holder to access data of that link. The access policies specified by states specify the data that will be made available. The data that will be made available upon a query depends on the present state of interactions as stored by a data holder. A data user will not necessarily have the same state, a customs authority for instance may only be aware that a transport movement was started and does not know the latest state of that movement.

An index supports event distribution (sharing an event with the proper data holder(s)) based on input of a data holder initiating a commercial relation, the existing of a commercial relation (previous events are stored by an Index), or for legal compliance.

An index must support data quality validation (correctness and completeness of event data and query (results)) and either in its internal IT systems or by its index. Data quality is specified by an organization profile (see Service Registry).

The functionality mentioned here can be accessible via open- and webhookAPIs and semantic technology. Each organization must make a choice, where semantic technology is the preferred choice since it enables a more open way to query for data on states and has flexibility in access policies and authorization.

2.6 Identity, Authentication, and Authorization (IAA)

IAA is about trust in access to (links to) data. The data is business data (e.g., order data), a design, or an organization profile. IAA relates to authorization of users, i.e. employees of a participant, and architectural components (Service Registry and Index) that provide (access to) data. Safe and secure data transfer is addressed separately by connectivity protocols for the Index.

IAA is built upon two pillars[1]:

- **Organizational trust** – each organization that requires to be a node must implement measures that assure trust, for instance cyber security measures and an Identity and Access Management (IAM) registry. Rules for creating this type of trust will be formulated by a legal framework. It also covers authorization of employees to act on behalf of its employer and non-repudiation of actions taken by these employees.
- **Inter-organizational trust** – each organization must share an identity with another organization that can be verified by that other organization when sharing events, queries, and/or query results.

Authorization is internal to each organization and is the basis for access control. Organizations thus do not know authorized users of other organizations; they trust that authorization is properly implemented by others (organizational trust).

Each node must have at least one endpoint with inter-organizational trust (Identity and Authentication); it may have multiple ones (e.g. one for its business services and another one for data sharing). Identity and authentication must be based on a completely distributed solution based on which is provided and governed by:

- a regulator (providing– establishing a legal data sharing framework (e.g. EC) and accreditation of registration authorities,
- a trusted registration authority acting as issuer of verifiable credentials, and
- a certification body for organizational trust.

The implementation of such a distributed solution with Verifiable Credentials (VCs) and Decentralized Identifiers (DIDs) is still under development. A registration authority may for instance have a DID issued by a regulator allowing it to act as issuer after a potential participant is certified. Any two nodes that share data may set up a persistent channel with DIDs after verifying each other's VCs. The latter only needs to be done once, which limits the number of

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[1] There is also trust at business level, i.e. the trust in properly executing business activities for customers according to agreements made with them. This trust is outside scope of IAA.

interactions and improves performance. Existing standards, and solutions (like OAUTH2.1) can be applied to create inter-organizational trust (applicable to data of a Service Registry and an Index). This intermediate level requires one or multiple Identity Brokers acting as intermediate Registration Authorities. Preferably, a regulator is a public body and different roles are implemented by different organizations (separation of concern).

3   Governance and legal aspects

The proposed approach has implications for standardization and governance. Configuration of the PI Data Sharing Infrastructure is distributed if these configurations adhere to a meta level standard and are implemented via proposed governance agreements. This requires a legal framework for creating trust. This section briefly elaborates governance and potential legal aspects.

3.1   Governance

Governance is basically on the protocol stack and the upper ontology. The protocol stack consists of various elements that are prone to standardization, are already (based on) open standards, or already have a governance structure. For instance, connectivity -, node security -, and presentation protocols are already based on open (or defacto) standards.

The following elements of the protocol stack are generic and prone to standardization:
- **Multimodal data sharing ontology** – the upper ontology for data sharing supporting business activities and compliance with concepts like Digital Twins, events, states, and state transitions.
- **Interaction patterns** – a set of interaction patterns to support commercial transactions or compliance-based data sharing that specify access control policies.
- **Linked Event Protocol** – the way of sharing events with links to data.

Any other aspects are subject to further governance, which may result in additional standards.

Since the upper ontology creates an open PI data sharing infrastructure, alignment procedures need to be established and implemented. An example of such a procedure is that any concept or data property that is common to two or more designers is part of the upper ontology. Furthermore, particular Industry Associations, Communities, and regulators must be recognized designers, i.e. they must represent the interests of a number of users. Any designer can utilize the upper ontology for innovative applications by creating a lower ontology that can later be proposed as part of the upper ontology.

Governance of these rules requires a governance board, where recognized designers and logistics stakeholders (enterprises and authorities) collaborate. A support organization and advisory board will support the governance board for direction and daily operation.

3.2   Legal aspects

Creating an open PI data sharing infrastructure, which is a complex system, requires regulation relevant for its correct and trusted operation. As IAA identified, there is a separation between organizational – and inter-organizational trust. Additionally, also the behavior of any organization that requires to participate in the open PI data sharing infrastructure must be validated. The approach can be formulated as follows:
- **Organizational trust** – each organization must implement a list of applicable acts, regulations (list to be provided), and functionality for accountability. The latter is internal IAA and non-repudiation functionality like logs and audit trails.

- **Behavior** – the behavior of each organization as specified by its organizational profile must be published and validated or certified. In case of enterprises, it must include all relevant public and private compliance aspects for which data sharing requirements are published (e.g. private rules like The Hague-Visby rules). Behavior also must include data quality aspects (completeness, correctness, timelines, etc.). In case an organization utilizes a third party (e.g. a platform), that third party acts on behalf of its customers.
- **(Continuous) monitoring** – organizational trust and behavior requires monitoring, either continuously or periodically.
- **Change management** – any changes to an organizational profile in terms of its behavior must be validated and/or certified. This enables the extension of the infrastructure with new functionality.

Of course, this is just a simplified outline for which a legal framework can be formulated. A certification authority can perform continuous or periodical monitoring as a basis for a registration authority for issuing a VC/DID. Such a certification authority can be supported by an (online) testing, validation, and certification environment.

4 Conclusions and future work

This paper proposes a set of agreements, the protocol stack, as a means for constructing the PI Data Sharing Infrastructure. The upper layer protocols are given special attention, since these specify semantics and data sharing functionality by alignment of specific developments by Industry Associations, communities, and regulators. To facilitate alignment, semantic web standards are proposed, modeling alignment concepts like Digital Twins, events, states, and state transitions. This so-called upper ontology for multimodal data sharing is the basis for individual organizations to specify their data sharing requirements and – capabilities, implement these by for instance Application Programming Interfaces (APIs) or semantic web technology, and develop data quality validation solutions. The latter is the way forward, since it supports all potential queries of a data user that don't require standardization. Thus, it provides flexibility. Alignment and the support of different technologies contributes to adoption, which requires an adoption and migration strategy.

Adoption requires more attention, combined with governance and legal aspects. Various stakeholders of different domains need to be involved like Industry Associations, communities, regulators, and public (and private) policy makers at national, EU, and global level (e.g. EC DG CNECT/Move/Agri/etc., WEF (World Economic Forum), UN CEFACT, WCC (World Customs Council), and the World Bank). Most of them still take the traditional approach to data sharing based on pushing data or implementing a subscription method. These approaches are supported by new technology like blockchains with NFTs (Non-Fungible Tokens) and VCs (Verifiable Credentials). An overarching approach is required that considers all developments and integrates them into the proposed approach in this paper. Innovation in standardization is required, involving proper standardization bodies. One observation from practice that requires more attention is that private initiatives are competing and do not lead to an open data sharing infrastructure. A public initiative must be taken.

And still more technical work needs to be done like exploring the potential of so-called Large Language Models like chatGPT for alignment, matching, and query formulation. Also a prototype of the infrastructure supporting one or more (artificial) use cases must be developed (first prototypes of components are available via FEDeRATED (federatedplatforms.eu)). At the same time, already existing implementation initiatives must be coordinated and supported to realize the infrastructure.

Acknowledgements

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A Framework for Developing a Regional Freight Transport Observatory

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Abstract: *Previous research has highlighted the lack of freight data as a significant barrier to producing evidence-based freight policy planning. This lack of freight flow visibility makes the formulation of freight policy a piecemeal. The aim of this research is to look at the feasibility and the requirements for establishing a Regional Freight Transport Observatory (RFTO). Eight cases around the world are analysed according to a framework that is consistent with the five dimensions of data stickiness. This research provides a profile of the current state-of-the-art practices in urban freight data sharing which lead to the generation of key ideas for the establishment of the RFTO. Analysis showed that the formulation of freight policy received very limited attention which confirms the need for the proposed research about the RFTO. An independent, neutral, third-party trustee could be a useful approach for transport and logistics data sharing. RFTO is a novel concept that advocates a partnership between public and private stakeholders in securely sharing regional freight traffic information and thus could provide improved visibility on urban freight traffic movements with the goal to inform and support freight policy development and to help develop better approaches to support freight logistics practices in urban areas.*

Keywords: *Last-Mile Logistics, City Logistics, Freight Data Sharing, Freight Data Analytics*

Conference Topic(s): *last mile & city logistics*

Physical Internet Roadmap (Link): *Select the most relevant area for your paper:* ☐ *PI Nodes,* ☐ *PI Networks,* ☒ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

1 Introduction

In recent years, urban logistics has been undergoing a major transformation due to the change in shopping behaviours. The growth in online shopping has led to a significant increase in urban delivery trips led primarily by haulier and couriers (Rivera-Royero, et al., 2021). In particular, the increases classified as "freight transport by road" and "postal and courier activities" have been up to 114% and 147% respectively during this period (ONS, 2022). These additional delivery trips are exerting more pressures on the already congested urban road networks, kerbside accesses, as well as other issues such as environmental impacts (Jaller and Pahwa, 2020; Strale, 2019).

In the context of the West Midlands (WM) region of the UK, freight transport has been high on the agenda of the local transport authority who is responsible for assessing and planning for the region's future transport needs so that the transport network can satisfy the demands of businesses and a growing population. Hence, the question is what can be done to balance the negative impacts for the need to reduce carbon and vehicle miles (and thus congestion) in the urban areas, whilst accommodating the growth in consumer demand as well as the wider economic growth. Freight Strategy research in the WM region has specifically highlighted that lack of freight data as a key issue hindering quality analyses of changes in freight demands, identification of constraints,

measuring of capacity shortfalls, as well as quantifying benefits of proposed interventions (WMCA, 2016). This creates significant disadvantages for freight planning. The extensive and fragmented nature of the urban logistics industry can be one of the reasons. Industry stakeholders may only focus on their own operational issues and struggle to see the overall picture (Janjevic, et al., 2019). This lack of visibility is acknowledged as "freight blindness" (NIC, 2018; TfWM, 2021), making the freight policy formulation a piecemeal. This characteristic is also recognised in other regions (TfSE, 2022) as well as at national level (NIC, 2018) of the UK. With the existing available data, it is difficult to draw firm conclusions as well as to test any freight proposals put forward by industry and other stakeholders. In the long-term freight plan of the UK Department for Transport (DfT), the challenge of lack of visibility and understanding of the freight network is also acknowledged (DfT, 2022). Ultimately there is a need to break down the barrier between the public and private sectors to allow better understanding of what are often seen as complementary challenges (TfWM, 2021). Enabling both sides to see each other perspectives will be key to developing and implementing measures collaboratively which support shared objectives.

The WM being a leading area of the UK for transport innovation, a project was therefore commissioned by TfWM within the WM Future Transport Zone programme to address this need. This research was conducted as part of this project that looks at the possibility of establishing a Regional Freight Traffic Observatory (RFTO) to address the underlying issues of the freight blindness at the city or metropolitan level. This research will provide a profile of current state-of-the-art practices in sustainable urban logistics, which involve a requirement analysis for the development of the RFTO. The ultimate goal will be to pursuit the possibility of establishing the RFTO for the development of urban analytics by collecting, analysing and disseminating information that will have the potential to directly inform policy development in this area. This paper, in particular, will focus on a review of current practices and initiatives related to urban transport and logistics data sharing among stakeholders. This includes a total of 8 cases from Europe, Singapore, Hong Kong, and the US. The next section will first describe the development of a framework for the review of these cases. Major findings from the review would then be summarised for which useful lessons can be drawn. This will include a profile of state-of-the-art practices in urban freight data sharing which lead to the generation of key ideas for the establishment of the RFTO. Some future research ideas that are essential to put the proposed RFTO into real practices will also be identified.

2 Development of the Current Research Framework

Urban logistics is a complicated system involving multi, inter-related, and inter-connected stakeholders. The core components, system performance assessment and policy formulation should all be data and information driven. At the same time, data and information flows between stakeholders are highly commercially sensitive and thus data confidentiality and privacy are essential. A systematic literature review of research in urban logistics also concluded with similar results (Lagorio, et al., 2016) and recommended that future research should focus on (i) stakeholders involvement; (ii) urban logistics ecosystem; and (iii) common framework and data sharing platforms. These are well aligned with the purpose of the current study in addressing the underlying issues of freight blindness in the urban logistics enviornment. In view of this, critical issues related to data sharing approaches are reviewed.

Bechtsis, et al., (2022) proposed a generalised data sharing and monetisation framework for data-driven secure, resilisent and sustainable supply chains. This framework consists of 3 levels of progressively increasing data sharing boundaries and of another 3 layers with data monetisation activities. Data sharing levels starts from intra-organisation within a single partner, to inter-organisational within the supply chain ecosystem, and eventually extends to external public data

sources. Data monetisation activities start by data collection and management at each level. Collected data are then processed and safely propogate to the second layer of data storage for a sustainable and reliable network. At the third layer, stored data are analysed to produce useful information and then flow back to the storage layer.

To investigate the issues related to data and knowledge sharing in general, Huang et al., (2017) theorised a concept of knowledge stickiness to describe the difficulties in transferring knowledge by five contributing factors. This concept of stickiness was then adopted to describe the barriers to inter-agency data sharing in China (Zhou, et al., 2021), which included five dimensions, *(i) data sharing willingness; (ii) data sharing ability; (iii) data articulatability; (iv) data residence; and (v) data absorptive capacity.*

In the context of urban logistics data sharing, this data stickiness concept can identify the potential barriers for the effective functioning of the data sharing platform. Should these barriers be properly addressed, it can facilitate the smooth sharing of data among various stakeholders. Therefore, these data stickiness dimensions can be further extended to establish the research framework for this study. The correspondence between the data stickiness concept and the current research framework is summarised in Figure 1.
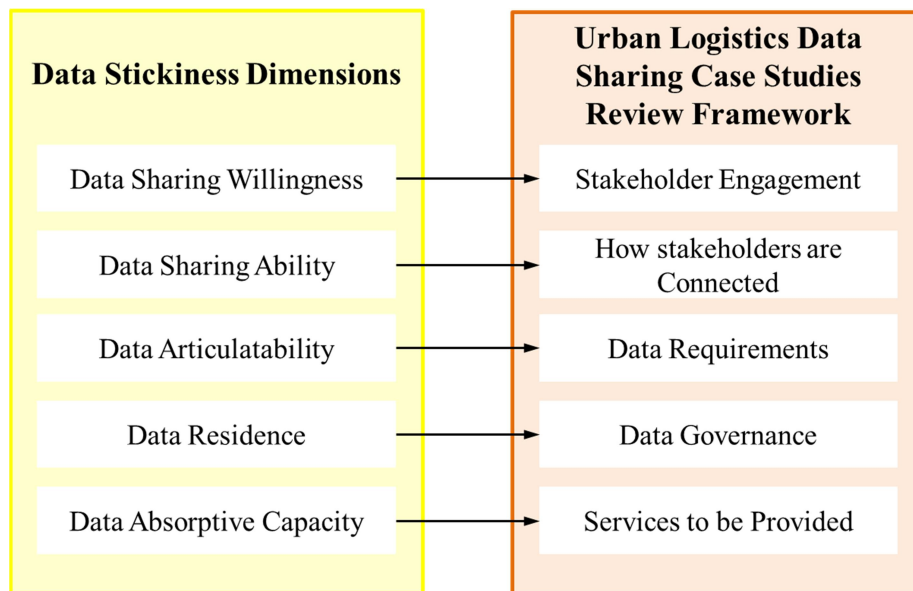
Figure 1: Correspondence between Data Stickiness and the Current Research Framework

Data Sharing Willingness is related to stakeholder engagement, which is totally aligned with the multi-stakeholder characteristic of urban logistics. Therefore, it is important to understand how stakeholders are engaged and motivated to actively involve in sharing data.

Data Sharing Ability refers to the technological infrastructure and the supporting software packages in sharing data. As discussed earlier, logistics stakeholders are largely operated independently with their own internal data managmement systems. The technological solution in connecting these individual and potentially different systems is another key dimension to the success of the data sharing platform.

Data Articulatability concerns about the data readiness, that is whether the data to be shared are readily available and collectable in the appropriate form and quality. In the context of urban logistics, it is related to the identification of the required types of data which would be useful in deriving deeper insight and visibility for other users in the data sharing platform.

Data Residence is the legal, regulatory and privacy restrictions of the data to be shared. Due to the strict confidentiality and commercial sensitivity of data, how the shared data are to be stored and used are of great concerns of the stakeholders. This would undoutedly affect their willingness to participate. So, it is critical to clarify the governance structure and mechanism for the data sharing platform so as to provide confidence for stakeholders to engage securely.

Data Absorptive Capacity is the practical and innovative applications of shared data. The ultimate goal of sharing data is to make better uses of the shared data in providing better visibililty and deeper insight to the urban logistics system, as well as further unlocking the potentials of shared data (e.g. vehicle route planning and optimisation). Understanding how the shared data can be used it is critical to the success of the data sharing platform. This is related to the services to be provided by the urban logistics data sharing platform.

3   Overview of the Reviewed Cases

With an aim to generate ideas for the development of a RFTO, a total of 8 cases were reviewed and summarised in Table 1. It is important to note that the cases reviewed in this study are not exhaustive. Selection of these cases was based on the availability of appropriate literature according to the research framework and the cases' relevancy to the current study.

Table 1: Summary of Reviewed International Transport and Logistics Data Sharing Initiatives

Project Name	Location	Brief Description
Architecture for EurOpean Logistics Information Xchange (AEOLIX)	EU	It demonstrates how stakeholders are connected together within a centralised data sharing facility with achievable benefits in terms of cost savings and logistics support.
Collaborative Urban Delivery Optimisation (CUDO)	Singapore	It highlights the potential for logistics data sharing to facilitate negotiations between shippers and carriers, and to optimise the consolidation process in urban last-mile logistics operations.
An Intermodal Transport Data Sharing Programme (Data Trust)	Hong Kong	It shows the importance of managing data access rights to ensure and respect data privacy, eventually provides data controller with confidence to share data.
Freight Logistics Optimisation Network (FLOW)	United States	It reflects the importance of engaging stakeholders and their commitments to share data, under the leadership and co-ordination of public agencies, to address the freight movement knowledge gap.
iSHARE Scheme	The Netherlands	It shows how sharing of data can be managed and governed under an independent, neutral, third-party organisation with a transparent supervisory and consultative structure involving various stakeholders.
Shared European Logistics Intelligent Information Spaces (SELIS)	EU	It demonstrates how stakeholders are connected with a decentralised approach using the concept of supply chain community nodes (SCN).
Freight Traffic Control 2050 (FTC2050)	London, UK	It demonstrates how vehicle and delivery job order data can be gathered to derive useful information

		showing deeper insight that could help making policy decisions in urban last mile logistics.
FreightShare Lab (FSL) Platform	Edinburgh, UK	It highlights the benefits of data sharing between logistics business partners and how the benefits can be shared among stakeholders.

The purposes of data sharing for each of these cases were first compared and then analysed with respective to the above framework, which included (i) stakeholders engagement; (ii) the overall concept of data sharing; (iii) data requirements; (iv) data governance; and (v) services to be provided.

3.1 Purpose of Data Sharing

The review indicated that most transport and freight data sharing cases were mainly aimed at facilitating collaboration between stakeholders to minimise empty goods vehicle trips and to improve their utilisations, which would eventually lead to reduction in business costs, vehicle energy consumptions and exhaust emissions. Through sharing of freight data, the platform would be able to provide supply chain visibility. These help raising the awareness of a wider spectrum of stakeholders about the benefits of sharing freight data with their counterparts and thus further motivate more operators to participate in the data sharing platform.

3.2 Stakeholders Engagement

Stakeholders are key players of the data sharing platform. Their willingness to engage is critical to the success of the proposed RFTO. According to the review of these cases, the following stakeholder groups could be identified around the scope of urban logistics:

End Users – those who will use the information provided by the RFTO to actively involve in urban logistics operations. These include suppliers, carriers, retailers, consolidation centres and other logistics services providers. They represent one major source of data required for depicting the overall picture of freight traffic movements.

Public Authorities – primarily include local transport authorities, and other public agencies, altogether to provide the rules for and information on the key road network and the distribution of major transport and logistics facilities.

Service Providers and Developers – those who provide contents and services to End Users, Public Authorities, and customers. They provide methods and algorithms to generate useful information and analytics from the shared data, or using the platform's functionalities to develop a service to be offered to various users.

Service Enablers – those who provide the data sharing telematics infrastructures and technologies (e.g. IT solution consultants) to address issues related to system connectivity, as well as the transmission, storage and receiving of data and information.

Technology Suppliers – those who provide the physical systems and hardware such as on-board systems and mobile devices that are used to deliver services to end users.

3.3 How Stakeholders are Connected Together

These cases revealed several approaches for connecting participants to perform data exchange, aggregation and optimisation functions. The first one is a centralised approach that included (i) a connection module to connect various participants together within a centralised facility or information space; (ii) an analytical module to perform basic data analytics that would deliver

useful information to end users; and (iii) a value-added module to conduct advanced analytical and optimisation functions.

Some other cases employ a decentralised approach that relies on a "node" or "community" concept. Local collaborations and connections are established within a specific group of users (i.e. a node or a community). The node's co-ordinators, who look after data exchange issues within the node or community, are then connected together to become an associated network.

A third approach tends to adopt a more passive mode in which data sharing is completely voluntary, and hence relies heavily on stakeholders' motivation and willingness to participate. It is more suitable for projects with strong commitments from stakeholders. This approach might be appropriate in the context of RFTO, particularly if a more phased, organic, bottom-up approach is followed, but comes with its own disadvantages in terms of capturing the full potential of the RFTO.

Apart from the approach for connecting participants, the identification, authentication and authorisation of members together with a set of agreements building around these three aspects are essential to ensure a uniform, easy-to-connect, and controlled way of sharing data. The "Mobility Data Space" can be an example platform of this kind for consideration.

3.4 Data Requirements

Data to be shared is closely related to logistics players' daily operations. To support the core functions of the proposed RFTO, data requirements should be derived from the services to be offered. The data requirements mentioned below only represent, based on the review, some examples and the list is not exhaustive. The review indicated that delivery job order and vehicle data are required, including:

- Freight vehicle data - vehicle manifest data such as vehicle and driver locations (via GPS devices, mobile phone, etc.), collection and delivery schedules, vehicle sizes, capacities and availabilities as well as barcode related activity data;
- Delivery job data (or order data) - time, date, volume and cost information of the job;
- Other data, for example, parcel barcodes, delivery addresses, manifest ID number, driver ID numbers, and various temporal information about barcode related activities.

To derive spatial and/or temporal properties of major logistics facilities and freight movement information, data such as locations of warehouses and distribution centres (at postcode level), vehicle flows, truck load ratios, and gross vehicle weight information (from highway weigh-in-motion devices) is necessary.

3.5 Data Governance

No matter which particular structure is adopted for connecting stakeholders, the data sharing platform needs to be operated by an entity that ensure safe, secure and smooth data sharing operations. It was clear from the review that the RFTO should be implemented in the form of an independent, neutral, third-party Trustee. Governance of data shared by member organisations should be done through a set of agreements clearly stating the membership's terms and conditions. The Trustee shall be responsible for the overall operations of the RFTO, which mainly include membership management activities (i.e. joining and leaving of members), agreement enforcement activities (i.e. making sure members are conform to the agreements they signed), as well as platform marketing activities (i.e. promotion of the platform to a wider span of stakeholders).

3.6 Services to be Provided

One of the key functions of the data sharing platform is to utilise and process the shared data, and eventually convert them into anonymised and useful information that provide insights to various users. Based on the review of international experiences, the platform should possess the capability and functionality to derive data analytics and the results should be disseminated through visualisation tools that display the spatial and temporal properties of freight traffic movements. Participants should also be granted with access to these functionalities, analytics and visualisations. Commonly used forms of displaying system outputs are dashboards showing statistical and delivery schedule information, geospatial and temporal graphics displayed by different attributes such as type of goods, time of day, day of week, etc. Additional value-added services such as models and optimisation functions could also be provided.

4 Ideas for the RFTO

Based on the analyses in Section 3, this section elaborates some initial ideas for the establishment of the RFTO.

4.1   Vision of RFTO

It is clear from the review that stakeholders' motivation and willingness to participate in any data sharing initiative is directly related to the benefits they can obtain from sharing their data. International experiences also showed that very positive results can be realised from sharing data. Therefore, the ultimate ambition of the proposed RFTO should be:

- To facilitate and manage data sharing between stakeholders collaboratively;
- To provide improved visibility along the supply chain;
- To support business logistics operations;
- To improve evidence-based reporting; and
- To inform transport and logistics policy formulation.

4.2   Stakeholders Engagement

As discussed earlier, the proposed RFTO should include End Users, Public Authorities, Service Providers and Developers, Service Enablers, and Technology Suppliers. It is recommended that an evolution approach be adopted for stakeholder engagement. At the initial stage, stakeholders should first be invited to identify key challenges and issues in their logistics operations. These can serve as inputs to the design, planning and development of the RFTO. In the next stage, stakeholders who are interested to participate could collaboratively work in groups to address the more detailed functional, technical, operational, and legal issues with an aim to create an initial set of agreements of data sharing conditions. Finally, the overall governance, data integrity and sustainability issues would be addressed at later stages before the platform is launched.

This approach could ensure that the existing challenges and issues in the urban logistics sector are identified and considered in the RFTO. It also helps to create an impression to the stakeholders that their concerns are being considered and addressed at the development stage. In particular, engaging stakeholders throughout the development process (especially the End User group) ensures that they would be kept informed of how they can benefit from it.

4.3   How Stakeholders are Connected Together

In light of the above review, the trusted third-party model can be considered as one of the options to improve business to government data sharing. Also, stakeholders need to collaborate together so as to provide a thorough understanding on urban freight travel demand. The future planning and transport enhancement would not be as influential without such data insight.

The government, data providers and the trusted third party should work closely on building a trusted system that can serve the data sharing purpose by adding value to create a more effective and integrated transport and logistics system, whilst also balancing each of the data providers' commercial interest. The US passive data sharing approach could also be another option forward as it is bottom up but at the same time driven by the government. Given the cultural proximity of US and UK, it might also be worth to consider.

However, no matter which approach is adopted, the platform should pay attention to:

- Identity and Access Management (IAM), which are critical and need to be appropriately addressed to ensure data security, and data are being used in the way that are permitted;
- Data owners should retain controls of their own data within the data sharing platform. It means that they should have control over what data to be shared with whom under what particular conditions.

4.4 Data Requirements

The RFTO could set up a pilot using currently available data such as locations of major logistics facilities to derive the spatial (or temporal) distributions on maps. Currently available sources of traffic flow data (e.g. loop detectors and cameras in the urban areas, weight in motion) could also be explored to see what can be achieved by better utilising these readily available data. It is anticipated that useful freight traffic information such as vehicle flows on the urban road network might be obtained from these data sources.

Through exploring multiple data sources, there would be clear evidence of data insight and adding value to create more effective and integrated transport and logistics system and their associated facilities with enhanced user experience and effective use of resources.

It is also essential to set up common data formats that allow data providers to contribute partial data with ease, as this can also address concerns on revealing commercially sensitive information.

4.5 Data Governance

The RFTO should be managed and operated by an independent, neutral, third-party Trustee. Governance of data shared by member organisations should be done through a set of agreements clearly stating the membership's terms and conditions. A supervisory and/or advisory governance structure may also be included to monitor the performance of the Trustee as well as providing guidance and inputs to the operations of the RFTO. Inclusion of such structure could also impose accountability on the Trustee. The constituency of the Trustee and/or the supervisory body should ensure transparency and sufficient participation of members of the RFTO.

Under the proposed third party trusted framework, the governance should be done through a set of agreements or Memorandum of Understandings (MoUs) signed between participating organisations and the Trustee so that data providers would share certain types of data with confidence that their commercial interests and privacy concerns are fully safeguarded while serving the interests of the RFTO.

The government should take the role of a facilitator to engage stakeholders in a collaborative and co-ordinated approach to develop the data sharing platform. The governance of the Trustee should be transparently accountable and performance frameworks should be results or outcomes oriented, rather than activity based.

4.6 Services to be Provided

The services to be provided by the RFTO should be able to address the operators' concerns, which means "how the establishment of the RFTO could possibly benefit them?". Therefore, the exact services to be offered by the RFTO should be derived during the system development stage. The services mentioned here represent, according to the above review, the typical services and/or functionalities that a logistics data sharing platform could deliver. These can be broadly categorised into two types: Generic Services and Specific Services.

Generic Services commonly refer to some basic statistically aggregated information (or more advanced data analytics) generated from the shared data. They could be accessed and available in the form of statistical reports or graphical displays via an interactive dashboard function. End Users and Public Authorities can get a deeper insight on urban freight operations, and make use of this information to support their decision making and policy development activities. Examples of Generic Services include supplier demand information, freight flow information, statistical indices reflecting the utilisation and congestion levels of logistics facilities, delivery performance information, spatio-temporal distributions of major logistics facilities.

Specific Services are functions for an individual End User or Public Authority. These can be delivered through specifically developed services by Service Providers and Developers, using the functionalities and Generic Services of the RFTO, and offer to a specific End User or Public Authority. Alternatively, up to the agreement of the participating members, the RFTO can also incorporate those functions and services within the architecture of its data sharing platform. Stakeholders, according to their identity within the data sharing platform, could be allowed to subscribe to those services. These services are usually related to user-oriented optimisation services. Examples of Specific Services include, demand mapping functions, vehicle routing optimisation, delivery round predictions, as well as collaborative delivery schedules and routes determination.

5   Conclusions

This paper performed a review of 8 data sharing initiatives. A research framework generalised from the theory of data stickiness was developed. Some key findings were identified from the critical review and eventually generated some ideas for the development of a RFTO in addressing the important issue of improving freight visibility.

The reviewed cases mainly shared data for improving business operations as the major focus in order to motivate stakeholders' participation. It was found that these cases generally did not include a specific objective to provide evidences supporting public policy evaluation. This highlights the uniqueness of the current study to inform freight policy formulation and to support better approaches to understand freight and logistics needs as part of policy and scheme development.

Whilst the Trustee and the government led approaches can be potentially suitable for the proposed RFTO, a further detailed study should be conducted to understand views of different stakeholders towards different approaches. No matter which approach is to be adopted, the platform should pay special attention to issues related to identity and access management as well as data ownership. Stakeholder engagement should adopt an evolution approach to encourage more active participations.

A pilot should be developed, using the currently available data, with a view to predict possible impacts of any policy changes affecting freight and logistics operations and how to best design these changes to account for stakeholders' needs. Results from the pilot could also be presented to various stakeholders to encourage wider participations.

It is clear from the review that an independent, neutral, third party trustee is a common approach for logistics data sharing. A further study should be conducted to work out the details (e.g. operations

and accountability structures, etc.) of the data governance mechanism in ensuring that data are shared in a safe and secure manner.

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Measuring Efficiency of Automated Road Freight Transport: The AWARD Approach

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Abstract: Autonomous vehicles will be a key ingredient of future road transport solutions. Even if significant progress has been made in technological developments and autonomous transport vehicle demonstrations, there are still challenges to be addressed before widespread adoption can occur, e.g., 24/7 availability in harsh weather conditions. Quantifying the performance of autonomous vehicles is crucial for logistics operators when deploying such solutions. This paper presents KPIs related to autonomous road freight transport. Furthermore, the evaluation methodology of the European H2020 project AWARD related to efficiency of autonomous vehicles is presented and initial insights from the project are sketched.

Keywords: L4 autonomous freight transport, vehicle efficiency, fleet management efficiency

Conference Topic(s): Autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms); ports, airports and hubs; vehicles and transshipment technologies.

Physical Internet Roadmap (Link): ⊠ PI Nodes, ⊠ PI Networks, ☐ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.

1 Introduction

Logistics services represent a fundamental element of today's economic activities. The last decades have demanded for continuously improving logistics performance. A number of challenges, such as the Corona-Pandemic, labor shortages, ambitious sustainability goals, digitalization or increasing freight volumes have put pressure on logistics service providers to optimize their performance. One potential solution to these challenges is the use of autonomous road transport vehicles.

Autonomous vehicles have the potential to address key issues in commercial transportation, such as the lack of qualified drivers, the number of fatal accidents with trucks, or 24/7 transportation. Significant progress has been made in the field of autonomous road freight transport with numerous prototypes on the road in Europe and North America. Companies like KAMAG in Germany and TuSimple in US have successfully demonstrated their prototype vehicles in commercial operation with key logistic companies such as DB Schenker and US Postal, respectively. However, there are still challenges to be addressed before widespread adoption can occur. From a technological point of view, the deployment of autonomous heavy-duty vehicles is hindered by the current inabilities of these vehicles to work with the right safety and functional level for 24/7 availability (e.g., in harsh weather conditions, dense fog, heavy rain or snow). This is a crucial pain point, as the majority of users are operating time critical

logistic flows, they must have the certainty that autonomous trucks will deliver an agreed throughput with agreed timing to integrate them in their logistic processes.

Quantifying the performance of autonomous road freight transport vehicles is crucial to be able to take informed decisions when it comes to the deployment and continuous improvement of them. This research paper derives performance indicators for autonomous road freight transport from related work. Furthermore, the paper illustrates the respective efficiency evaluation methodology designed in the EU-H2020 project AWARD (All Weather Autonomous Real logistics operations and Demonstrations) and sketches initial evaluation findings. The presented performance indicators comprise the evaluation aspects (i) fleet efficiency, (ii) vehicle efficiency, and (iii) the efficiency of handling of goods which may be affected by autonomous road freight transport. For these evaluation aspects, initial results related to differences between manual und autonomous operations will be sketched.

This research paper is structured as follows. Following the introduction, related work addressing performance indicators relevant for the efficiency of autonomous road freight transport is presented. Based on the related work, the evaluation methodology designed within the H2020 project AWARD is presented and initial results are sketched. This research paper concludes with a result discussion and an outlook on future work.

2   Related Work

Efficiency is a key ingredient of business success within the logistics domain. As such monitoring and improving efficiency represents an important logistics activity. Subsequently, related work regarding the measurement of transport efficiency as well efficiency measurement of autonomous transport vehicles is presented.

Andrejić et al. (2016) review related work on measuring transport efficiency and they distinguish between two basic aspects of measuring transport efficiency, i.e., (i) fleet efficiency and (ii) vehicle efficiency. Performance indicators for vehicle efficiency refer to the vehicle itself and may comprise, e.g., fuel consumption, vehicle emissions, vehicle range, vehicle capacity, or insurance costs. Fleet efficiency targets a higher decision level and aims at optimizing the management of a vehicle fleet to perform transport task. Today, IT systems (fleet management systems) support transport logistics providers in this endeavor. The subsequent Table 1 adapts the literature review from Andrejić et al. (2016) and summarizes measures related to transport efficiency within the categories (1) vehicle efficiency and (2) fleet efficiency. In general, vehicle efficiency indicators can be classified to operational indicators (e.g., fuel consumption, vehicle capacity, driving distance, emissions, etc.), financial indicators (e.g., labor costs, insurance costs, fuel costs, etc.), and quality related indicators (e.g., quality delays). The same categorization can be applied for fleet management efficiency indicators, Thereby, operational indicators are for example total number of trucks, total capacity, average load factor of trucks, total fleet fuel consumption, total fleet emissions, etc. Financial indicators for fleet efficiency are e.g., total wages, total fuel costs, total insurance costs, etc. Quality indicators for fleet management could be total number of transport failures.

Table 1: Transport efficiency indicators review. Adapted from Andrejić et al. (2016)

Publication	Vehicle efficiency indicators	Fleet efficiency indicators
Andrejić et al. (2016)	Fuel consumption (l), number of stops (deliveries), distance driven (km), number of shipped pallets	Number of vehicles, fuel costs, total truck operating time (h), distance driven (km), shipped tons(t), vehicle utilization (%)
Andrejić et al. (2013)	Fuel consumption (l), vehicle maintenance costs, shipped pallets, distance driven (km), number of stops (deliveries)	Number of vehicles, number of employees in transport, fuel costs, invoices (demands), driver's overtime, driver's overtime per driver, tour/driver, delivery/driver, tons/driver, pallets/driver, distance/driver, time truck utilization, space truck utilization, failures in transport
Cruijssen et al. (2010)		Equipment (e.g., number of trucks, number of trailers, total loading capacity etc.), labor (e.g., total wages, (drivers') experience, total hours worked, number of employees, etc.)
van Donselaar et al. (1998)	Direct cost/truck, wages/driver, hours/truck, hours/driver, speed, (un)loading time/trip, turnover/trip, loading capacity, variable costs/km	km/truck (km/trip & number of trips/truck), load factor when not empty, % km driven empty, turnover / (1000 kg*km)
Kim (2010)	Labor cost, fuel cost, oil cost, supplies cost, taxes/insurances/etc., transportation distance, transportation amount, transportation distance	Average efficiency (%), no. of efficient trucks, efficient trucks (%), minimum efficiency (%)
Kuosmanen and Kortelainen (2005)	Mileage, fuel consumption, undesirable outputs (CO_2, CH_4, N_2O, CO, NO_x SO_2, emissions…)	
Simons et al. (2004)	Labor, energy consumption, operating costs, vehicle emissions, fuel, transport losses or wastes (driver breaks, excess loading time, fill loss, speed loss, quality delay)	

In the field of autonomous transport vehicles, Innamaa and Kuisma (2018) present results of a survey with 77 expert for the impacts of automation in road transportation. They define overall twelve impact areas of automation and investigate related key performance indicators. With respect to efficiency, especially the areas (i) vehicle operations / automated vehicles, (ii) use of automated driving, (iii) energy or environment, and (iv) costs present relevant indicators from the automation domain. Following, the top 3 ranked KPIs for each area are listed in Table 2.

Table 2: Top 3 KPIs for assessing the impacts of automation in road transportation. Adapted from Innamaa and Kuisma (2018)

Area	KPI
Vehicle operations	# instances where driver must take control per 1000km
	Mean and max duration of the transfer of control between operator/driver and vehicle (when requested by the vehicle)
	Mean and max duration of the transfer of control between operator/driver and vehicle (in case of manually overruling on/off)
Use of automated driving	# instances where driver must take control per 1000km
	Use of automated driving functions (% of km of maximum possible use)
	Comprehensibility of user interface (expressed on a Likert scale, e.g. 1–9, low–high)
Energy or environment	Energy consumption of a vehicle (liters / 100 km or miles per gallon or electric equivalent)
	Tailpipe carbon dioxide (CO_2) emissions in total per year and per vehicle-km or -mile
	Tailpipe criteria pollutant emissions (NOX, CO, PM10, PM2.5, VOC) in total per year and per vehicle-km or -mile
Costs	Capital cost per vehicle for the deployed system (infrastructure, monetary value)
	Cost of purchased automated vehicle (market price, monetary value)
	Operating cost for the deployed system (per vehicle-hour or per vehicle-km or mile, monetary value)

The fleet efficiency, as investigated in related work of transport efficiency, is not explicitly defined as KPI-area by Innamaa and Kuisma (2018). However, further KPI-areas such as safety, personal mobility, travel behavior (modal share, distribution on routes, etc.), network efficiency, asset management (physical and digital infrastructure), public health, land use, and economic impacts are investigated by the authors. These areas define KPIs either on a generic level or out of scope of measuring efficiency of automated road freight transport.

3   AWARD Efficiency Measurement Approach

3.1   AWARD Overall Testing and Evaluation Methodology

In terms of the overall testing and evaluation methodology, the AWARD project (see AWARD project (2023)) adopts the FESTA handbook (see ARCADE Project (2021)). The Handbook was originally produced by the Field opErational teSt supporT Action (FESTA) in 2008. The handbook aimed at guiding upcoming automotive field operational tests and a new wave of EU projects. Since then, the handbook has been repeatedly updated by follow-up networking projects, collecting lessons learned (e.g., from FOT-Net, CARTRE and ARCADE). The FESTA handbook mainly targets large-scale user tests, but in recent years it has been successfully applied in various smaller testing campaigns, as well. A core contribution of the handbook is the FESTA V, which is the procedural model for guiding the conduction of Field Operational Tests (FOTs). Figure 1 depicts the proposed steps to be taken within the FESTA V application.
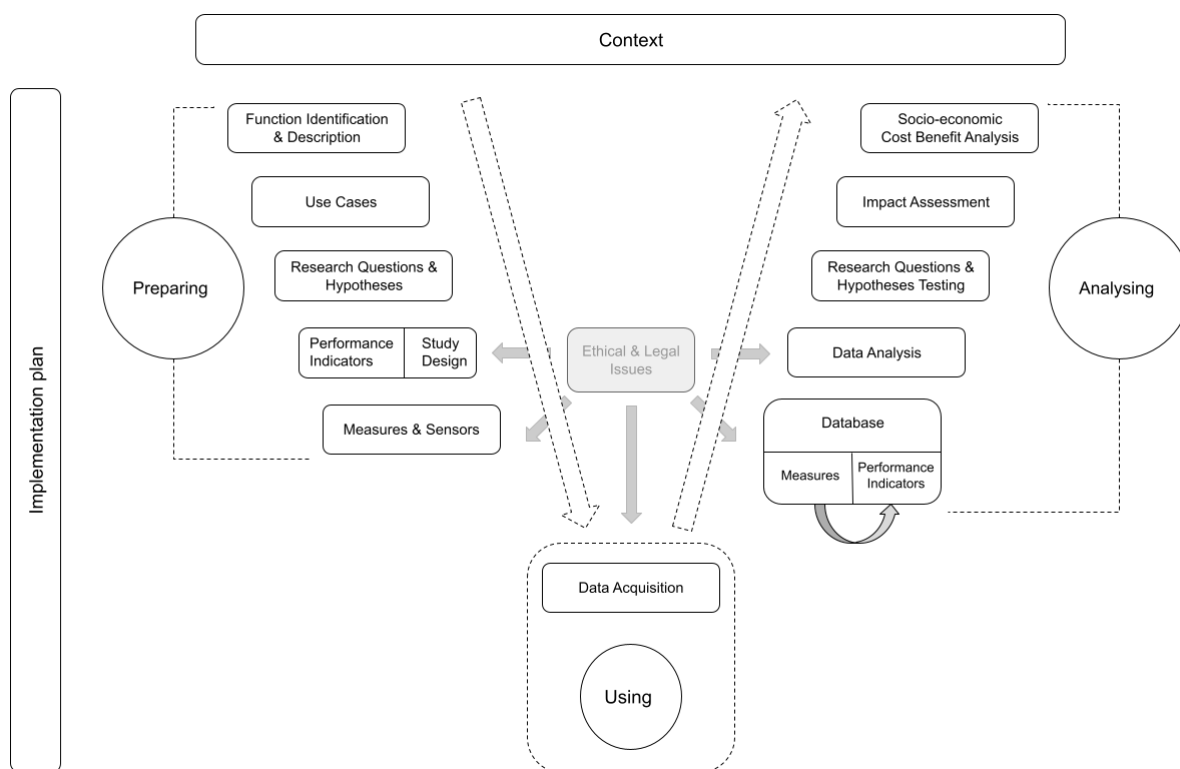
Figure 1: FESTA V - procedural model for field operational tests. Adapted from ARCADE Project (2021)

The first project year targeted evaluation preparations covered the left side of the FESTA V. As in FESTA, the main topics in the beginning of a study are to scope research questions and work towards an agreed focus and data to be collected. Tests and data collections have to be planned from the perspective of statistical evaluation – commonly this means collecting enough data both with and without the tested system in use. In addition to the operative tests in the final project year, the AWARD project has performed earlier testing related to product development and safety validation. Before the operative tests can begin, a certain amount of pre-testing and fine tuning is necessary, to ensure smooth performance. The pre-testing period, however, must also include log data collection for checking correctness and quality. User-related aspects such

as training and agreements are also necessary. The test plans in general are a joint product of both the test site teams and the evaluation experts. In general, the AWARD evaluation activities are divided into five main areas:

1. User and stakeholder evaluation
2. Safety impact assessment
3. Process efficiency and quality evaluation
4. Environmental impact assessment
5. Technical evaluation.

This paper focuses on measuring efficiency of automated road freight transport, which refers to area 3: Process efficiency and quality evaluation in the AWARD project. For this area, a generic evaluation design is presented in the next section. This generic evaluation design may be tailored to the application in different use cases.

3.2   AWARD Efficiency Evaluation Design

In the AWARD project the object of investigation is an Automated ground Goods Transport System (AGTS). The defined objective of the AGTS is described as "*Automated ground transport of goods in a defined area under harsh weather conditions*". The AGTS comprises different sub-systems such as

- Automated Driving Vehicle (ADV): i.e., the vehicle and its components (interfaces, communications, sensors, etc.). The ADV is in charge of the physical process of moving goods.
- Logistics Operation & Fleet Management (LOFM): This system controls the overall workflow.
- Supporting Infrastructure (SI): This system comprises the physical and digital elements that belong to the infrastructure and will interact with the ADV, e.g., barriers, stationary sensors, etc.
- Supporting Logistics System (SLS): This system is involved in loading/unloading operations.

In the AWARD project, real-world logistics use cases form the basis for demonstrating and evaluating the AGTS. The use cases support summarizing vehicle tasks in different settings, e.g., driving in operational areas or on public roadways, automation of different vehicles such as baggage tractors, trucks, or forklifts. Four generic use cases are studied within the AWARD project: (i) Loading/Unloading and transport with an automated forklift, (ii) Automated baggage tractor operation at the airside of airports, (iii) Hub to hub shuttle service, e.g., from production site to logistics hub, and (iv) Container transfer operations and boat loading at ports. (Fröhlich et al., 2021)

In an initial step, the project partners identified three generic evaluation areas related to efficiency, i.e., fleet efficiency, vehicle efficiency, and the efficiency of handling of goods. As shown in Figure 2, for each area research questions related to the influence on (1) financial indicators, (2) operational indicators, and (3) quality indicates were defined. In the following, hypotheses related to the research questions were formulated and prioritized. Overall, the evaluation experts defined more than 40 hypotheses. Subsequently, Table 3 sketches highly ranked hypotheses related to the research questions for fleet efficiency and vehicle efficiency. In the AWARD project, the research design for the efficiency of handling of goods has also been detailed. However, due to the limited length of the paper, this aspect is not further detailed.
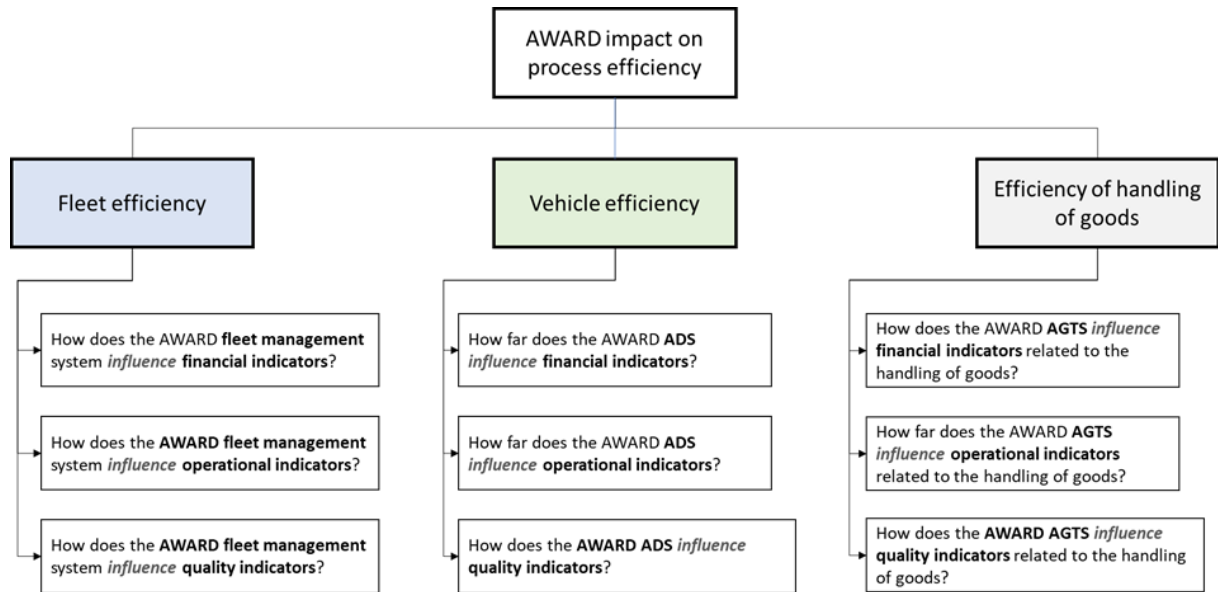
Figure 2: AWARD process efficiency evaluation areas and research questions

Table 3: Research questions and hypotheses related to fleet efficiency and vehicle efficiency

Research Question	Hypothesis
How does the AWARD fleet management system influence financial indicators?	The FMS reduces fuel costs
	The FMS reduces total costs per kilometer
How does the AWARD fleet management system influence operational indicators?	The FMS increases vehicle utilization
	The FMS minimizes the distance driven
How does the AWARD fleet management system influence quality indicators?	The FMS minimizes the number of vehicle breakdowns
	The FMS minimizes the average maintenance downtime
How does the AWARD ADS influence financial indicators?	The ADS supports reducing personnel costs
	The ADS decreases costs of vehicle operation
How does the AWARD ADS influence operational indicators?	The ADS reduces net transfer time
	The ADS increases vehicle uptime
	The ADS decreases personnel time to support (AD) vehicle while driving
	The ADS reduces fuel consumption
	The ADS decreases vehicle speed

	The operational availability of the ADS (with respect to varying environmental conditions) is lower than the availability of a manually operated vehicle
How does the AWARD ADS influence quality indicators in operations?	The ADS increases the timeliness of transport orders
	The ADS increases the transport reliability

The related work presented in this paper supported categorizing the research questions and hypotheses as well as defining measures and data needs to answer them. To investigate the hypotheses and research questions defined in AWARD, a mixed method and data gathering approach will be taken. For each data need, data within the baseline situation of the use case as well as within the AWARD AGTS application situation needs to be collected. However, the data collection will be tailored to the different AWARD use cases depending on the accessibility of data as well as the possibility to collect data during the project duration.

4 Initial Results

The airport use case in AWARD addresses the automated baggage transport at the airside of the Oslo airport in Norway. At the test site, first tests of different transport routes have already been performed with the vehicle and with related safety validation. The tests are performed with a TLD baggage tractor, which is instrumented with EasyMile's level 4 automated driving system and also integrated with the fleet management system (FMS) of Applied Autonomy. This setup allows to dispatch transport orders, record performance measures and any issues while performing the transport task. During the tests, trained operators from Oslo airport accompany the vehicle and additionally report issues in a logbook. The operators report additional information to certain types of stops and reasons they observed. As such automatically collected data from the vehicle and the fleet management system as well as the manually collected data by the operators provide a basis for the efficiency evaluation in the AWARD project. To validate the results also focus groups with vehicle operators are performed.

The targeted long-term advantages of automating baggage tractors identified by the use case stakeholders are (i) reduction in number of drivers / solve driver shortage, (ii) safety improvements, (iii) better utilization of luggage tractor capacity (supported by the FMS), (iv) less driving, if automated vehicle trips are better planned and managed (supported by the FMS), (v) less manual planning with improved fleet management.

The targeted speed of the automated baggage tractor is designed to be similar to human-driven tractors at the airside, with a maximum speed of up to 20 km/h. At present, the vehicle operates at a top speed of 15 km/h in automated mode. Since some other vehicles on-site travel at 30 km/h, the automated tractor is frequently overtaken. Initially, based on focus group discussions, other drivers did seem to get frustrated. However, the situation improved substantially within just a few days, as people became aware that the new vehicle was automated.
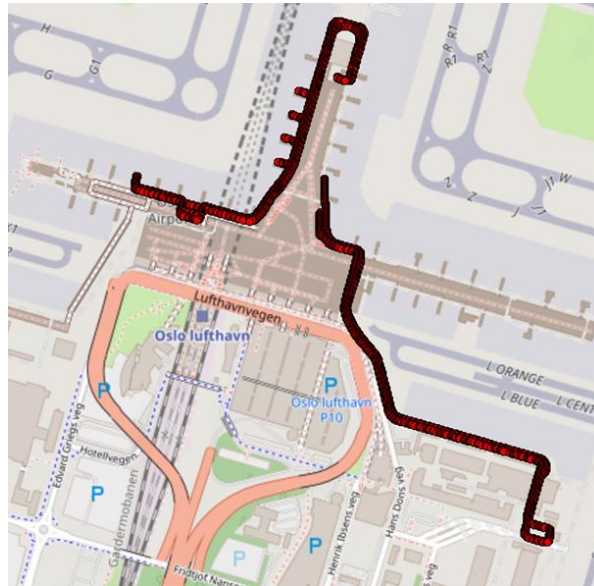
Figure 3: First test routes at Oslo airport. Map created with GPS Visualizer.

The initial tests were conducted during the first half of June 2022, totaling 50 hours of driving. The results indicated efficiency differences between the two different transport routes tested (Figure 3). According to the operators' statements, route 1 was more complex, with more crossings and other surrounding traffic participants. Consequently, the automated tractor required around 50% more time for the route compared to a manually driven tractor. In contrast, for route 2, operators reported only minor differences compared to manually driven tractors. In general, operators felt safe in the vehicle, and no critical situations were observed during the tests. Despite being slower than a human-driven vehicle, the automated vehicle was still fast enough to complete its tasks during the plane turnaround time.

No real-life tests under harsh weather conditions have been conducted thus far. Rain or crossing pedestrians did not significantly impact the tests, with only one safety stop due to rain and one case of the safety driver having to rearm the vehicle after stopping for a pedestrian. The most common reasons reported for safety stops, totaling around 50 each, were annotated as "no obstacle" or "route blocked". Baggage carts left by human drivers frequently blocked the intended vehicle route at turning points. Improved coordination between human and automated operations or maintaining more separation between them could alleviate such situations.

In these initial tests, safety stops required a safety operator (or, eventually, a teleoperator) to actively support or drive the vehicle for approximately 5 minutes per operational hour. It seems feasible for one teleoperator to oversee multiple vehicles. A comprehensive data analysis across different test phases and technological improvements is still necessary. This ongoing work will offer further insights into the efficiency of the automated transport vehicles developed for the AWARD use cases.

Based on real-world findings, the project will also conduct a simplified efficiency simulation of the test site, considering potential changes to the situation and key performance indicators if more automated vehicles were in use.

5   Conclusion

Efficiency of transport logistics is key. However, challenges in commercial transportation, such as the lack of qualified drivers, the number of fatal accidents with trucks, low load factors, time pressure, 24/7 transportation services, or climate laws demand for innovative transport

solutions. Autonomous transport vehicles combined with sustainable propulsion systems may be one innovation to support logistics providers in the near future. In the AWARD project, an automated ground transport system targeted towards harsh weather conditions is developed and tested within four different use cases. To be able to support potential users of automated transport vehicles to take informed decisions with respect to current automation solutions, efficiency evaluation is relevant.

This paper presented the AWARD testing and evaluation methodology. Thereby, specifically the evaluation design regarding process efficiency and quality was presented. Furthermore, related work in the field of measuring transport efficiency informed deriving categories and efficiency measures encoded in the evaluation design. Finally, initial results from one of the AWARD use cases – the airport use case – were sketched. The main evaluation and data gathering activities will be performed in 2023. For this reason, detailed results on concrete efficiency gains or losses with respect to automation are not reported in this paper and present future work.

Acknowledgements

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A Proposal and Evaluation of a Digital Twin Framework for PI-Hubs using Re-enforcement Learning based Multi-Agent Systems Model

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Abstract: *The Physical Internet (PI) provides a way to enhance logistic network performance spanning the social, financial, and environmental domains. Hyperconnected City Logistics (HCL) encompasses logistic activities arising within PI across the greater metropolitan region. To enable PI to operate as an open, collaborative network, a standard form of data exchange amongst network participants is required.*

GS1 Scan 4 Transport's Digital Link (GS1DL) is a data sharing standard enabling tracking of products through the supply chain. This includes the realization of shorter and more consistent processing times at goods transfer points within facilities. The potential impact of utilizing the GS1DL within a collaborative environment is yet to be investigated. Digital Twin (DT) enables real-time monitoring of assets' statuses and tracking of containers, leading to a real-time virtual representation of the physical facility, integrating the various computer network systems.

This study proposes a novel Digital Twin framework for PI-Hubs, integrating a re-enforcement learning based multi-agent system (MAS). Real-time location of goods flowing through the facility will be used by machine learning to predict the likelihood of containers arriving at the outbound docks, to be subsequently re-allocated to outbound vehicles via a reallocation optimization algorithm. The evaluation of the DT framework on PI-Hub's operational performance will include the assessment of Scan4Transport's Digital Link standard.

Keywords: *PI-Hubs, Data Standards, Automation, Collaboration, Operational Planning, Digital Twin, Hyperconnected City Logistics, Goods to Vehicle Allocation Problem*

Conference Topic(s): *autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs); distributed intelligence last mile & city logistics; material handling; Modularization; omnichannel & e-commerce logistics; PI modelling and simulation; hubs; technologies for interconnected logistics (Artificial Intelligence, IoT, machine learning, digital twins); vehicles and transshipment technologies.*

Physical Internet Roadmap (Link): *Select the most relevant area(s) for your paper:* ⊠ *PI Nodes,* ☐ *PI Networks,* ☐ *System of Logistics Networks,* ⊠ *Access and Adoption,* ☐ *Governance.*

1 Introduction

The Physical Internet (PI) provides a way to enhance logistic network performance spanning the social, financial, and environmental domains. PI-Hubs are key components for PI's

functional performance, serving as goods transshipment facilities among numerous carriers, where goods are transshipped between vehicles operating across the network (Ballot et al., 2021).

Hyperconnected City Logistics (HCL) embodies logistic activities arising within PI across the greater metropolitan region. This includes servicing of ecommerce based last mile deliveries (LMD) to homes via a nearby PI-Hub, such as an access or local hub (Crainic & Montreuil, 2016).

To enable PI to operate as an open, collaborative network, a standard form of data exchange amongst network participants is required. Currently, majority of logistic service providers (LSPs) utilise their own standards for data encoding and sharing, such as: the final destination, handling requirements and status updates. Upon receipt of inbound goods from various carriers each operating with their own proprietary standards & methods for sharing information, a PI-hub will face significant variability in processing times. This uncertainty may lead to adverse impacts on proceeding operations such as sorting, consolidating and loading of outbound vehicles.

Moreover, in the absence of a unified data standard, a PI-Hub may be forced to adopt its own approach, resulting in additional processing times for carriers operating outbound vehicles who will need to decode PI-Hub's data standard to extract the relevant information. Without the utilization of a unified data standard, collaboration within PI networks will be significantly impeded.

GS1 Scan 4 Transport's Digital Link (GS1DL) is a data sharing standard enabling tracking of products through the supply chain. This includes the realization of shorter and more consistent processing times at goods transfer points within facilities. The potential impact of utilizing the GS1DL within a collaborative environment is yet to be investigated (*Scan4Transport Pilot Report*, 2021). Therefore, this research seeks to investigate its role in facilitating efficient operations within PI-Hubs.

To enable optimal operational decision making amidst high volume of goods expected to flow through PI-Hub facilities, autonomous real-time decision making is necessary. There has been significant advancement of computational capabilities to process large amounts of data via sensors attached to the assets such as: identification & tracking sensors (eg: radio frequency identification tags (RFID) & 2D-QR); & environmental sensors (eg: temperature, vibration, gas, light & humidity) (Taniguchi et al., 2020; Tran-Dang et al., 2020). Further, with advancement in geographic information systems (GIS), it is possible to visualise, on a real-time basis, the data captured and the resulting analysis.

Digital Twin (DT) enables real-time monitoring of assets' statuses and tracking of containers, leading to a real-time virtual representation of the physical facility, integrating the various computer network systems such as: the Warehouse Management Systems (WMS), Transportation Management Systems (TMS), & Enterprise Resource Planning (ERP) (Taniguchi et al., 2020). This can assist in making more optimized operational decisions. There has been limited investigation of DT within PI-hubs.

Thus, this study proposes a novel Digital Twin framework for PI-Hubs, utilising a re-enforcement learning based multi-agent system (MAS). Real-time location of goods flowing

through the facility will be used by machine learning to predict the likelihood of containers arriving at the outbound docks, to be subsequently re-allocated to outbound vehicles. The evaluation of the DT framework on PI-Hub's operational performance will include the assessment of Scan4Transport's Digital Link standard.

1.1 PI-Based Collaboration Focused Studies

There have been a number of studies investigating ways of enhancing collaboration within PI networks. For example, ICONET sought to develop a cloud-based PI-framework and platform, building communications hub software enabling collaboration amongst various parties within the SCN (*New ICT Infrastructure and Reference Architecture to Support Operations in Future PI Logistics Networks*, 2019). Similarly, CO-GISTICS was an European project leveraging cooperative intelligent transport systems to enhance sustainability performance of networks within seven European logistics hubs. Further, PLANET, an EU project, designed a platform for collaborative planning called the Symbiotic Digital Clone. It serviced TENT-T Corridor participants (Zuidwijk et al., 2022).

Scan4Transport, a subsidiary of Global Standards One (GS1) has developed a novel 2D QR code called the Digital Link (GS1DL). This technology can foster collaboration amongst network participants along with enabling digital twin applications via its tracking and traceability functionality. The QR code can be encoded in a standardized way, critical product & delivery information including: origin, destination, & delivery handling requirements (*Encoding Transport Process Information - GS1 Implementation Guideline*, 2021). Furthermore, each time the code is scanned, the location of the scan (and thus the associated goods) is logged, enabling real-time spatial and temporal updates. This updated data can aid digital twin applications including data visualization and real-time operational decision making.

To date, no studies have been conducted towards assessing its suitability for operationalizing collaborative SCNs and its role in enabling digital twin functionalities (*Scan4Transport Pilot Report*, 2021). Its ease of adoption amongst users and enabling functionalities makes it a powerful candidate for assisting in the manifestation of PI. Thus, this research will focus on GS1DL's role in enhancing PI-Hub operations, both with respect to data transmission between carriers and the PI-Hub operator, and in enabling digital twin functionality via real-time operational decision making.

2 Problem Definition

A PI-Hub facility has its own outbound vehicles that services deliveries. It receives orders that it fulfills via its storage facility along with serving as a transhipment hub for goods incoming from inbound vehicles. Located within an urban area, thus constrained by size, it is likely to experience congestion and variable travel times of containers flowing through its facility and variability in inbound vehicle schedules due to urban traffic (McKinnon, 2015). Further, bottlenecks arise in crossdocks during loading of the vehicles at the outbound docks (Pach et al., 2014).

Within such a turbulent environment, real-time operational decisions need to be made including the allocation of goods to their respective outbound vehicles. Without real-time tracking of the goods, enabling real-time decision making, goods delayed due to congestion or late arrival at inbound docks, may result in sub-optimal loading factors for outbound vehicles and longer dwell times. Tracking can arise with the use of GS1DL, whereby the QR codes are scanned as the goods enter/exit through the facility at key junctures, including but not limited

to: inbound & outbound docks; sortation area; & storage areas. A re-enforcement learning based algorithm can then be utilised to determine the likelihood of the containers arriving at the outbound docks, which in turn informs the goods to vehicle re-allocation model. Further discussion is provided below.

3 Methodology

Figure 1 provides an overview of the proposed conceptual framework integrating the re-enforcement learning (RL) based predictive algorithm and the container to vehicle re-allocation algorithm. The RL algorithm is trained on past historical data, based on real operational data to be gathered from a large logistics company. It can also be simulated via discreet event simulation.
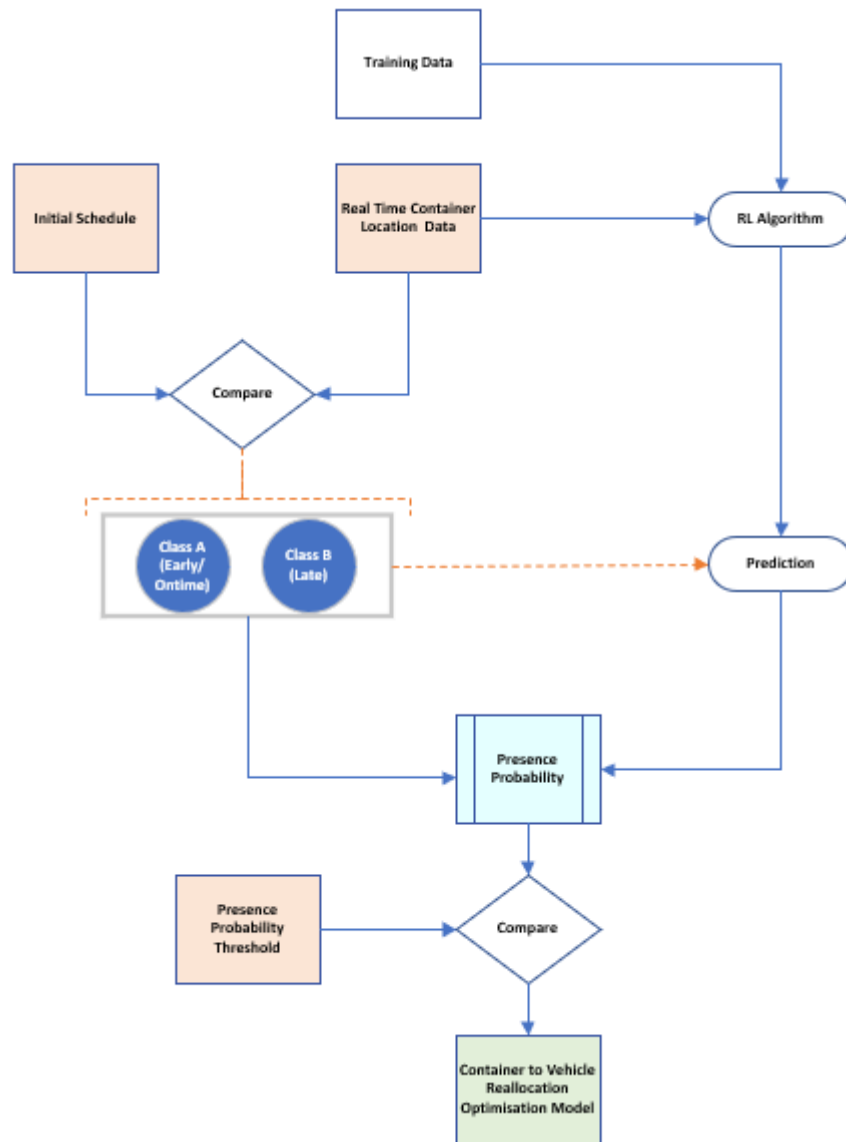
Figure 1 - Conceptual Framework of Re-enforcement Learning based Predictive Model and Container to Vehicle Reallocation Optimisation Model. Adapted from Prakoso et al. (2022).

Initial schedules of the inbound and outbound vehicles are used to allocate containers to respective outbound vehicles. Once at the facility, the containers' real time location is logged via scanning of the GS1DL code attached to each container. The captured real-time location is

used to predict the estimated time of arrival at the outbound dock where the container is to be loaded onto the allocated outbound vehicle. This enables a comparison with the initial schedule, and helps classify the container into one of two categories: Class A – where the container is expected to arrive earlier or on time as per initial schedule; or Class B – where the container is expected to arrive later than initial schedule. Subsequently, trained on historical data, RL algorithm assigns a presence probability for that container, reflecting the likelihood of it being in the class specified. Only those classified as late, ie in class B, and above a pre-defined presence probability threshold will be considered for the container to vehicle reallocation algorithm.

Prakoso et al. (2022) implemented a similar methodology for a chemical plant, dealing with the slot reallocation problem, where vehicles were reassigned to docks based on their ETA at the facility. Inspired by Prakoso et al. (2022), this study seeks to utilise presence probabilities for optimally allocating goods to vehicles based on their real-time location within the facility.

Further, Figure 2 provides an overview of how the RL based predictive model and reallocation optimization models are integrated with the multi-agent system. Real data is used to train the machine learning model that predicts the presence probability of the arriving goods at the outbound docks. Based on the presence probability of the arriving containers, the goods are (re)allocated to vehicles. Furthermore, in between these optimal reallocations, there may be perturbances that arise, including equipment breakdown within the facility or dock malfunction, resulting in inaccessibility to the respective outbound vehicle. This may mean that the containers may need to be re-allocated to other vehicles.
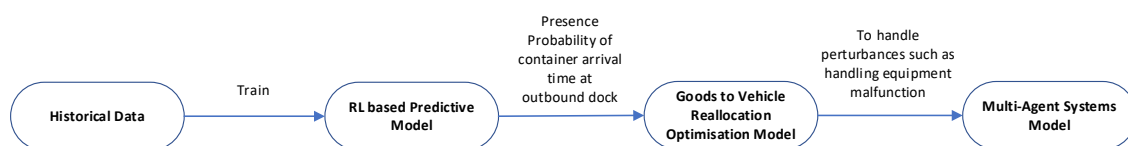
Figure 2 - Overview for integrating re-enforcement learning based Predictive Model, Goods to Vehicle Reallocation Optimisation Model, and the Multi Agent Systems Model

Figure 3 outlines the proposed multi-agent systems framework for handling such perturbances. Containers provide their real-time location data via the periodic scanning of the GS1DL QR code, which gets shared with the Physical Internet Management System (PIMS, as introduced by Tran-Dang & Kim (2018)). PIMS also receives operational status updates for the outbound docks and the AGV transporters, enabling optimal reallocation of the containers to the outbound vehicles under perturbances.
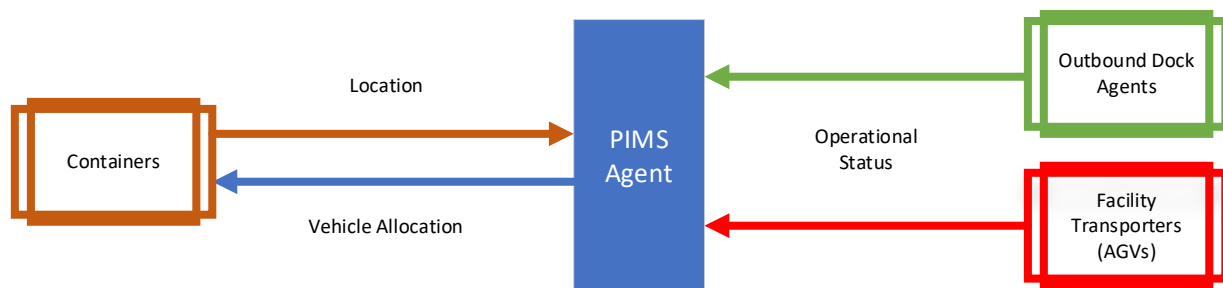
Figure 3 - MAS Architecture for handling perturbances

Three scenarios will be considered. The base case will be compared against two scenarios. The base case encompasses non-digitised, manual operations within the hub, including

unique electronic data interchange (EDI) between each carrier & hub operator. Such characteristics may result in delayed loading/unloading times & sub-optimal vehicle scheduling, consolidation, routing and loading of containers. The process is summarised in Figure 4.
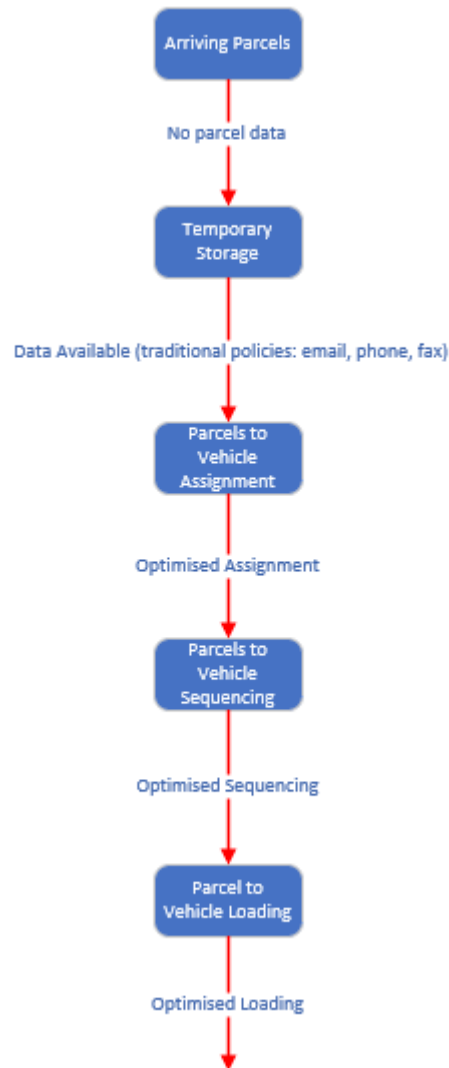
Figure 4 - Base Case: Facility without GS1DL, using preestablished electronic data inter-exchange with carriers and shippers to exchange data (Optimisation Model) and no real-time tracking through facility to enable parcel to vehicle reassignment.

The first scenario will be where GS1DL is utilised for EDI between carriers and hub operators The shorter and more consistent handling times during the product transfer between the vehicle and the hub should enable lower storage and personnel costs. Furthermore, the first scenario will include the utilisation and assessment of the Digital Twin framework for container tracking and the monitoring of assets operating within the PI-hub. DT is enabled via the scanning of the GS1DL QR code at key processing points within the facility. Figure 5 encapsulates this process.
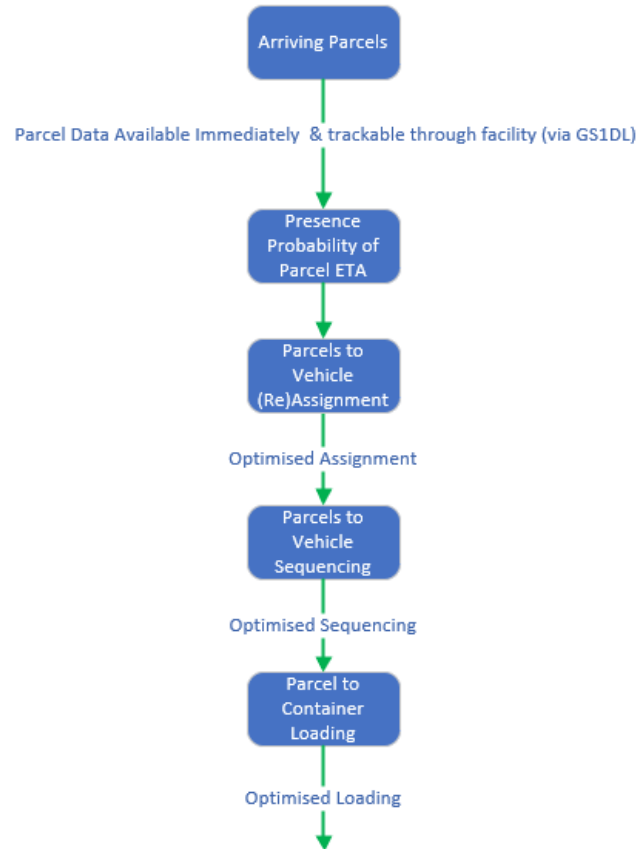
Figure 5 - Carriers and facility are GS1DL enabled with location tracking of goods, utilising the DT framework. Thus, presence probability of container ETA at outbound dock can be formulated via RL model, informing the container to vehicle assignment model.

The second scenario will consider internal perturbations including facility transporter and dock malfunctions. The objectives of the model will be to minimise makespan and maximise the volumetric capacity utilisation of outbound vehicles.
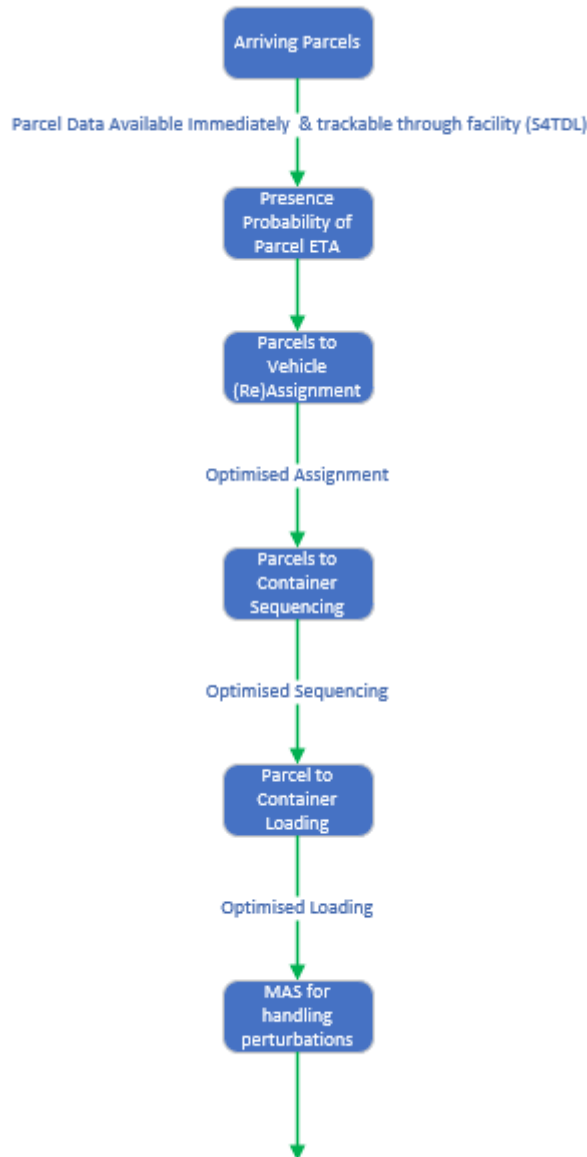
Figure 6 - Carriers and facility are S4TDL enabled with internal perturbations of facility transporter and dock malfunctions (Multi-Agent-System).

4 Conclusion

Harnessing the potential of Digital Twin technology, PI-Hubs can be greatly benefited. GS1DL is a strong candidate for enabling the use of such technology within the fast paced urban environments that PI-Hubs are expected to face. A novel DT framework integrating re-enforcement learning and optimization models has been proposed. Real-time location of goods flowing through the facility are used by machine learning to predict the likelihood of containers arriving at the outbound docks, to be subsequently re-allocated to outbound vehicles using the reallocation optimization model. Perturbances such as equipment and dock malfunctions are handled via the proposed multi-agent system.

It is expected that with real-time temporal & spatial monitoring of the assets within the facility, coupled with a common data standard enabling shorter and more consistent processing times at transfer points, greater accuracy of predicting container ETAs at the loading docks should arise. This in turn is expected to enable the attainment of greater

outbound vehicle loading factors with lower dwell times. Hub operators will be the primary beneficiaries of this study, coming to understand the operational impact of integrating Digital Twin technology & GS1DL into their facility's operations.

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Identification of cargo bikes and drones related challenges, potential strengths and benefits to achieve sustainable futures

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Abstract: Nowadays, there is an ever-increasing acceptance regarding the opinion that the use of more sustainable urban freight transport has the potential to offer great energy and efficiency benefits which can be handled through the appropriate combination of various measures such as: The creation of small urban supply chain centres, the use of clean vehicles and technologies with a low environmental footprint, the establishment of "first or last mile" value-added services and the smooth integration of urban freight transport within the framework of urban mobility´s management. This study examines, via an extensive literature review, the potential strengths, benefits, and challenges of the implementation of drones and cargo bikes for the last-mile deliveries in the urban logistics sector and specifically in large urban environments. The aforementioned literature review revealed the importance of different weather conditions on the flying capabilities of the unmanned aerial vehicles and the quality of urban environment´s components upon the safe delivery of goods through the utilisation of cargo bikes. Ultimate goal of this study is to contribute in tackling identified challenges, so the drone and cargo bikes implementation may become possible to a larger degree and deliver even more value to the logistic companies and the society.

Keywords: Cargo bikes; Unmanned aerial vehicles; drones; green logistics

Conference Topic(s): Choose the most relevant topic(s) from this list and remove the rest: distributed intelligence last mile & city logistics; logistics and supply networks;

Physical Internet Roadmap (Link): Select the most relevant area for your paper: ☐ PI Nodes, ☐ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.

1   Introduction

The sector of supply chain plays an important role in promoting economic development and economic globalization (Yang et al., 2019). However, the adverse effects of the logistics sector and freight transport on the environment are becoming more pronounced. The continuous growth of urban population and the extension of cities´ areas lead to an increase in the need for urban transport (City Logistics). The latter are associated with various issues such as the ever-increasing problem of traffic congestion, air pollution, noise, road accidents, energy consumption, and the large amount of greenhouse gases produced by fuel consumption (Chatziioannou et al., 2020). According to an analysis by the European Union (Eurostat, 2021), in 2019, road freight transport accounted for 76.3% of total land freight transport, followed by rail transport that accounted for 17.6%.

In recent years, due to the strong negative footprint on the environment, governments, companies, and citizens around the world tend to shift to a more environmentally conscious attitude. The same has happened in the transport sector, where concerns for a more ecological approach have multiplied, leading to the appearance of the term of "Green Logistics". However, it was not until 1990 (Srivastava, 2007) that the importance of green logistics was recognized as a significant economic and social issue. Current trends indicate a need for integrating environmental management into day-to-day operations (Srivastava, 2007). Therefore, the replacement of a part of conventional vehicle deliveries by environmentally friendly modes of transport could lead to a significant reduction of negative impacts worldwide, including the improvement of road safety, the enhancement of comfort concerning the interaction between heavy vehicles and vulnerable road users, the improvement of air quality and the reduction of congestion. On the other hand, this new necessity may increase the complexity of supply chain, and also create conflicts of interest between ecological and economic demands (Ebinger et al., 2006).

Several studies focusing on the introduction of cargo bikes in the supply chain, indicate their suitability for a significant share of freight movements (Narayanan and Antoniou, 2022), while an important increase in road safety is also observed, due to the reduction of accidents (Koning and Conway, 2016). In addition to cargo bikes, drones are now also used in an ever-increasing number of commercial applications. Cargo bikes and drones have also the ability to assist towards the establishment of Physical Internet´s (PI) concept so that to introduce alternative and sustainable means of transport within logistics operations (especially considering last mile delivery), actively contributing to the sustainable character of freight transport.

The objective of the paper is to transfer knowledge to researchers, the private sector of logistics and policy makers, and contribute in tackling identified challenges, so the drone and cargo bikes implementation may become possible to a larger degree and deliver even more value and benefits to the logistic companies and the whole communities that are directly or indirectly impacted by current shortcomings of the conventional methods of last-mile delivery.

2   Alternative Means of Freight Transport

Nowadays, the transportation landscape has been enriched with various innovative modes of transport as an alternative to conventional vehicles, such as electric trucks, cargo bikes, drones, etc. (McCunney and Cauwenberghe, 2019). Hence, in the following lines a presentation of drones and cargo bikes approaches for freight transportation can be appreciated so that to understand the dynamics of each mode as well as the combination of them in the effort towards sustainable development.

2.1 Drones and Cargo Bikes Utilization in Urban and Peri-urban Networks

One of the technologies that can satisfy consumers' needs for immediate delivery is the Unmanned Aerial Vehicles (UAV), commonly known as drones. The latter have varying degrees of autonomy and automation and are usually controlled remotely by an operator who is a few meters to several kilometres away or autonomously via on-board computers (Aiello et al., 2021) and can be characterized as a driving force behind the vision of Advanced Aerial Mobility (AAM) for the establishment of an 'on-demand' delivery of goods and emergency services (Boucher, 2015). The potential use of drones for 'last mile' deliveries is seen as an innovative technology that has been proposed in recent years, thanks to the advantages they offer over conventional modes of transport, such as the ability to overtake traffic, the capacity to cover longer distances, their ability to fly without a pilot but also their capacity to immediately take off in small areas (Goyal et al., 2021).

On the other hand, cargo bikes are bikes that are specially designed to carry small or large loads. Cargo bikes come in many forms, ranging from the traditional two-wheeled bicycle, three-wheeled models (cargo-trikes), and purpose-built four-wheeled models with electric pedal-assist motors for specific commercial needs". Types of cargo bikes can be found with or without electronic assistance (Joerss, 2016). The use of cargo bikes is a solution for environmental, economic, and social issues of many European cities, offering at the same time a new concept in mobility and quality of life that is the reason why they have been utilized adequately for the promotion of sustainable freight mobility and the replacement of conventional vehicles (Nocerino et al., 2016).

The combination of drones and cargo bikes is ideal for freight transport, as neither of these modes can, with some exceptions, cover the full route from origin to destination. Despite the capabilities of drones and cargo bikes, no freight transport applications were found (until now) that successfully mix these two transportation modes. On the contrary, the analysis of the existing literature showed that there is a common practice to combine either drones or bicycles with conventional vehicles or trains (Crisan and Nechita, 2019). The combination of drones and cargo bikes can be one of the most efficient ways of delivering small parcels, generating a positive impact on the environment, the reduction of freight costs as well as the faster delivery of packages. Nevertheless, both cargo bikes and drones have some limitations that need to be considered. Researchers Dybdalen and Ryeng examined the conditions for efficient movement of cargo bikes in winter months. They noticed that the uneven surfaces with accumulations of snow or ice tend to lead to bounce and possible skidding of the bicycle. Moreover, auxiliary batteries lose power faster and have a delay in charging under low temperatures. Some cargo bike users have reported that ice and cold temperatures intensify the wear and tear on the bike, raising the need for more frequent maintenance (Dybdalen and Ryeng, 2021). In steep hills is difficult to use cargo bikes, especially if the load is heavy, as it greatly increases the total delivery time (Dybdalen and Ryeng, 2021).

Regarding drones, there are two important conditions to be considered for the beginning of provision services in freight transport. The first one is related to technical feasibility-safety and the second is associated to existing legislative frameworks (Nentwich and Horváth, 2018). On a technical level, the most important limitation is the drone´s battery. At present, the flight duration of drones is limited due to the lack of batteries capabilities (Conceicao, 2019). Adverse weather conditions are another factor by which the drones are affected. High wind speeds, rain and snow make drones´ flying impossible. The legislative ones are also particularly important restrictions, such as the prohibition of drone flights over hospitals, camps, government buildings, airports, etc. These restrictions arise due to safety standards but also because of drones' ability to collect images, which can be recorded, stored, and even uploaded to the internet, thereby infringing private life. In addition, drones can be equipped with other devices, the use of which may assist the collection and processing of personal data, thus violating the applicable law upon the rights of citizens regarding the protection of privacy and data (Fridewald et al., 2017).

2.2 Vehicles Categorization

This section will deal with the categorization of vehicles and the recording of their main technical characteristics per category so that to have a clear idea about the differences, the similarities, and the selection of right equipment for the job. Several types of cargo bikes and drones will be presented through the following table for economy of words and space.

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Table 1: Key features and types of vehicles concerning cargo bikes and drones (Joerss et al., 2016; Watts, 2012).

ID	Category	Types of Vehicles	Key Features
1	Drones	Micro Air Vehicles or Nano Air Vehicles (MAV or NAV).	Vehicles of small size, capacity to reach low altitude flights (<330 m) short flight duration (5–30 minutes).
2	Drones	Vertical Take-Off and Landing (VTOL)	No special take-off or landing space is required, Vehicles of small size, capacity to reach low altitude.
3	Drones	Low Altitude, Short Endurance (LASE)	Short duration flights (from 45 minutes to 2 hours) at relatively low altitude (up to 450 m). Their weight is relatively small (2–5 Kg) and their wingspan is usually less than 3 meters.
4	Drones	Low Altitude, Long Endurance (LALE)	Flight duration of more than 20 hours. Ability to cover several kilometres away from ground control stations, carrying a considerable payload of several kilograms.
5	Drones	Medium Altitude, Long Endurance (MALE)	High operational requirements (used for military operations). MALE drones have advanced aerodynamic design and control systems and can operate at altitudes above 9000 m. Ability to fly (20–40 hours) and hundreds of kilometres away from the ground stations.
6	Drones	High Altitude, Long Endurance (HALE)	They are the bigger and most complex category of UAVs that can operate even as "very low orbit satellites" remaining at an altitude of over 14 km for days, weeks or even months.
7	Cargo Bikes	Messenger Cargo Bike	Cargo bike has 2 wheels, and their basket is located on the front and/or rear of the handlebar with dimensions of 0.03 – 0.05 sq.m. It has a load capacity of up to 20-40 kg and used for small parcels.
8	Cargo Bikes	Rear-load cargo bike	Cargo bike has 2 wheels and can load up to 100 kg. The cargo basket is located on the back of the bike and its dimensions are 0.4 – 0.8 sq.m. Electric assistance is also available.
9	Cargo Bikes	Front-load cargo bike	This type can carry a load of up to 125 kg. The cargo basket is located between the steering wheel and the front wheel with dimensions of 0.1 – 0.7 sq.m. Electric assistance is available.
10	Cargo Bikes	Rear-load cargo trike	Load capacity of up to 300 kg. The basket is on the back of the bike with dimensions of 0.5 – 1.5 sq.m. Electric assistance is necessary for its usage.
11	Cargo Bikes	Front-load cargo trike	Maximum load capacity equal to 200 kg. Cargo basket is located at the front of the bike with dimensions of 0.2 – 0.6 sq.m. Electric assistance is necessary for its usage.

2.3 Physical Internet and Alternative Means of Freight Transportation

The primary objective of City Logistics is to mitigate the adverse effects of freight vehicle movements on urban living conditions, specifically congestion and environmental impacts, without negatively affecting social and economic activities (Crainic and Montreuil, 2016). PI constitutes a modern approach of freight transport and logistics that aim to enhance and fortify the economic, environmental, and societal efficiency and sustainability of moving, storing, delivering, and using physical goods worldwide (Montreuil, 2011). The concept of PI involves the integration of various modes of transportation and logistics services into a single, interconnected network that allows for seamless movement of goods across the supply chain (via several hubs) and is based upon the idea of modularization, standardization, and collaboration, where goods are broken down into smaller units that can be easily transported and stored, and different logistics providers work together to move these units from one point to another (Montreuil, 2011).

In this point comes to the conversation the introduction of alternative and sustainable means of transport such as cargo bikes and drones so that to collaborate with the PI concept in a beneficial symbiosis for sustainable development. The latter can be justified through the positive impact that the adoption of drones and cargo bikes, for last-mile delivery purposes, will have upon the society via the reduction of greenhouse gases, the reduction of congestion phenomena, the mitigation of air pollution and noise, the enhancement of transportation system´s level of service and the improvement of livability of the people within a certain geographic region (Boysen et al., 2021). On the other hand, the demand for hubs in a PI network using cargo bikes and drones will depend on various factors such as the volume and frequency of shipments, the distance between the origin and destination, the capacity of cargo bikes and drones, and the availability of suitable landing and pickup locations. In general, the PI network using cargo bikes and drones will require decentralized hubs that serve as intermediate points for transferring and consolidating cargo since both are not able to cover long distances. These hubs will need to be strategically located especially in places where there are access restrictions (e.g., pedestrian zones) and where parking space is rare to ensure optimal routing and reduce delivery times.

The main priority of this paper is to review studies upon the factors that affect the flight performance of drones and to identify the environmental parameters that impact the quality of cargo bikes usage. More specifically, through desk research, the most important parameters in the movement environment of drones and cyclists were identified and recorded. Initially, a literature search was carried out, concerning studies related to a) the effects of weather conditions on the flying ability of drones, based on long-term - historical data about factors such as the speed of wind, temperature, rainfall data and b) all types of cycling travels, with the aim of identifying those factors that influence the choice of routes by cyclists. We then analyzed publications investigating whether cyclist accidents are statistically correlated to route´s environmental characteristics, followed by publications that statistically correlate the cyclist's perceived safety with the route´s environmental characteristics, and publications that statistically correlate the actual route choices that cyclists make in accordance with the features of the routes. The full text of these initially screened articles was then read against the research aim. This led to a review pool consisting of 38 articles, that were re-read, revised, and analyzed. The inclusion criteria of the selected investigations were defined as peer reviewed academic journals and conference papers written in English that are in line to our research objective. We decided to focus on peer reviewed journals and conference papers so that to ensure the quality of selected corpus. The search was conducted using Google Scholar.

3 Literature Review about the Environmental Factors affecting the Flight Ability of Drones

Weather conditions are an important factor that can significantly affect the efforts towards drone applications expansion. International studies show that global flying ability is at higher rates over hot and dry continental regions and at lower rates over oceans and at high latitudes. With the growing demand for drones, there is a need to better understand the effects that different weather conditions have on these systems (which include operators, observers, and aircraft) to plan and execute a delivery successfully. The classification of weather hazards to drone operations ranges from moderate to adverse and finally to severe (Ranquist et al., 2017).

Table 2: Classification of Hazards according to Weather Conditions.

Severity	Hazards	Weather Types	Operations	Sources
Moderate	Reduced visibility.	Fog	BVLOS	(Ranquist et al., 2017).
		Haze	BVLOS	
		Glare	VLOS	
		Cloud Cover	BVLOS	
Adverse	Loss of communication Loss of command Loss of control Reduced operator effectiveness Diminished aerodynamic performance.	Wind and turbulence Rain Solar Storms Snow and Ice Temperature and Humidity	VLOS BVLOS VLOS BVLOS VLOS	(Ranquist et al., 2017; Joslin, 2015; Warner, 2015; Hansman and Craig, 1987; Cao et al., 2014).
Severe	Unacceptable risk for operator and personnel Severe damage to or loss of aircraft.	Lightning Hail Tornadoes Hurricanes	BVLOS BVLOS BVLOS BVLOS	(Ranquist et al., 2017).

4 Environmental Parameters Affecting the Mobility of Cargo Bikes

In the literature there is a significant amount of research that examines the factors that affect the quality of a route for cyclists. The criteria by which the quality of the route is evaluated differ from survey to survey and consider the following themes: a) Objective safety (factors that increase the likelihood of a cyclist accident); b) Subjective safety (factors affecting cyclists' sense of safety); c) The statement of preference and route preference (surveys relating routes, declared to be preferred by cyclists, to the characteristics of those routes). Through literature analysis, the following factors/parameters were identified as the ones mainly affecting the choice of routes for cyclists.

Table 3: Identification of Environmental parameters affecting cargo bikes mobility.

ID	Factors	Sources	Description
1	Bicycle Infrastructure	(Reynolds et al., 2009)	Existing bicycle infrastructure (either as bicycle lanes or separated cycling routes) is one of the main factors that increase safety (both objective and subjective) for cyclists.

2	Street Lighting Elements (horizontal signings, public lights)	(Boettge et al., 2017)	Lack of lighting increases the likelihood of an accident and is often a cause of road crashes. Street lighting elements (horizontal reflective markings, light poles, etc.) are beneficial because they make visible points that would otherwise be dangerous and could cause cyclists to fall.
3	Number of Car Lanes	(Chataway et al., 2014)	The increase in cyclists risk appears to be proportional to the number of road´s traffic lanes, as more accidents occur in roads having more than two traffic lanes per direction. Such a result is logical because on such roads cars accelerate more and therefore cyclists become more vulnerable.
4	Width of Road lanes and bike-lanes	(Hamann and Peek-Asa, 2013)	The width of the road significantly affects safety, with wide roads increasing the likelihood of an accident to occur. In particular, the research of Hamann and Peek-Asa (2013) showed a 37% increase in the probability of an accident for every 3 meters of increase in the total width of the road.
5	Slopes	(Zimmermann et al., 2017)	This parameter is directly related to lower safety levels and consequently constitutes an inhibiting factor for bicycle utilization as considerably increases the probability of accidents for cyclists to occur.
6	Bicycle Infrastructure in Pedestrianized Areas	(De Rome et al., 2014)	The most numerous and serious accidents occur in mixed bicycle-pedestrian infrastructures. Proximity of cyclists to pedestrians often creates a sense of insecurity.
7	Velocity and Speed Limits	(Hamann and Peek-Asa, 2013)	Speed limits on roads (and by extension the actual speeds that the vehicles are allowed to develop) significantly affect the concept of objective safety for cyclists.
8	Intersections and Joints	(Strauss et al., 2015)	Intersections (signalized or not) are considered as high-risk points for cyclists. Consequently, the number of accidents increases in accordance with the number of signalized intersections that a cyclist encounters on his/her route.
9	Traffic Load	(Ghekiere et al., 2018)	Traffic load is considerably associated with the reduction of cyclists´ safety, in contrast to light traffic roads which were judged to be the most suitable environments.
10	Sharp Turns	(Broach et al., 2012; Zimmermann et al., 2017)	Lack of visibility due to sharp turns is a frequent cause of accidents. According to Zimmermann et al. (2017) and Broach et al. (2012) cyclists do not choose left turns on high-traffic roads, preferring to perform detours to avoid them.
11	Routes Length	(Hood et al., 2011)	Cyclists, prefer shorter routes, something that is totally expected, since every extra pedalling increases their fatigue. In parallel, cyclists are more sensitive to the characteristics of the environment through which they travel and consequently are willing to increase the length of their route in search of a safer environment.
12	Quality of Road Surface	(Ghekiere et al., 2018)	The quality of road surface constitutes another environmental parameter that affects the utilization of cargo bikes. Its importance is highlighted by Ghekiere et al. (2018) and is associated with high rate of accidentability.

5 Discussion and Conclusions

In modern societies, the mass accumulation of people in urban centres has led to elevated emissions of carbon dioxide. The goal of every urban centre, mainly because of climate crisis, is the reduction of these pollutants. Thus, integrating cargo bikes and drones into freight transport can benefit in achieving this goal. The resulting benefits from the use of cargo bikes and drones in freight urban and peri-urban transport are important as they contribute to the society via the reduction of greenhouse gases, the reduction of congestion phenomena, the mitigation of air pollution and noise. Within this context, the purpose of this article is to identify the environmental characteristics and elements that are important for cyclists during their journey, as well as the environmental factors that affect the flying ability of drones.

The most essential factors resulted to be traffic load along with speed limits and the circulation of heavy vehicles. The research showed that increased traffic, as well as higher speed limits, pose a greater risk to cyclists. The latter also feel particularly uncomfortable when riding next to heavy vehicles, as there is an increase in the number and the severity of accidents when the share of heavy vehicles in the traffic composition is high. Cycling infrastructures as well as the existence of slopes also constitute important elements for cycling adoption as they are the backbone for comfortable and safe cycling travels. Two more factors that can seriously affect the sense of cyclists´ safety are road intersections-joints and the width and number of road traffic lanes as the interaction between cargo bikes and motorized vehicles raise the possibility of road accidents occurrence. All the previous mentioned factors can be related and considered by several public policies that are not isolated countermeasures but form part of Sustainable Urban Mobility Plans to assure continuity and generate sustainable futures. The policies that have been identified as closely related to the cargo bikes and drones' environmental factors can be seen in the following lines:

- Reorganization of road network hierarchy and speed limits reduction.
- Creation of peripheral roads around the settlements to avoid through flows.
- Upgrade of intersections in the road environment to enhance road safety.
- Creation of exclusive and mixed-use cycling infrastructure and bicycle parking spaces.
- Implementation of traffic calming measures.
- Creating a smart freight supply system with innovative tools.
- Promotion of Urban Air Mobility schemes.
- Traffic management of heavy vehicles.
- Replacement of asphalt paving materials on the streets.

Regarding drones, the literature review highlighted the effect of mainly atmospheric factors, which can cause moderate to very severe hazards. Moderate hazards are those resulting from phenomena that reduce visibility but do not damage the aircraft, such as fog, glare, and cloud cover. Adverse hazards are related to weather conditions that may cause loss of control and communication, and may adversely affect the operator, such as wind and turbulence, rain, solar storms and extreme temperatures. Finally, severe hazards are those that would result in serious damage or loss of drone and would place the operator or personnel in a dangerous situation. These hazards include thunderstorms, lightning, hail, tornadoes, and similar phenomena.

Safety issues in the operation of unmanned aircrafts are critical, due to the exponential increase in the number of these aerial vehicles and the involvement they now have in many sectors, such as industry, medicine and especially in the commercial sector. Nowadays, through innovative perspectives in terms of legislation development, several steps have been implemented for drones´ usage to be safer. In general, there are several challenges accompanying the use of

drones within urban centres that should be considered to achieve their broad utilization, these include the following: a) Legislation framework; b) Civil liability insurance; c) Protection against illegalities related to specific applications; d) Weather conditions and air traffic control. The present research can be enriched through participatory methods so that to organize the aforementioned identified factors in order of importance and help researcher, practitioners and policy-makers enhance their freight transport paradigm towards greener and cleaner solutions.

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Behavioural and theoretical considerations of physical internet adoption

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Keywords: *Physical internet, supply network, behaviour theory*

Conference Topic(s): *Logistics and supply networks; material handling; PI impacts; PI implementation..*

Physical Internet Roadmap (*Link*): *Select the most relevant area(s) for your paper:☐ PI Nodes, ☐ PI Networks, ☐ System of Logistics Networks, ☒ Access and Adoption, ☒ Governance.*

1   Introduction

Physical internet (PI) is an ambitious paradigm spanning across firms, supply chains and countries to make a consolidated and interconnected network of logistics for handling goods. Ballot, Montreuil, and Meller (2014) define the physical internet as:

"A global logistics system based on the interconnection of logistics networks by a standardized set of collaboration protocols, modular containers and smart interfaces for increased efficiency and sustainability."

In a similar fashion to the actual digital internet, where all agents can be in contact with each other and exchange information and services, PI provides a collaborative decentralized environment of public and private agents to exchange logistics information and services using standard technical protocols (Nickerson and Muehlen, 2006). PI is aimed at ultimately providing the context to enable π-containers being a global and standardized loading unit; where goods irrespective of their physical characteristics can be packaged and shipped with little to no interruption to get to the destination.

In the last few years, PI has gained momentum and has grown rapidly especially in Europe (Pan, Ballot, Huang, and Montreuil, 2017) resulting into the formation of the European Technology Platform Alliance for Logistics Innovation through Collaboration in Europe (ETP-ALICE or ALICE[1]), which aligns various groups of stakeholders involved in PI. ALICE proposes five areas of development as the roadmap for PI which include technical/operational aspects of PI (i.e., "From Logistics Nodes to PI Nodes", "From Logistics Networks to Physical

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[1] https://www.etp-logistics.eu/

Internet Networks", and "Developing the System of Logistics Networks towards the Physical Internet") as well as human aspects of PI (i.e., "Access and Adoption" and "Governance").

As such, there is still much room for empirical and practical studies surrounding PI (Pan et al., 2017) especially with respect to ALICE as a bold new vision for global logistics. Perhaps one of the main challenges to make PI a reality is to identify the components and necessary conditions to implement PI (Plasch, Pfoser, Gerschberger, Gattringer, and Schauer, 2021), which can be translated in wide access and adoption of PI by various logistic networks and their stakeholders. While most scientific literature on PI has been primarily focused on the technical/operational aspects of the PI (the design of modular PI loading units (Landschützer, Ehrentraut, and Jodin, 2015) and PI hubs (Ballot, Montreuil, and Thivierge, 2012; Montreuil, Meller, Thivierge, and Montreuil, 2013) among others), very few studies have so far looked into the human aspects of PI especially with respect to use, access and adoption of the PI.

The ALICE RoadMap provides a detailed plan of the milestones that will need to be achieved to implement the PI (ALICE-ETP, 2020). A range of technologies will need to be developed and adopted by various stakeholders. Models for understanding and predicting how individuals will respond to technologies will be important to construct. This will involve determining how to transform current logistics nodes and networks to more be more open and seamless. The adoption of innovative technologies such as GS1's Scan4Transport (S4T) that can provide better information about inbound and outbound flows that can reduce impediments for transhipment across modes and nodes.

To this end, in what follows we have investigated a number of major behavioral and technology-adoption theories to explore some future topics for research in the PI domain with respect to "Access and Adoption" and "Governance". The theoretical frameworks investigated in this manuscript are on individual level (e.g., Theory of Reasoned Action and Technology Acceptance Model) and firm/social level (e.g., Technology-Organization-Environment Theory and Diffusion of Innovation Theory) with each having novel propositions for future research in PI in better understanding of access and adoption of PI by individuals and across supply networks. Following our discussions of these theories, we highlight a few major topics for future research and their implications to contribute to the PI roadmap.

2 Behavioural and theoretical frameworks: Applications to PI Studies

Technology adoption and use theories are fundamentally proposed at levels of the individual and firm behaviour. At the firm level, the most well-known models are Technology, Organization, and Environment (TOE) and the Diffusion of Innovation (DOI). At individual level, Technology Acceptance Model (TAM), the Theory of Planned Behaviour (TPB), and the Unified Theory of Acceptance and Use of Technology (UTAUT) and their variations are some of the most applied models and theories in the literature for gauging user acceptance, adoption and use of the technology. We believe that in order to be able to predict the wide range adoption and acceptance of PI, researchers should consider applying these models to their empirical studies and case studies of PI adoption and report on strengths and weaknesses of PI with respect to the implications of these models. Below we briefly review the origins and main components of the aforementioned theories and their implications for PI studies.

2.1 Individual level theories

2.1.1 *Theory of Reasoned Action (TRA) and Theory of Planned Behaviour (TPB)*

Fishbein and Ajzen (1977) proposed the Theory of Reasoned Action (TRA), which posits that the intention behind an individual's action will result into the behaviour stemming from that action. In fact, one of the most basic fundamentals of technology adoption lies on individuals' intention behind adoption and use of the technology that would direct their behaviour toward that technology (Ajzen, 1991; Davis, Bagozzi, and Warshaw, 1989; Sheppard, Hartwick, and Warshaw, 1988). It is thus important to understand what variables constitute intention to predict user behaviour toward new technology. TRA suggest the following three key variables constituting intention, namely (1) attitude towards the behaviour, (2) subjective norms, and (3) behavioural intention.

Favourability or lack thereof toward a specific behaviour and its potential outcomes is referred to as "an attitude". Behavioural beliefs and the person's evaluation of outcomes of the behaviour constitute attitude. "Behavioural intention" refers to the factors motivating and influencing a certain behaviour. Naturally the stronger intentions are toward a certain behaviour, the more likely it is for the behaviour to be performed. While attitude and behavioural intention are more or less intrinsic, "subjective norms" has its roots in external factors, i.e., others approval or disapproval of behaviour that would impact whether an individual should consider performing the behaviour. Normative beliefs and motivation to comply constitute subjective norms. Thus, to summarize, TRA assesses a person's behaviour through their intention in performing a specific task. This behavioural intention in turn is affected by the person's attitude toward the behaviour and subjective norms.

Theory of Planned Behaviour (TPB) is an extension to TRA as proposed by Ajzen (1991) and includes an additional variable, namely "perceived behavioural control". Perceived behavioural control and subjective norms are shown by Ajzen (1991) to correlate significantly with behavioural intentions, further prediction consumer behaviour. Control beliefs and perceived power constitute perceived behavioural control. It has also been shown that external variables such as demographic variables, personality traits and other distinguishing personal attitudes might affect behaviour within TRA and TRB frameworks. Figure 1 below shows TRA and TPB.
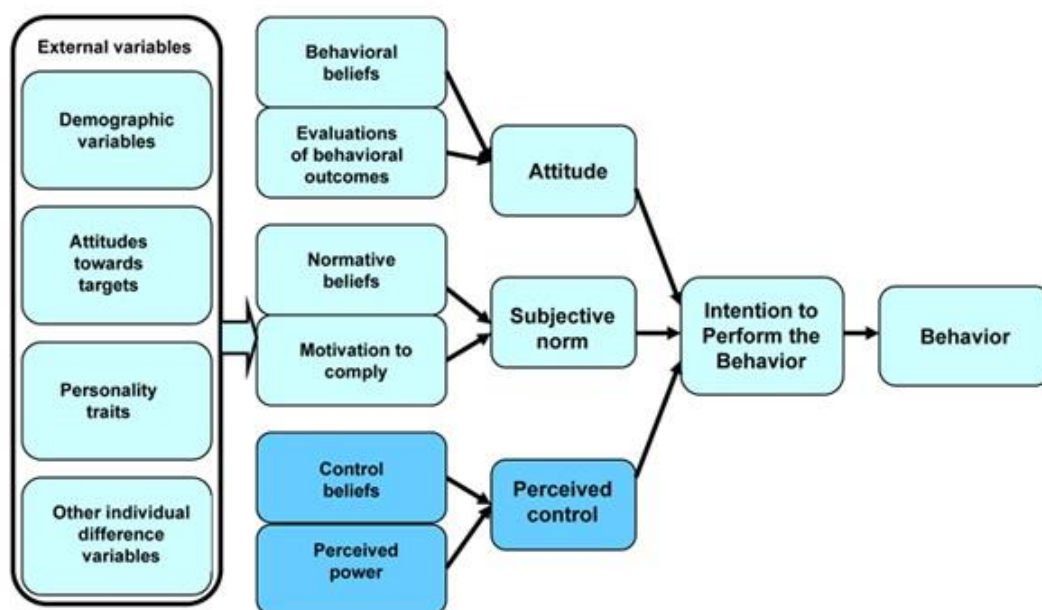
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Figure 1. TRA and TPB and their variables[2]

With respect to the implications of TRA and TPB for future research in PI and ALICE's roadmap and the five areas of development for the PI, the following higher order topics can be investigated by supply chain and logistics scholars:

- *How can attitudes, subjective norms and perceived controls of decision makers in logistics networks toward PI be assessed toward their use and adoption of the PI?*
- *What subjective norms and from which stakeholders are the most influential in use and adoption of the PI?*
- *What are some external personality-related and demographic-related factors affecting use and adoption of new technologies such as the PI?*

2.1.2 Technology Acceptance Model (TAM)

Technology acceptance model (TAM) was developed by Davis et al. (1989) as an extension to TRA in the context of information technology. In this context, Davis et al. (1989) defines behavioural intention of an individual as their willingness to use the system, which is in turn based on two variables namely 'perceived ease of use' and 'perceived usefulness'. Perceived Ease of Use is the "degree to which a person believes that using a particular system would be free of effort" (Davis, 1989: 320), both physically and mentally. In other words, the less mental and physical effort is needed to use a system, the perceived ease of use will be higher. Perceived usefulness refers to how the use of the system would improve the performance of the individual in their opinion. Some components of perceived usefulness are efficiency, effectiveness, and usefulness for the job of the system. Perceived ease of used can affect perceived usefulness where a technology is easy to use then its perceived usefulness can increase for the user. Perceived ease of use and perceived usefulness according to TAM are the main determinants for use and adoption of IT.

TAM was extended later by Venkatesh and Davis (2000), known as TAM2, to include social influence (e.g., voluntariness and subjective norm) and cognitive instrumental concepts (e.g., output quality and job relevance). Variables for perceived usefulness in TAM2 are namely subjective norm, image, job relevance, output quality and result demonstrability with experiences and voluntariness being the two moderators in the model. In TAM 2, the immediate variables affecting behavioural intentions are thus subjective norm, perceived usefulness and perceived ease of use.

TAM3, suggested by Venkatesh and Bala (2008), was an extension to TAM2 and is similar to TAM2 but introduces external variables of "anchor" and "adjustment" to perceived ease of use. Variables included in anchor are computer self-efficacy, perceptions of external control, computer anxiety, and computer playfulness while variables included in adjustment are perceived enjoyment and objective usability. TAM3 is shown in Figure 2 below.

With respect to the implications of TAM and its extensions for future research in PI and ALICE's roadmap and the five areas of development for PI, the following higher order topics can be investigated by supply chain and logistics scholars:

- *How can perceived usefulness and perceived ease of use of the PI among PI's major stakeholders be assessed with respect to TAM and its extensions?*
- *What factors according to TAM3 most facilitate the adoption and acceptance of PI?*

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[2] Adopted from https://www.med.upenn.edu/hbhe4/part2-ch4-figures_of_TRA-TPB.shtml

- *In addition to experience and voluntariness, do other demographic and personality trait factors affect PI adoption and use according to TAM3?*

2.1.3 Unified Theory of Acceptance and Use of Technology (UTAUT) and UTAUT2

Perhaps one of the most comprehensive technology acceptance and use is Unified Theory of Acceptance and Use of Technology (UTAUT) and UTAUT2 since Venkatesh, Morris, Davis, and Davis (2003) proposed it by comparing eight different models of technology adoption empirically and conceptually and extended it later (see, Venkatesh, Thong, and Xu, 2012) to incorporate seven variables that are linked to behavioural intention, namely (1) performance expectancy, (2) effort expectancy, (3) facilitating conditions, (4) social influence, (5) computer anxiety, (6) computer self-efficacy, and (7) attitude toward technology usage. Moderators of UTAUT and UTAUT2 are age, gender and experience. Below is a brief overview of all these main and moderator variables and their significance in UTAUT.

Performance Expectancy: is the degree to which the individual perceives the new technology helps them improve their performance. According to Venkatesh et al. (2003), performance expectancy is the strongest predictor of behavioural intention in adoption and use of a new technology.
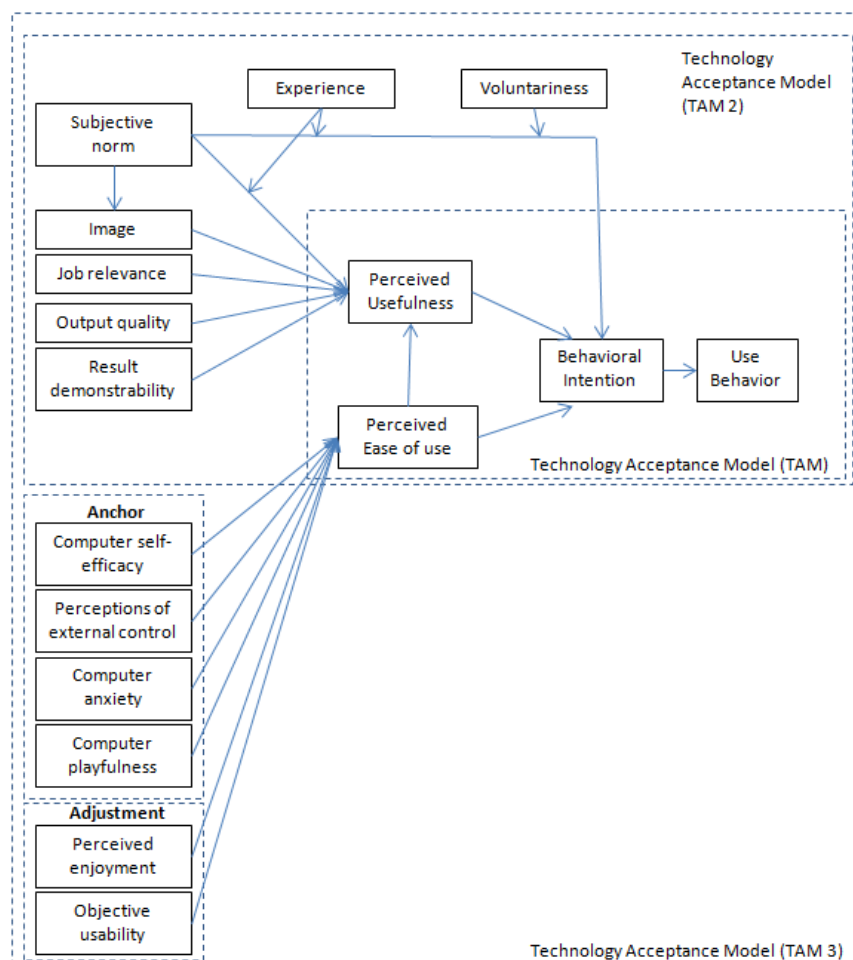
Figure 2. TAM3 and its variables adopted from Boughzala (2014)

Effort Expectancy: is "the degree of ease associated with the use of the system" (Venkatesh et al., 2003, p. 450). According to Venkatesh and Zhang (2010) effort expectancy of a particular technology has significant links with adoption of that technology.

Social Influence: is somewhat similar to "subjective norm" in TRA/TPB being "the degree to which an individual perceives that important others believe he or she should use the new system" (Venkatesh et al., 2003, p. 451).

Facilitating conditions: is "the degree to which an individual believes that an organizational and technical infrastructure exists to support the use of the system" (Venkatesh et al., 2003, p. 453).

Performance expectancy, effort expectancy, social influence and facilitating conditions were the original variables proposed in UTAUT and were extended to include habit, hedonic motivation and price value later on in UTAUT2 (Venkatesh et al., 2012).

Hedonic Motivation: is "the fun or pleasure derived from using a technology" (Venkatesh et al., 2012, p. 161) and is a significant predictor of adopting new technologies such as PI.

Habit: is an automatic behaviour ensures future use of technology if the previous use of technology has already become a habit to the individual.

Price Value: is the cost to benefit ratio to the user. Figure 3 below shows the UTAUT2 model and its variables.

With respect to the implications of UTAUT(2) for future research in PI and ALICE's roadmap and the five areas of development for PI, the following higher order topics can be investigated by supply chain and logistics scholars:

- *Which of the seven main independent variables in UTAUT(2) has the most significant impact on PI adoption and use?*
- *How can PI adoption and use be improved/guaranteed through UTAUT(2)?*
- *What is the impact of age, gender and experience in use and adoption of PI according to UTAUT(2)?*
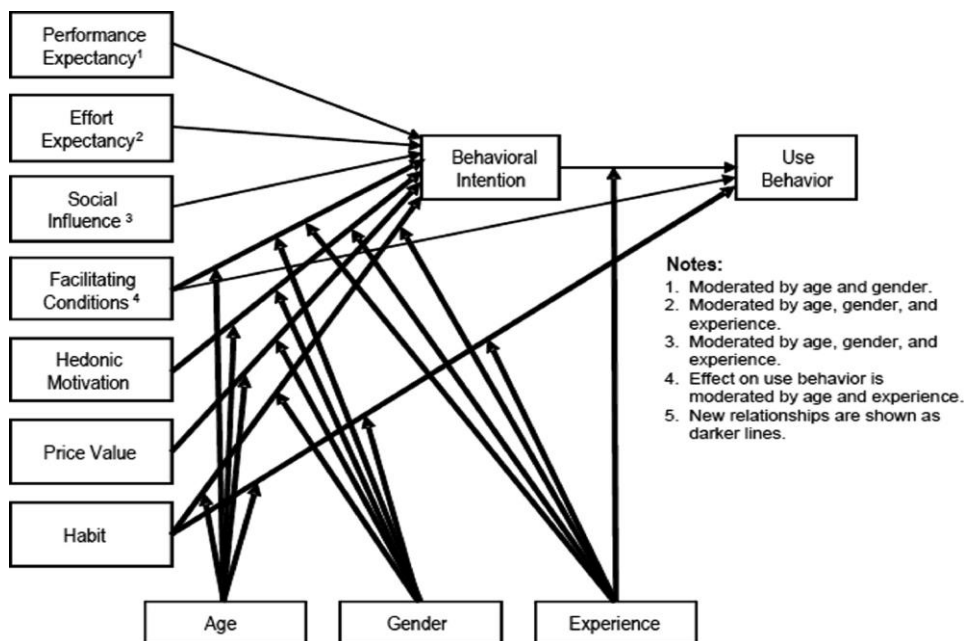
Figure 3. UTAUT2 and its variables adopted from Venkatesh et al. (2012)

2.2   Firm level theories

2.2.1   Diffusion of Innovation Theory (DOI)

The Diffusion of Innovation Theory (DOI) explains the procedure through which innovation is diffused throughout the firm (Rogers, 1983). "Diffusion" in this context is referred to the channels through which innovation is communicated with people in the firm. Also, innovation in this context is referred to any new practice, idea or an object to be adopted by the firm. In order to diffuse the innovation, one might first evaluate the innovation (technology) and its fit to the firm. To this end, Rogers (1983) proposed five attributes (variables) using which the firm can gather information on the innovation. These five attributes, as shown in Figure 4, are relative advantage, trialability, compatibility, complexity, and observability.
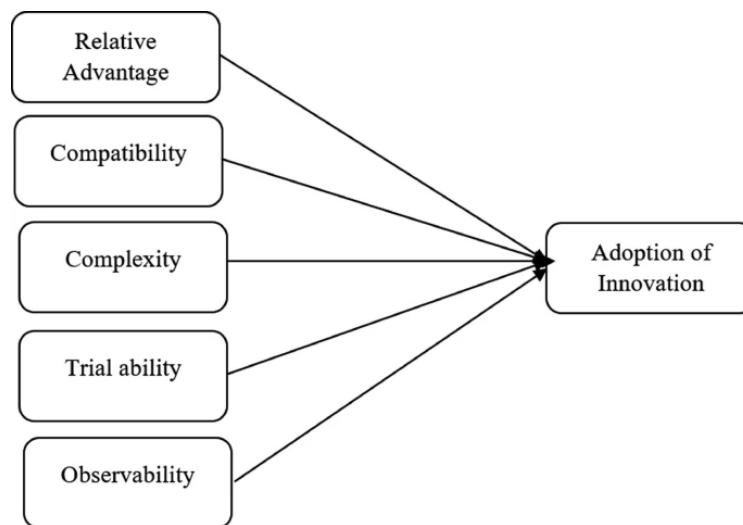
Figure 4. DOI and its variables adopted from Vatanparast (2012)

Below provides a brief overview of the five main variables in DOI (see Figure 5):

Relative Advantage: is the proportional superiority of the innovation compared to the current practices in the firm. Relative advantages is synonymous with "perceived usefulness" in TAM (Nysveen, Pedersen, and Thorbjørnsen, 2005).

Compatibility: is the extent of conformity of the innovation with existing attributes of the system including values, experiences and requirements of people who are going to adopt the innovation.

Complexity: refers to the level of difficulty adopters of innovation will face in understanding and using the new technology. Naturally there is a reverse relationship between complexity of the innovation and rate of adoption of the innovation.

Trialability: refers to the fact the chance the users might get to experiment with the innovation to a limited extent. Being able to work with the trials of the innovation can increase the rate of adoption of innovation.

Observability: refers to how visible are the outcomes of the innovation to the users. In other words the more tangible results an innovation can make, the higher should be its rate of adoption.

With respect to the implications of DOI for future research in PI and ALICE's roadmap and the five areas of development for PI, the following higher order topics can be investigated by supply chain and logistics scholars:

- *Which of the five attributes of DOI are most influential and adoption and continuous use of PI?*
- *What factors contribute to increasing relative advantage of PI, its compatibility, trialability and observability while also reducing its complexity of use among stakeholders?*
- *How can DOI be used to predict the adoption of PI in logistics networks?*

2.2.2 Technology-Organization-Environment (TOE) Framework

The technology–organization–environment (TOE), proposed by Tornatzky, Fleischer, and Chakrabarti (1990), explains the whole process of developing innovations to its adoption and implementation within firms. TOE looks into the adoption of technology from a firm's perspective and analyse the adoption decision of the firm based on the three elements of technological, organizational and external environment contexts. As can be seen in Figure 5 below, the "technology" context refers to all technologies and innovations already used by the firm and also available in the market and can be accessed by the firm that can impact decisions surrounding technological innovation in the firm. The "organization" deals with resources and characteristics with the firm such as firm size, slack resources, linking structures between employees, and communication processes within the firm. For instance, with respect to linking structures, informal linking agents (e.g., gatekeepers and boundary spanners), facilitate the adoption of innovation. Or the more decentralized the organizational structure, the more likely it is to adopt innovation. With respect to communication processes, for instance, top management's attitude and communications toward innovation can foster innovation adoption in the firm. Size can be considered as a proxy for availability of resources, and thus more slack, which can potentially increase innovation. However, the literature on slack and size so far is not quite conclusive (Baker, 2012). Finally, the "environment" context refers to factors such as presence of support infrastructure (e.g., technology service providers), regulatory environment and industry characteristics (e.g., higher levels of competition fostering more innovation) that impact technology innovation decisions of the firm.

With respect to the implications of TOE framework for future research in PI and ALICE's roadmap and the five areas of development for PI, the following higher order topics can be investigated by supply chain and logistics scholars:

- *According to TOE framework, what organizational, technological and external environmental factors have the highest influence on PI adoption and use by firms in interconnected logistics networks?*
- *With respect to external environment context according to TOE framework, which types of infrastructure should be present to ensure successful PI adoption and use?*
- *With respect to organizational context according to TOE framework, which linking structures should be present to ensure successful PI adoption and use? In the same context, would the size and slack resources of the firm matter in adoption and use of PI?*
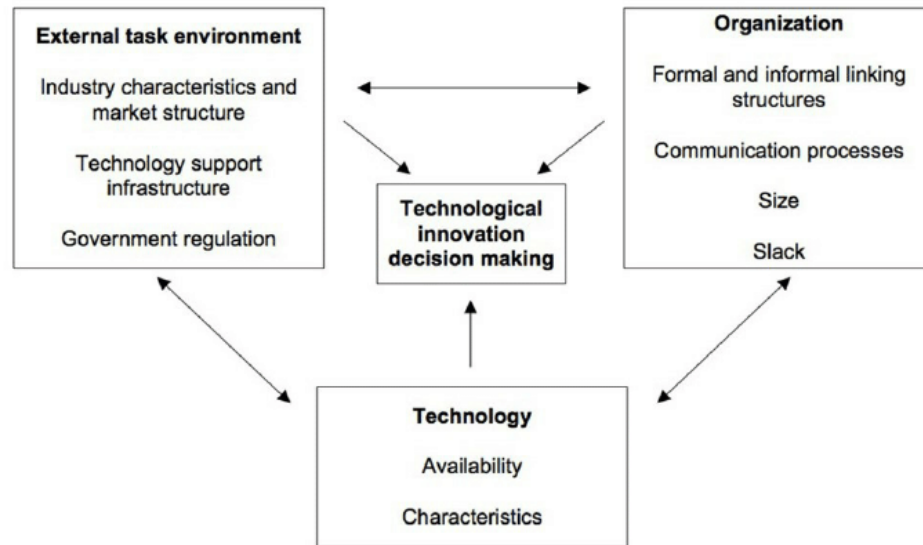
Figure 5. The TOE framework adopted from Tornatzky et al. (1990)

3 Conclusion

The current paper aimed at initiating the discourse surrounding behavioural and theoretical aspects of PI access, use and adoption. We reviewed three behavioural theories of technology adoption on individual level, namely Theory of Reasoned Action (TRA) and Theory of Planned Behaviour (TPB), Technology Acceptance Model (TAM1,2,3), Unified Theory of Acceptance and Use of Technology (UTAUT1,2) and two theories of technology adoption on firm level, namely Diffusion of Innovation Theory (DOI) and Technology-Organization-Environment framework (TOE) and their implications for future studies revolving around PI. While current discourse in the literature revolves primarily around technical aspects of PI implementation, we believe addressing the behavioural aspects of PI access and adoption such as behavioural intentions of adopting PI (i.e., TRA, TPB, TAM, UTAUT) as well as how PI is communicated in firms to employees (e.g., TOE) or how complex it is to use PI by people and firms (e.g., DOI, UTAUT2) could all predict the future widespread adoption of PI across logistics networks.

In fact, so far, the efforts made in the adoption of standard load units such as π containers, adopting of data standards for interchanging goods (e.g., GS1 Scan4Transport), and adoption of tracking and tracing technologies (e.g., GPS) are all steps into the right direction to facilitate technology accessibility/availability and provision of external infrastructure to consolidate logistic networks into a PI. Having said that, still much is to be learnt on how PI is perceived on individual and firm level and what is further needed to improve the perception of PI and its ease of use among various groups of stakeholders.

Perhaps one caveat of the theories reviewed in this paper is that they do not provide "an interorganizational" view of PI access and adoption. How PI would be perceived across supply chains and logistics networks would perhaps require an extension to the existing theories of technology adoption on the individual and firm level, which can be considered as a much-needed topic for future empirical studies.

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A data governance framework for a federated logistics data space

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Abstract: Data sharing is an emerging area in logistics. Although the potential of data sharing in logistics is widely recognised, data sharing in inter-organisational collaboration models still need to be thoroughly investigated. This article examines the benefits of data sharing in logistics using a federated data space. The data space involves parties such as rail transport, inland waterways, and port community systems to share their data on shipment possibilities. This promotes visibility over the shipping modalities and facilitates a modal shift. We explore and derive the International Data Spaces (IDS) initiative's conceptual framework on federated data space for secure, controlled, and trusted data sharing in logistics. The logistics industry is driven by small and medium-sized businesses with relatively small investment capacity and IT capabilities, as well as a small number of global firms running their own IT systems. Federated data space offers interoperability for data sharing between discrete platforms through data space connectors. These connectors utilise common protocols to support these services. This approach allows the participating organisations to use any platform they are comfortable with to connect to the entire network of data ecosystems. The article also investigates what kind of data should be provided, who will be the provider, and how it will be shared among users.

The dynamics of such data space are complex and have strong concerns about data sensitivity. Involved parties are reluctant to exchange confidential information with competing companies or relinquish their data ownership control. Federated data space needs to address the complexity of accessing the data, the responsibilities of actors in the data space, and decision rights to ensure that data sharing is bound ethically and empowers trust between the parties. To address these concerns, data governance needs to be put forward in the logistics data space that defines responsibilities and data ownership. Inspired by the data governance framework for a federated data space in different sectors, such as healthcare, we explore their principles and potential outcomes in logistics.

This paper contributes to the data governance framework for a federated logistics data space toward a Physical Internet as follows: a.) we define the pillars for a data governance framework for a federated logistics data space, b.) we identify the actors in the ecosystem based on their role, c.) we explore the usage of policies between the actors for sharing sensitive data in a collaborative environment. This fills the knowledge gap in contriving a trusted data-sharing ecosystem. The suggested framework supports practitioners and policymakers in identifying, understanding, and improving the data governance framework in the federated logistics data space and Information System ecosystem. Federated logistics data space with a concrete data governance framework enables data interoperability and provides standardised platform services for data sharing. This facilitates a modal shift and creates opportunities for sustainable logistics.

Keywords: Modal shift, Federated data space, Data Governance, Sustainable Logistics.

Conference Topic(s): *Interconnected freight transport; technologies for interconnected logistics*

Physical Internet Roadmap *([Link](#)): Select the most relevant area(s) for your paper:☐ PI Nodes, ☐ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☒ Governance.*

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TNO

Performance of Self-Organizing Logistics: a Practical Comparison between Centralized and Decentralized Logistics

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Abstract: In the vision of Physical Internet there is no central authority that regulates decision making and asset use, the decision making is decentralized to make logistics self-organizing. A theoretical downside of decentralization is reduction of system performance due to lack of system overview leading to sub-optimal decisions. This research shows that the system performance is not significantly reduced when making decentralized decisions in a trucking network on small problem instances. Furthermore, the theoretical advantages of decentralized control compared to centralized are evaluated with the practical implementation.

Keywords: Autonomous transport, Centralized control, Container logistics, Self-organizing logistics (SOL), Supply chain management

Conference Topic(s): Autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms) business models & use cases; logistics and supply networks.

Physical Internet Roadmap (Link): Select the most relevant area for your paper: ☐ *PI Nodes,* ☐ *PI Networks,* ☒ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

1 Central and decentral control structures in logistics

The advancements in digitalization and automation within transportation and logistics are creating new opportunities for organizing supply chains. Real-time connectivity and improved data sharing allow for innovative decision-making methods that can alter the control structure of logistics operations. More (autonomous) data-driven decision-making can be applied in various control structures, including centralized coordination (control tower approach) and decentralized coordination (self-organizing approach). These advancements lead to new opportunities for transport companies to improve methods of scheduling assets in daily practice, reducing inefficiencies in their operations and reducing costs and energy or fuel use. The question at hand is which methods of governing fleets of vehicles and optimizing transport scheduling are most suited to real world transport problems and most effective in decision support in transport operations.

Centralized control structures, known as the control tower approach, involve one party collecting and analyzing data to make optimal operational decisions that are communicated to parties in the logistics chain. This approach has the potential to optimize performance at the system level, placing the interests of the chain above individual interests, and standardizing communication through one system. On the other hand, a decentralized control structure is characterized by each unit in the logistics chain making independent decisions (self-organization) based on local intelligence and autonomy, with the goal of achieving more flexible operations or allowing for prompt rescheduling. Next to increased autonomy, there can also be an advantage in data governance, as autonomy on vehicle level enables a situation where specific vehicle and driver data does not need to be shared and only communication on which

orders to transport is required. Physical Internet is a concept that aims to create a global logistics network that is more efficient, flexible, resilient, and sustainable by integrating these two approaches.

This work focusses on specific on one decentral and one central approach, where most likely a hybrid form with collaboration between centralized and decentralized logistics is necessary to get to a functioning Physical Internet. A hybrid form allows for the efficient use of resources, improved flexibility, and increased resilience and sustainability in the logistics network (Quak et al., 2018) and as such, a hybrid approach could combine the advantages of both control methods. An example of a hybrid approach is developed by Phillipson (2015).

To allow for effective decision-making and coordination across the Physical Internet, it is important to create proper control structures for the problem at hand. In the study Hopman et al. (2022), a framework was developed to examine the trade-offs and conditions that are most appropriate for different control structures, from centralized to decentralized. Their research suggests a hybrid approach to enhance the collaboration between centralized and decentralized logistics. This paper focusses on the extremes and not on a hybrid approach by comparing decentral with central scheduling. In this study, we researched a real-life logistics problem of order scheduling, which resembles a combination of job shop scheduling and vehicle routing with time-window constraints. The theoretical benefits and drawbacks of both centralized and decentralized approaches are examined by practical experiments to discover and close the gap between theory and practice as discussed in section 4. The three experiment data sets are real world data originating from a Dutch transport company. One of the main activities of this company is transporting deep sea containers by truck to and from multimodal terminals in the hinterland.

Key contributions of this study are:

1. The Talking Trucks problem (Pingen et al., 2022) is formulated with Mixed Integer Linear Programming to include the geographical component which was missing in the centralized Linear Programming control structure in the previous study (Karunakaran, 2020).
2. The solution of the exact, central method is compared with the solution from the decentral approach to evaluate the gap in optimality.

Firstly in this paper, the background on comparing central and decentral control in transport planning problems and the specific case study is described. This is followed by a description of the approach of comparing control methods and the Mixed Integer Linear Program (MILP) formulation of the central planning problem. The problem has been solved for 3 instances. Section 4 describes the comparison to previous decentralized solutions from Pingen et al. (2022). Section 5 wraps up on the comparison of central and decentral scheduling methods.

2   Background of self-organizing trucks

In previous research by Pingen et al. (2022) on self-organizing trucks, decentralized planning results were compared to the planning of a human planner, a random assignment of orders to trucks, a greedy assignment, a reinforcement learning model, and a modified centralized control to obtain a good understanding of the performance of decentralized control. However, the central control method in this previous study included a modification to the problem to increase scalability: it was assumed that all trucks always start and end at their depot in between orders. As a result, subsequent orders with a start location close to the last end location were not explicitly considered to be executed in that order. This step was taken to reduce the problem

complexity, making it easier to solve the linear planning problem. However, in order to make a better and more equal comparison between the performance of centralized and decentralized control on the same problem, this study examines a centralized control approach that does take the geographical component into account.

2.1 Centralized versus decentralized control

To choose the appropriate control method, sufficient knowledge about the constraints of the application and how the different control methods align with these is crucial. A centralized control method, using exact methods, is likely to require more computational time to find a solution than a decentralized control method, as the scheduling problem is NP-hard and decentralizing the decision making is a way of batching the problem to smaller subproblems and reduces the required computational effort, as, for example, shown by Lalla-Ruiz and Voß (2016). Therefore, a decentralized control method is better suited for dynamic situations where quickly generating new plans after disturbances is crucial. However, a decentralized approach may not necessarily lead to an optimal solution. Pingen et al. (2022) briefly discuss the theoretical advantages and disadvantages of a centralized solution for the Talking Trucks problem. Differences include the scalability of problems that can be solved, dealing with heterogeneous agents with different preferences or limitations, and the quality of the solution.

Using heuristics, a centralized method can be sped up to reach a suboptimal solution; an example of this is dividing the problem into sub-problems to solve them in a limited time. This example can already be considered decentralization, but from a centralized perspective with global information. On the other hand, a possible disadvantage of the decentralized approach is that the obtained solutions may not be optimal, as decisions are based on a limited set of local information.

In a decentralized method, each agent has its own decision logic to optimize its decisions in the planning process, before communication and coordination with other agents takes place. In this logic, the individual preferences of an agent can be processed, and the logic can be different for each agent or uniform for all agents. As the agents do not necessarily share all information with each other, a decentralized control method can relatively easily lead to a local optimum for the system, and therefore not reach the global optimum. Depending on the problem and the intended objectives, different strategies and heuristics in the individual decision logic of the agents can have an effect on the speed of the planning process and the quality of the solutions. In this research, we further examine the quality of solutions of the previously developed decentralized method of Talking Trucks, by comparing it with the outcomes of the central control approach in this research. The aim is to better understand the differences between central and decentralized methods.

3 Comparing self-organizing with exact central truck planning

To gain insight in the optimality gap between the decentralized talking trucks solutions and the optimal solution for the provided variant of the Vehicle Routing Problem with Time Windows (VRPTW) we have formulated an MILP for this problem and used exact methods to get to an optimal solution. The problem formulation can be found in section 3.1. We have used the SCIP-solver (Bestuzheva et al., 2021) to get to the optimal solution. Formulating and implementing the exact problem from a central planning perspective provided us with insight into what is needed to develop such an approach for a real world trucking company. Given this insight from implementation and additionally the analysis of results from experiments allowed us to compare

the requirements and performance of central planning with self-organizing decentral planning. This comparison is provided in the second part of the results section.

3.1 Talking Trucks problem formulation

In this section, the mixed integer linear programming (MILP) formulation for the Talking Trucks problem is provided. The problem is to assign container transport orders to available trucks in the fleet. Container transport orders include picking up a deep sea container, which we for the scope of this paper consider to be a full truck load, driving a certain route to one or multiple stops. Stops can either be picking up a container (with or without trailer), live loading of a container or delivering a container. At pick-up, it can either be that the container is already loaded onto a trailer which the truck needs to couple, or that the truck needs to bring an empty trailer on which the container is loaded at arrival. Similarly, at delivery, the truck can end with or without an empty trailer. We call this the trailer state. To change trailer state between orders, we added so called "trailer state orders" in which a truck can (de)couple a trailer at a depot. We assume trailers are an infinite resource, they are always available and provide no planning constraints. The trailer state orders add travel time and distance to the schedule. The schedule is static and made one day ahead.

Orders can have routes of multiple stops. However, for planning constraints, only the location and trailer state of the first and last stop are relevant, as well as the total travel time in between the first and last stop of an order. Therefore, this formulation assumes "flattened" orders, where orders only contain information about the first and last stop. The travel time between stops is combined into travel time from the first to the last stop, and the order of stops cannot be changed. Initially, each stop has a specific time window defining the first possible arrival time and the deadline before which the container must arrive at each stop. This time window at each stop and driving time in between stops define a condensed time window at the first stop for the "flattened order". A visualization of this process is shown in Figure 2.
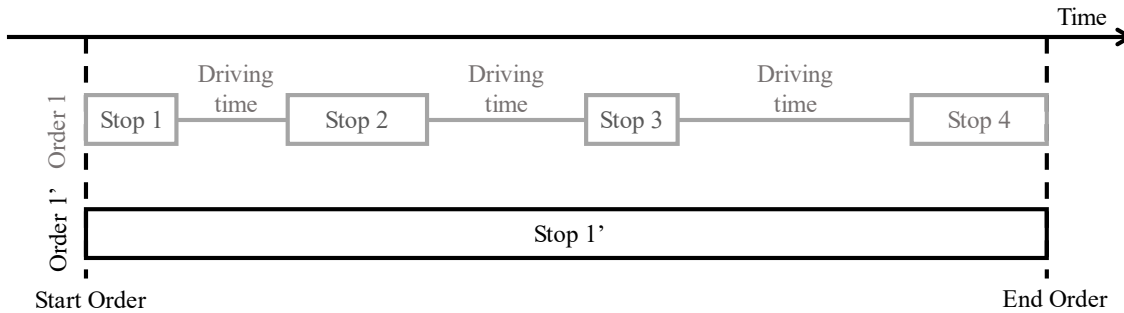
Figure 1 Schematic example of a "flattened" order. Order 1 is the original order and Order 1' is the flattened order.

The orders need to be assigned to trucks. Hence, the problem definition includes a fleet of vehicles, where each vehicle has a start and end time of its shift and each vehicle starts and ends at a certain depot. All vehicles start without a trailer. The notation for this problem is given in Table 1. The combined decisions to be made are (a) which vehicle is going to transport which order (b) at which point in time.

Table 1: Notation for the Mixed Integer Linear Program

Notation	Description
$x_{i,j,k}$	vehicle k travels from order i to order j; **binary decision variable**

$s_{i,k}$	arrival time of vehicle k at order i; **continuous decision variable**
V	set of vehicles
C	set of orders
N	set of orders and depots
d_k^s, d_k^e	start and end depot of vehicle k; $d_k^s, d_k^e \in N$
o_i	total handling time of order i
$p_{i,j}$	travel time from order i to order j
$t_{i,j} = o_i + p_{i,j}$	total time between the start of order i and the start of order j
$[a_i, b_i]$	a_i is the earliest possible start time, and b_i is the latest possible end time of order i
$[e_k, f_k]$	e_k is the start time of vehicle k, and f_k is the end time of vehicle k
TS_i^{start}, TS_i^{end}	TS_i^{start} is the trailer state at the start, respectively end (TS_i^{end}), of order i

3.1.1 Optimization objective

In general, the Talking Trucks problem knows different objective functions, as the objective that best fits company goals can vary daily, given customer requirements and operational deviations. In this research, we want to compare our results with the results from Pingen et al. (2022), who have optimized with the goal to maximize the number of on-time deliveries and minimize the number of trucks used. In order to make the decentral decision making steer towards the system objective (from a company perspective), Pingen et al (2022) have translated the system objective into objectives for individual trucks. For this MILP, we have defined the following two objective functions to align with the company objective. Having multiple objectives makes the formulation proposed in this paper a multi-criteria problem, for which, in theory, a mixed, weighed, objective can be calibrated to obtain the best required result (Jozefowiez et al., 2008). In this research no extensive search to best fit multiple criteria has been done. The the effects of two different objectives, providing two different scenarios, have been analyzed.

The objective of the first scenario is to minimize the arrival time at the end of day depot, such that the working time of the drivers left at the end of the day is maximized. This can be seen as slack in the schedule to account for delays and disruptions. The second scenario has as objective to maximize occupancy (ratio of the effective driving time with load and the total available time of a truck) and in parallel minimize the total travel time, in other words: to minimize the driving time between orders, without load. Both scenarios aim to schedule all trucks as efficiently as possible by maximizing asset usage, which is in line with the company goals. Being on time is provided as hard constraint as described in the next section.

Objective per scenario:
1. Minimize arrival time at the end of service, depot:
$$\min \sum_{k \in V} s_{d_k^e, k}$$
2. Maximize truck occupancy and minimize travel time:
$$\max \sum_{k \in V} \frac{\sum_{i \in N} \sum_{j \in N} x_{i,j,k} \cdot o_i}{f_k - e_k} - \sum_{k \in V} \sum_{i \in N} \sum_{j \in N} x_{i,j,k} \cdot p_{i,j}$$

3.1.2 Constraints

The constraints for the planning problem are given below. They all follow from the problem description as described before and are generic for a VRPTW. Note that the travel time constraint (5.) for the start time of subsequent order was initially not linear, but has been linearized using the big-M method (Dantzig, 1948).

1. Pick each order exactly once: $\sum_{k \in V} \sum_{j \in C} x_{i,j,k} = 1,$ $\forall i \in C$
2. Each vehicle starts at its start depot: $\sum_{j \in N} x_{d_k^s,j,k} = 1,$ $\forall k \in V$
3. Each vehicle ends at its end depot: $\sum_{i \in N} x_{i,d_k^e,k} = 1,$ $\forall k \in V$
4. Orders are sequential: $\sum_{i \in N} x_{i,h,k} - \sum_{j \in N} x_{h,j,k} = 0, \forall h \in C, \forall k \in V$
5. Linearized travel time constraint: $s_{i,k} + t_{i,j} - M(1 - x_{i,j,k}) \le s_{j,k},$ $\forall i,j \in N$
   $\forall k \in V$
6. Account for time windows: $a_i \le s_{i,k} \le b_i,$ $\forall i \in N, \forall k \in V$
7. Account for working hours: $s_{i,k} + t_{i,d_k^e} - M(1 - x_{i,d_k^e,k}) \le f_k,$
   $e_k \le s_{i,k} + M(1 - x_{d_k^s,i,k})$ $\forall i \in N, \forall k \in V$
8. Trailer state constraint: $x_{i,j,k}(TS_i^{end} - TS_j^{start}) = 0,$ $\forall i,j \in N, \forall k \in V$

Two scenarios, each with one of the two objective functions and these constraints, have been implemented and experimented on using three test cases. The results are presented in the next section.

4 Experiments

4.1 Numerical results

In this study, we have optimized the MILP of the Talking Trucks problem using the two previously mentioned variants of the objective function. The first objective function aims to minimize the total arrival time at the depot at the end of the day. This scenario is referred to as CENTR1. In addition, we have optimized the MILP with an objective function that combines the maximization of vehicle occupancy and minimization of travel time. This scenario is referred to as CENTR2. In the experiments, we will compare the results of optimizing these two objective functions with the results of the decentralized planning technique from Pingen et al. (2022), as well as the planning results of the human planner Van Berkel, as described in Pingen et al. (2022). Each planning technique – decentralized (DECENTR), human (HUMAN), and the central variants (CENTR1/CENTR2) – has been applied to three different days. Specifically, we have applied these techniques to plan a subset of the orders from Dutch logistics company Van Berkel on September 24th, October 1st, and October 8th, 2021 (experiment 1, 2, and 3, respectively). Experiment 1 has relatively short time windows for orders (15 minutes), while experiment 3 has relatively long time windows (up to 12 hours). Moreover, there are differences in truck properties between the different experiments; in experiments 1 and 2, the trucks are relatively homogeneous in terms of working hours, while they are more heterogeneous in experiment 3. The size of the analyzed problems is up to 10 trucks and up to 40 orders per instance. With these relatively small instances the SCIP-solver took around 3 minutes to find an optimal solution on a regular notebook (i7-8650U 1.90GHz) for scenario CENTR1, where the CENTR2 scenario finds solutions within around 5 minutes. This was on these small instances already significantly more than the matter of seconds the decentral approach required (Pingen et al., 2022).

Note in the results below that the human planner outperforms the exact method. This is due to the fact that this planner breaks some of the constraints to achieve a better solution, but does not abide by the rules of the problem which the algorithms have to adhere to. This human flexibility in adherence to the constraints can be observed in the negative waiting time in the Human planner scenario for experiment 2 in Table 3.

The most relevant outcomes are:
- In experiment 3, the driving time with and without load are equal for the decentral and central approaches, in other words, the decentral solution is equal to the optimal solution found in both exact central scenarios, see Table 2;
- In experiment 1, both exact central approaches found a solution with 32 km less driving time without load, which means a reduction of 9% of the total driven 373 kilometers in the decentral solution. In the second experiment, the exact central solutions are 5% lower in total km compared to the decentral solution, see Table 2;
- The distribution of waiting time before the first order (start of day), in between orders (middle of day) and at the end of day is quite different for the various solutions, see table 3. This depends on the timing of certain orders and this is influenced by the difference in objective functions.

Table 2: Total number of driven kilometers per experiment

Exp.	With load				Without load			
	DEC.	CEN.1	CEN.2	HUM.	DEC.	CEN.1	CEN.2	HUM.
1	280.45	280.45	280.45	263.27	93.82	61.68	61.68	110.64
2	910.18	910.18	910.18	900.76	389.31	326.83	324.52	432.30
3	873.61	873.61	873.61	858.01	93.63	93.63	93.63	93.63

The results show that CENTR1 and CENTR2 get to similar, but slightly deviating solutions. This is to be expected, given the same planning problem with objective functions that have a similar goal of maximizing asset use, and hard constraints such as delivering all orders on time. The number of driven kilometers with load is equal for all scenarios as the same transport orders have been executed. The interesting comparison is on the number of kilometers driven between transport orders, without load, where the exact method performs up to 30% better than the decentral approach in experiment 1.

Table 3: Average time of waiting per vehicle (in hours).

Exp.	Start of day				During the day			
	DEC.	CEN.1	CEN.2	HUM.	DEC.	CEN.1	CEN.2	HUM.
1	2.31	0.36	0.74	1.49	0.23	1.83	0.50	0.45
2	2.44	0.12	0.34	1.24	0.35	1.30	1.15	-0.20*
3	2.27	0.5	0.5	1.06	0.08	0.0	0.0	0.0

Exp.	End of the day			
	DEC.	CEN.1	CEN.2	HUM.
1	7.37	6.91	7.78	7.17
2	2.37	4.13	4.09	4.40
3	3.62	4.58	4.58	3.68

Table 4: Problem size and computation time per scenario in minutes on a regular notebook (i7-8650U 1.90GHz). In comparison the human planner required 1 day of work.

Exp.	# orders	# trucks	DEC.	CEN.1	CEN.2
1	38	8	< 1	1	3
2	37	9	< 1	3	5
3	41	9	< 1	6	8

4.2 Central and decentral control in theory compared to practical experiments

Implementing, experimenting and analyzing the VRPTW with decentral and central based solution algorithms provides a base to evaluate advantages and disadvantages of the different approaches. There are four points to compare the central and decentral method on: solution time, scalability, distribution of the computation and distribution of the data.

The first point is the time it takes to find an optimal solution. For the exact central algorithm, this is the time it takes to find a globally optimal solution. For the decentral algorithm, this can also be a local optimum. In our experiments, we have seen that the decentral algorithm took less than 10 seconds to find an optimum, while the solution time for the central algorithm ranged from 2 to 15 minutes. In our current formulation, both methods are very fast compared to the human planner, who needs 6-8 hours to get a schedule.

With more decision variables, the exact method computation time scales exponentially due to the fact that the problem is NP-hard. The decentral method computation time scales linearly. This means that the bigger the problem, the bigger the gap in solution time between the decentral and exact method, in favor of the decentral solution method. The solution time is also influenced by the size of the solution space: the central solution method needs significantly less time in experiment 1 compared to experiment 2 and 3 (see Table 4). This is due to the tighter time windows in experiment 1, which lead to a smaller search space.

Another comparison for the different solution methods is the distribution of the computation of the schedule. In the exact method, computation is done on one machine, while the computation of the decentral method is distributed to the machines of each agent. This means that the computation demands of each machine is smaller in the decentral method, because the decentral method only explores the neighborhoods of each agent. The central method can search the entire

solution space, which means that the computation demands can be heavier. The heavier demand in computation time by the central method is also observed in the experiments.

Lastly, the distribution of the data is different for the two methods. For the central method, the data is stored in one location in order for the algorithm to take everything into account. In the decentral solution method, a major part of the data is stored on agent-basis and not centrally. Especially the vehicle and driver specific data are only known to the vehicle and do not need to be shared with other entities. The information on the available transport orders is still provided to the trucks via a central information point, in this case the transport company. The resulting individual truck schedules can be shared to an overseeing entity such as the truck company, however, in theory, this is not necessary. The distribution of data is a relevant factor in developing real world truck scheduling methods. For companies the location and storage of the data can be a sensitive topic, because the transport data is commercial sensitive information for the transport company, but mainly for the concerning shippers. The latter is because production volumes and product launches are trade sensitive information. Transport companies therefore need to be careful in sharing transport data. The decentral approach provides a method of distributing data in a different manner than the central approach and provides opportunities for transport companies to collaborate in transport planning without giving complete insight in company data.

5 Conclusions and recommendations

5.1 Conclusions
The implemented MILP solved with the SCIP-solver leads to optimal solutions for the provided scenarios when given enough runtime. As expected, the solutions show equal and better results on the performance indicators compared to results from the same experiments with the decentral Talking Trucks approach. The main takeaway is that for these, rather small, experiments, the optimality gap between the decentral solution and optimal solution is small, but is present. These experiments already show that it depends on the specific experiment whether the decentral method approaches the exact method optimum. There is an exact match in results in experiment 3, but in experiment 1 the central method gets to a solution with 30 km less empty driven kilometers compared to the decentral scheduling solution, which is a 10% reduction in driven kilometers for this day.

Both the decentral approach and the exact central method are manners to create schedules for these small problem cases in a reasonable amount of time, especially compared to the time the human planner needs to schedule all orders. The decentral approach wins from the exact methods on computation time, especially when looking at bigger instances where the decentral approach scales linearly in computation speed compared to the exponential growing computation requirement of exact methods.

Next to scalability of the problem size, the decentral approach also has other organizational and implementational advantages compared to the exact central approach. Truck and truck driver information do not have to be shared with other entities, only preferences on available transport orders are shared and negotiated. This allows for new ways of collaborating and (self) organizing logistic structures.

5.2 Recommendations
Given the small experiment instances analyzed in this research, it would be interesting to extend the comparison to larger and more varying datasets, because the used experiments are relatively

small. The main questions to verify on larger instances would be to compare scalability of exact methods compared to decentral approaches to be able to draw further conclusions on the instances for which exact methods are most relevant and in which situations decentral or hybrid forms are a better option.

In this research we have approached the static problem with a one day ahead scheduling, where in the logistic practice a real time rescheduling method, which really requires high computation speed, could benefit from a fast, decentral approach. Researching applicability and performance of decentral methods in such a setting requires attention.

Additionally, the logistic planning problems in practice have broader scopes than single company truck fleets. Looking into multimodal, or even synchromodal, planning problems and especially situations of multi-fleet or multi-company problems could provide insight in advantages and benefits of the decentral planning approach and get logistic systems closer to the Physical Internet. This would contribute to the goal of making our transport systems more efficient and sustainable.

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Closing the information gap of multimodal transports

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Contribution abstract

Customer and freight related information is essentially to enable and ensure reliable transport chains. Therefore, real-time information along the transport service is to be made available by the participating companies to enable each service provider to optimise its resources and dispositive control of its processes. This paper deals with the result of the project RRTM-C which tested a closed information chain of an exemplary daily multimodal container shuttle service running in Austria between Vienna to Bludenz. The used information and data were provided by combining the tools that the project partners OeBB (Austrian Federal Railways), Asfinag (Austrian Motorway and Expressway Financing Joint-Stock Company) and shipper company Venz Logistik use for their daily operation. By connecting the main tools of the partners via specialised interfaces a continuous, cross- modal exchange of information including a stable prediction of ETA (Estimated Time of Arrival) of the containers in the terminals was made possible. The system was tested successfully in real transport conditions in June and September 2022. Additionally, an optimisation model of the involved container terminal was implemented to research the effects of different scenarios of different grades of information availability in the container terminal.

RRTM-C was a national cooperative implementation project that that was funded by the Austrian Ministry of Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK) and the National Railway Infrastructure Funding Agency (SCHIG).

Objectives

The customer information in the case of rules and deviations in the area of freight transport is essentially based on the information relationship between the individual participants along the transport and process chains and the data and information generated and used therein. Therefore, real-time information along the transport chain is to be made available by the participating companies to enable each service provider to optimise its resources and dispositive control of its processes in order to be able to react in time to deviations that occur at short notice. The tools available at the project partners ÖBB, Asfinag and Venz for the ongoing collection of ETA (Estimated Time of Arrival) are to be connected via suitable interfaces so that a continuous, cross-modal exchange of information is made possible. These interfaces also include methods for guaranteeing data sovereignty and data protection to the data brought in. This was designed so openly that in future a scalable and portable

solution can be offered for information transfer and coordination across companies, transport modes and countries. The solution was tested and evaluated on an exemplary transport chain (daily shuttle train from Vienna to Bludenz). This will be an imported step towards improving plannability and reducing empty runs and waiting times in the event of deviations from the original ETA. With the implementation of the project idea, an increase in the attractiveness of long-distance transports by rail can be expected will help to shift long-distance freight transports from road to rail.

Method

The project goal was to set up a connected system to exchange data and information of two infrastructure and the participating logistic company that are managing a daily multimodal container shuttle service in Austria rom Bludenz in Western Austria to Vienna in the East of Austria and then back to Bludenz. The considered transport chain is divided into several parts and transport modes. The first mile from the producer to the terminal Bludenz is carried out as a road transport on a federal road. The main run from Bludenz to terminal Vienna uses rail transport. The last mile from the terminal Vienna to the producer in the Greater Vienna Region has a longer part on the highway and a shorter section on the federal road system.

The unified ITU container number (ITU – intermodal transport unit) serves as the connection point that is represented in all data of the involved transport companies and transport modes. The container number is first used in the data of the logistic company to connect the information of the transported goods and the used transport unit with information of starting and end point as well as starting and delivery time. The project partner Asfinag has developed an information platform for users of the road tolling system in Austria (ETA Monitor©) that offers a service to give ETA information to customers based on their toll data when they fill in the relevant information (number plate of truck, starting and expected end time and starting and destination) in secure input form. The OeBB has implemented an internal data exchange platform (infra:infoHub©) that offers the possibility to connect all relevant data (container number with wagon number and train number as well as current position and ETA in destination railway station. The main idea of the project was to connect these three systems to offer a closed information chain to all involved parties and achieve a better planning situation for multimodal transport.

In a first step all transport processes, exchanged or needed data and all involved companies and stakeholders were documented in a graphic plan and were described in detail. Based on these first findings a system architecture and an implementation plan ware developed. The further work was concentrating on the definition of the interface protocols and connecting step by step the relevant components. Contemporaneous, the legal concept for ensuring the data sovereignty was set-up and all relevant legal aspects were collected and signed between the partners.
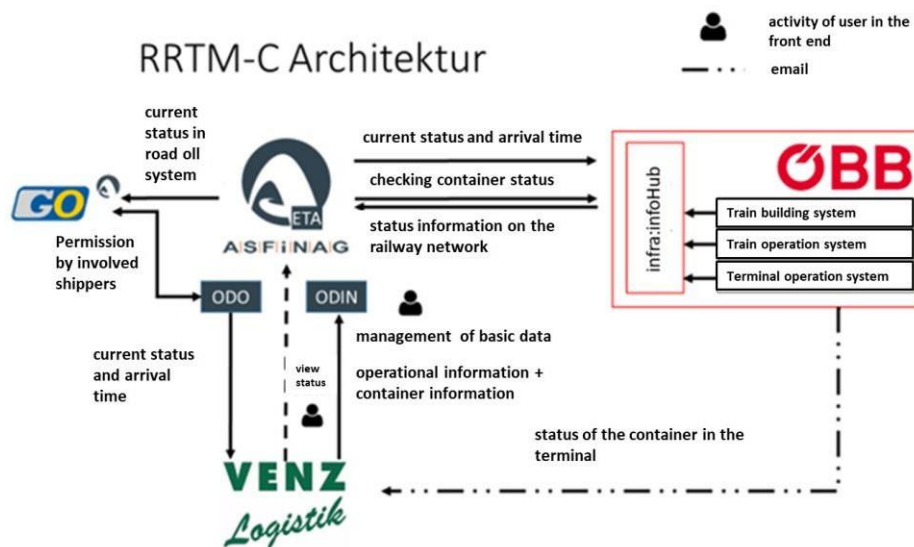
Figure 1 – system architecture developed in project RRTM-C (©AIT, Asfinag, OeBB and Venz Logistik)

The testing phase started in June 2022 and showed a highly reliable system for exchanging the relevant data. During this phase it was possible to track mainly all transports along their routes and the multimodal ETA was successfully tested.

Optimization model

As part of the project, an optimisation framework was developed that enables the user to abstractly represent and optimise the logistics processes within a container terminal. The central optimisation algorithm is based on a mathematical representation of the relevant aspects of the terminal as a system of linear equations and inequalities, a so-called Integer Linear Program (ILP).

This makes it possible to create possible scenarios of the effects of different arrival times of the investigated train in the terminal with its internal processes. For the implementation of the investigations, the real data must still be finally assigned to the intended variables. The necessary data sets include, among others:

- Geometry of the terminal (track plans, routes, crane tracks, etc.),
- Manipulation units (cranes, reach stackers, other necessary vehicles, etc.)
- Timetables from the railway operation,
- manipulation times,
- dwell times in the terminal of trains and trucks,
- sub-process durations,

Figure 2 – optimisation model for testing different scenarios (©AIT)

The layout of the terminal is shown in simplified form in the mathematical model. A terminal consists of tracks on which trains can be parked, lanes on which trucks can drive for loading and unloading purposes, and a container storage facility along the tracks. All these components are divided lengthwise into sectors. The representation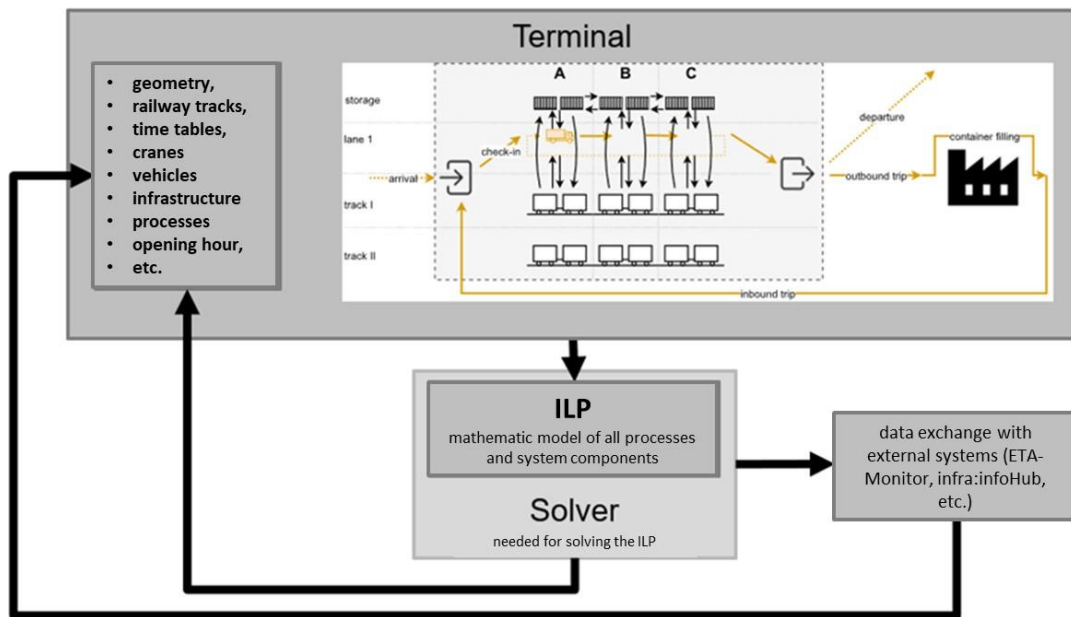 of the container warehouse is simplified in that the exact location of each container is not considered. Instead, each sector of the warehouse has a certain container capacity, which determines the number of containers that can be stored there at any given time. The loading of containers between trains and trucks always takes place within a sector - a container stored on a train in sector B can therefore only be reloaded onto a truck also parked in sector B. The loading of a container from or into a truck in sector B is also possible. Loading from or into the container depot, on the other hand, is possible between any sectors. The number of simultaneous loading operations is limited according to the available loading infrastructure (such as cranes and reach stackers).

For each train considered in the planning, the exact arrival and departure time as well as its parking position on the tracks of the terminal are known. This also indirectly results in the positions and the arrival and departure times of the containers loaded on the train that are to be unloaded and loaded in the terminal. The time availability of the individual trucks is also known and is taken into account in the planning.

The aim of the optimisation is to carry out all planned logistics operations as cost-effectively as possible within the time windows resulting from arrival and departure times. A possible logistics operation would be, for example, the unloading of an empty container from the train onto a truck parked next to it, the transport of this container to the customer for loading, its return transport to the terminal, the intermediate storage in the container warehouse and the final loading onto the train.

In order to be able to depict the resulting temporal dependencies in the model, the relevant parts of the terminal were modelled in the form of a so-called "time-space network" - a special type of graph in which the temporal component is represented in discretised form as a separate dimension. The physical transport route of a container can be represented in such a network together with the time schedule of the transport as a path in the time-space network.

For this purpose, a node is created in the time-space network for each physical location and each time necessary for this. Each node is always connected by at least one edge to the immediately following node at the same location - which represents a stay at that location. Furthermore, individual nodes

can be connected to the nodes of other locations if a transport between these two locations is possible. The time difference between these nodes corresponds to the duration of the corresponding logistics process - for example, if it takes five minutes to load a container from a truck onto a train, the lane node is connected to the track node five minutes later.

The model describes the transport of containers, trucks and loading infrastructure (such as cranes). The transport of containers must always be synchronised with the transport of the truck transporting them or the crane loading them (see figure 3).
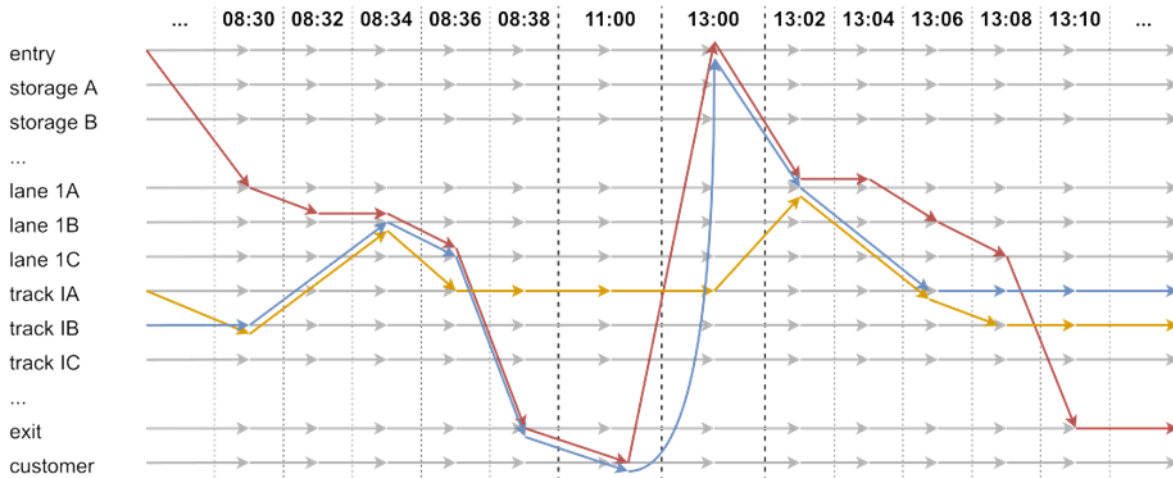
Figure 3 – example of a result from the optimisation model for testing specific scenarios (©AIT)

Results and evaluation

The evaluation and potential assessment are based on the assessment of the ETA Monitor / RRTM-C service management in ASFINAG (product development) and a questionnaire that was prepared during the trial operation. Some findings occurred in the interview and the evaluation.

- The targeted 75% of successful tracking via the system are good, but are considered to be potentially too low, especially with regard to the acceptance by the employees who organise dispatching and other logistical processes.
- The most important date in the application is to see at first glance when the expected arrival time is and whether it is on time or deviation from plan.
- The users of the system should be the dispatchers or, after connection via interface, the drivers directly.
- The application can contribute to the further development of intermodal freight transport by providing tracking and tracing functions without additional effort. In this way, fears can be taken away from potentially interested companies and hurdles can be removed. At the same time, the application is probably not a sufficient reason for deciding in favour of combined transport, time, costs, logistical effort and reliability are certainly more important here.
- For freight companies that successfully introduce the system, considerable time-saving potential is seen in connection with the frequent train delays: about 50%‑100% of the total delays could be saved in working time
- Further development of the application with regard to the display of the secured information that a) the container is on the wagon and b) the wagon is attached to the train (current implementation cannot check this a priori).
- Further development of the application and addition of output interfaces (e.g. for direct connection of driver apps).

Conclusion

In summary, the project was able to show that tracing and tracking could be implemented and put into operation within the framework of the technical possibilities and limits (e.g. tracking in road traffic only on the motorway) and thus a functioning solution with real data could be provided. The innovative content of the solution lies in the exclusive use of infrastructure data or existing/obligatory telematics (tolling data) as well as the linking of traffic information services of the infrastructure partners for tracking and tracing. In particular, no GPS boxes or similar are required, making onboarding easier and faster.

It is one big issue that the roadside part of the transport can be informed of the status of the trains running the container services. With the trustable knowledge regarding to the ETA the trucking companies have now the valid information that the train with the container to be transported to the recipient will arrive at a particular time. Finally, the project enables a stable prediction of ETA on a multimodal transport for the first time. Due to this there is no longer the problem that the trucking companies have to go to the terminal without knowing if their awaited container will arrive and at what time. This information implies no longer empty runs like in the past when n incident happened during the main run on the rail network.

Outlook

Due to the successful implementation and testing of the connection of the systems of the partners ASFINAG and OeBB Infrastruktur a follow-up project is being considered.

Digital Twinning platforms as an enabler for the ex-ante evaluation of PI-inspired interventions to last-mile logistics networks

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Abstract: One of the greatest challenges of the European last mile logistics sector is the requirement to decouple its economic growth from resource use and air pollutants emissions from transport operations. This requirement, alongside the rise of e-commerce and the phenomenon of urbanization, creates an urgent need for European Union's member states to identify and rapidly upscale innovative last-mile solutions that will ensure the green and digital transformation of European urban environments. To achieve such a goal, innovative frameworks such as the Physical Internet (PI) are required, which can lead to low-emission logistics services that remain competitive compared to the latest industry trends such as same- or next-day-delivery, real-time parcel tracking, and omni-channel distribution. The URBANE project introduces an Innovation Transferability Platform with Digital Twinning capabilities, under the Platform-as-a-service (PaaS) paradigm, which enables the project's Living Labs to assess the impact of the PI-inspired interventions before or during their implementation in the real-world context. In that regard, in the current article, a presentation of initial project results is given, including platform micro-services and Use Cases (UCs) that aim at supporting the transition to the PI.

Keywords: Digital Twins, PaaS, simulation, blockchain, trusted data sharing.

Conference Topic(s): interconnected freight transport; distributed intelligence last mile & city logistics; PI impacts; PI modelling and simulation; technologies for interconnected logistics (5G, 3D printing, Artificial Intelligence (AI), IoT, Machine Learning (ML), augmented reality, blockchain, cloud computing, digital twins, collaborative decision making).

Physical Internet Roadmap ([Link](#)): Select the most relevant area for your paper: ☐ *PI Nodes,* ☒ *PI Networks,* ☒ *System of Logistics Networks,* ☒ *Access and Adoption,* ☒ *Governance.*

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1   Introduction

The European Green Deal and the EU's objective to separate economic growth from resource use have increased the pressure on stakeholders in last-mile logistics networks and policymakers, to reduce the negative impact of environmental externalities of logistics operations on the urban environment. In the last years, this pressure has only intensified due to the rapid growth of e-commerce, reinforced by the COVID-19 pandemic, resulting in last-mile delivery being one of the most emissions-intensive sectors of the economy (Milewski & Milewska, 2021). Consequently, European cities need to adopt innovative solutions and create a transition path towards effective, safe, and sustainable last-mile logistics. Considering these emerging needs, as well as Logistics Service Providers' (LSPs) competitive pressures, such as same- or next-day delivery, rescheduling missed deliveries, and low prices, an innovative framework of solutions is needed to enhance the operational and environmental efficiency of European logistics. A highly anticipated answer to these requirements is the Physical Internet (PI, π) concept, which aims to bring the operational logic of the digital Internet to logistics networks.

The core idea within PI is to utilise modular and actively connected PI-containers that can be easily interchanged and transferred between different carriers and modern transport modes at PI-nodes of the interconnected logistics super network, based on standardised communication, collaboration, and routing PI-protocols. In this way, collaboration among different actors across the supply chain can be fostered, leading to greater interoperability and interconnectedness among parts of the global logistics network, which previously were disconnected. While PI's benefits have been both analysed (Ballot Eric et al., 2018) and showcased by big players in logistics (Tran-Dang et al., 2020), its adoption is in its infancy. While this is a common phenomenon with emerging technologies (Douthwaite et al., 2001; Wagner & Franklin, 2008), given suitable practices and strategies, the adoption of disruptive innovations can be accelerated in the Transport & Logistics (T&L) sector.

The URBANE project brings together a diverse group of public authorities, industry actors, and research experts to collaboratively create new solutions for last-mile delivery by combining PI-inspired approaches with the latest Internet Communication Technologies (ICT) and last-mile logistics modelling techniques. One of the main digital tools that are being developed is the Digital Twinning Platform, which is designed to function as a Platform-as-a-Service (PaaS) offering for city and logistics stakeholders. The platform utilises Digital Twins (DTs) technology to allow stakeholders to assess the impact of PI-inspired interventions before or during their implementation in urban contexts. As a result, regional authorities and LSPs, can simulate complex operational scenarios to evaluate how different real-world network parameters might affect short-term or long-term future operations (refer to Figure 1). The DT platform offers data-driven decision support capabilities for testing and implementing PI-inspired solutions in last-mile networks.
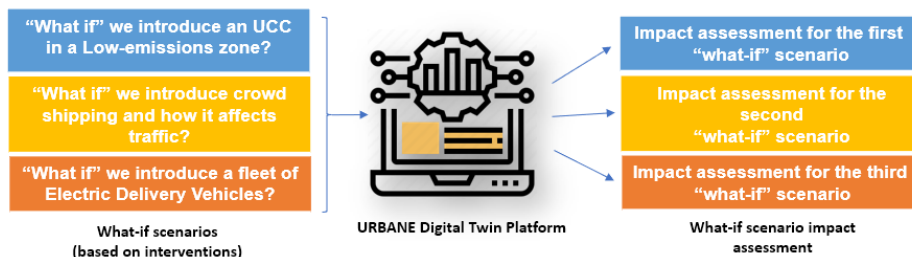

Figure 1: Use case examples for the URBANE Digital Twinning platform

As described in the sections that follow, URBANE will demonstrate prominent UCs of the DT technology, where platform users can utilize a range of digital logistics models and case-specific datasets to assess various "what-if" scenarios. These scenarios are comprised of

digitally modelled interventions in the logistics network (based on PI principles), whose impact on the logistics network would require more resources (i.e., case-specific model development, hiring of consultancies, digital infrastructure development, etc.) to be accurately estimated before actual implementation. The DT Platform supports the integration of several types of models, such as descriptive, diagnostic, predictive, or prescriptive analytics models (Cochran, 2018), which can be parametrised through a User Interface (i.e., DT Portal) and executed on a simulation execution engine. The DT platform features are complemented by trusted information sharing mechanisms built on blockchain technology.

This article is focused on two primary themes: *(i)* presenting some of the early results of micro-services of the DT Platform and relevant UCs under the Platform-as-a-Service (PaaS) framework, and *(ii)* introducing blockchain-supported AI-enabled Smart Contracts and Decentralized Identity Management technologies. The article highlights progress in PI-oriented thinking that has resulted from collaboration among industrial partners, public authorities, and researchers. Specifically, Section 2 of this article provides a review of PI-inspired innovative concepts and presents examples of primary PI enablers and expected benefits. Section 3 and Section 4 discuss the core technological aspects of the Digital Transferability Platform. Section 3 provides an overview of the DT micro-services and UCs under the PaaS framework, and Section 4 presents the expected services to be developed based on blockchain technology. Finally, Section 5 includes a discussion of how PaaS offerings and increased data sharing are contributors towards PI adoption, and Section 6 summarises the conclusions and next steps.

2 A review of PI-inspired innovative concepts

The PI represents a ground-breaking approach to logistics and supply chain management, that aims to make logistics systems more efficient, sustainable, and interconnected. At its core, the PI relies on an open network architecture that enables the seamless and interoperable exchange of goods, information, and services, thereby reducing communication barriers between stakeholders and facilitating greater collaboration. To achieve its objectives, the PI relies on a series of innovative concepts such as standardised protocols, container sizes, packaging formats, and modern transportation vehicles to improve LPSs' ability to address customer requirements, minimise environmental impact, and optimise delivery processes. Additionally, the PI leverages communication, collaboration, and routing protocols, as well as interoperability and traceability standards, to ensure seamless and efficient logistics operations among several LSPs. By encouraging new trade configurations and fostering collaboration between various stakeholders, the PI envisions establishing a sustainable, integrated, and effective global logistics super network, where logistics nodes are connected through standardised interfaces and protocols to enable the efficient transfer of goods from the source to the final destination.

The PI is a relatively new concept, and as a result, there is still a developing body of scientific literature on the subject, as well as the PI-inspired innovations, that may assist the transition from traditional segmented logistics networks to collaborative ones. Nonetheless, an increasing amount of research is being conducted on the PI, with numerous studies exploring its potential benefits and challenges (Eric et al., 2018; Montreuil & Nagurney, 2016). One of the most important innovations to achieve the PI is the standardisation of container sizes, shapes, and packaging formats that need to be handled across different countries, transportation modes as well as warehousing and storage facilities. Central to this standardisation of containers is the classification of PI-containers into several types of containers according to size and functionality. On the one hand, the following standardisation according to function has been suggested: transport containers (T-containers), handling containers (H-containers), and packaging containers (P-containers) (Montreuil et al., 2015). Further classification can be achieved based on the size and standard PI-container units (Montreuil, 2011). Given the proper

design of the PI-containers according to size and functionality, one of the end goals is to utilise modular containers, that enable the easier assembling, disassembling, loading, and unloading of goods by encapsulating the goods themselves, or other types of PI-containers. Importantly, PI-containers are envisioned not only to be modular, but also 'smart' and 'active'. Based on the smart PI-containers concept (Sallez et al., 2015), PI-containers can include 'active' tracking elements (i.e., wireless sensors and devices) instead of passive tracking technologies like bar codes. Based on this active connection, several benefits can be expected (Rizopoulos et al., 2022), such as real-time visibility of shipments, including location tracking, container security status (i.e., opening/closing of doors), hygrometry, vibrations, etc. PI-containers of all types should be able to interface with standard "smart" devices as well as PI-handlers and PI-sorters, which enable their efficient handling and manoeuvring in PI-nodes. PI-handlers fall under the umbrella of PI-movers, which are PI-inspired innovations that refer to systems and procedures that are connected to transporting, conveying, handling, lifting, and manipulating goods while they are in the logistic flow (Tran-Dang & Kim, 2018). While PI-movers as a term refers to innovations that are highly automated (i.e., autonomous ground vehicles, drones, robots), human agents can be PI-movers that overall manage and assist automated systems in loading, unloading, and transhipping PI-containers from one PI-mover to another (also assisting with information sharing and management, order management, etc.). An example where PI-movers are showing promising potential can be located within PI-inspired cross-docking facilities (Chargui et al., 2018), where high-speed PI-conveyors can be combined with an automated storage and retrieval system, and PI-sorters to replace a set of traditional forklifts that facilitate the loading, unloading, and transfer process.

When a node of the logistics network is equipped with the necessary PI-inspired infrastructure, protocols, and technologies, then it can serve as an enabler of the seamless consolidation, exchange, and routing of goods within the PI. The aforementioned PI-inspired cross-docking facilities are just one type of a PI-node, which refers to a set of facilities that serve as connecting interfaces between logistics networks. Based on the types of networks that are connected at each PI-node and each node's functionality, PI-nodes are classified into several types, such as PI-transits, PI-switches, PI-bridges, and PI-hubs (Chargui et al., 2022; Tran-Dang & Kim, 2018). When PI-nodes, such as rail-to-road and water-to-road PI-hubs, are designed accurately on a strategic, tactical, and operational level in order to exploit other PI-inspired innovations (Chargui et al., 2019), they can connect and improve logistics networks, but also promote sustainable modes of transport such as railways and waterways (Figures 2 & 3).
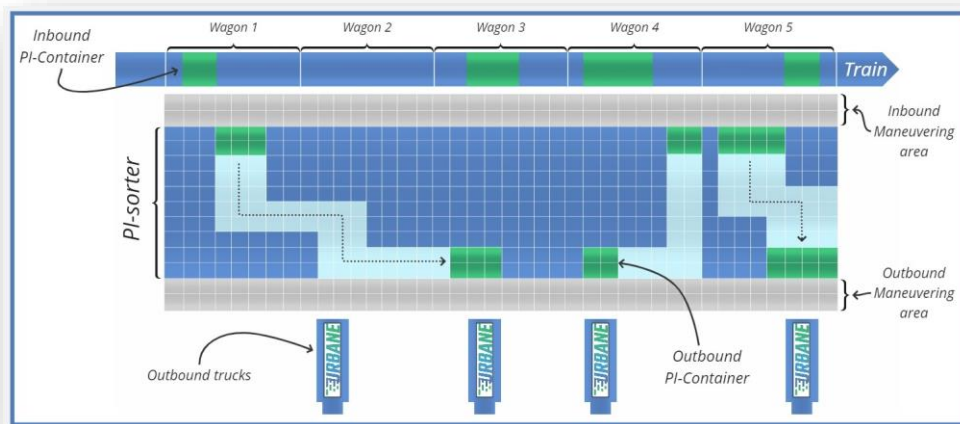

Figure 2: An example of a rail-to-road PI-inspired cross-docking facility (PI-hub), with a PI-sorter and two maneuvering areas.

PI-protocols are also worth mentioning, as they ensure that all PI-inspired innovations (refer to Figure 4) are integrated together by taking the central role of communication, negotiation, and coordination between stakeholders within the PI (Kaup et al., 2021). In contrast to the well-established protocols of the digital Internet, in the PI, some processes, such as packet aggregation and resending lost packages, are much more complex and display different properties as compared to the digital world. For these reasons, although the scientific world has already presented metaphors from the five-layer Internet Protocol model (application, transport, network, link, and physical layers), several PI-protocols and respective technologies may need to be combined to achieve the PI (Briand et al., 2022). An essential research direction in emerging PI-protocols is dynamic routing of PI-containers, as the main object of the flow-to-be-optimised while treating the different logistics sub-networks of the PI as heterogeneous autonomous systems (Gontara et al., 2018).
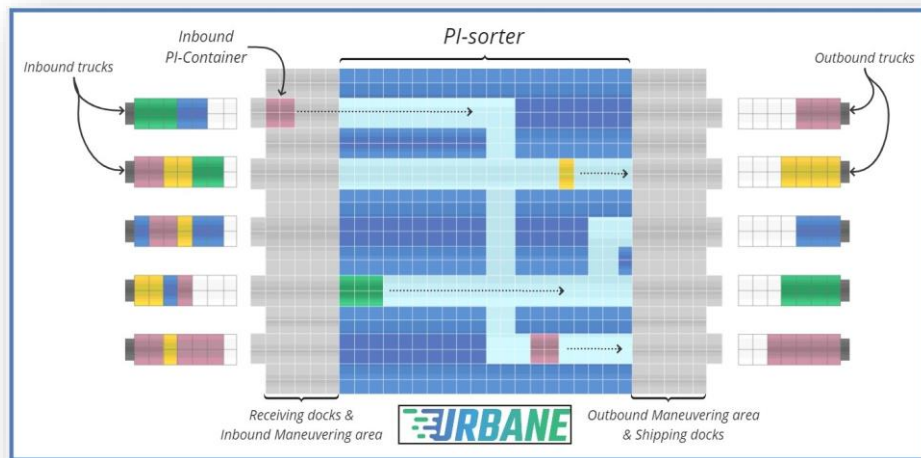
Figure 3: An example of a road-to-road PI-inspired cross-docking facility (PI-hub), including a PI-sorter and two maneuvering areas.

As in the case of the digital Internet, PI-protocols and related innovations have a central role in how communication between LSPs and logistics networks takes place to define how an object-to-be-shipped travels from one node of the PI to another. To achieve this communication, several innovations that have been presented up to now can play an important role. A first fundamental example is GS1's Electronic Product Code Information Services (EPCIS), which is a standardized data exchange format and architecture for real-time capturing and data-sharing related to the status of a shipment and related products, assets and services throughout the supply chain[1]. Potential adoption of EPCIS into practice can bring significant benefits to stakeholders, such as improved inventory management and visibility for LSPs (Soedarno et al., 2020), but can also be a major enabler of the PI since data stored in standardized formats can be exchanged between LSPs that are eager to collaborate and increase delivery efficiency. Supplementary to EPCIS, blockchain and smart contracts technologies can be important for the realization of the PI, which has been proposed as solutions that can bridge cyber and physical systems in multiple sectors (Fotiou et al., 2019). Blockchain and smart contracts solutions have been also proposed for the introduction of a synergetic application framework, which can facilitate the trusted data and value exchange between multiple actors in the PI network (Meyer et al., 2019). In the framework discussed, PI-containers serve as the centre of value exchange

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[1] GS1's EPCIS & CBV standards, https://www.gs1.org/standards/epcis

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of interest and can be traded and tracked by actors on a decentralized and transparent blockchain network that enables a more optimal routing of parcels between PI nodes.

A final reference within this section is the PI-concept of synchromodality, which can be seen as one of the desired impacts of the application of PI-inspired innovations, advanced analytics applications as well as increased and real-time data sharing across stakeholders. As an extension to intermodal transportation, synchromodality enables dynamic switching between various modes of transportation, such as road, rail, waterways, or air. Based on real-time data, the choice of transportation mode can occur depending on different factors such as cost, time, environmental impact, and other stakeholder requirements (Ambra et al., 2019b) within PI-nodes. Especially in the case of railways and waterways, which are more efficient and sustainable than road transportation for long distances and larger volumes of goods but must deal with the requirement of intermodal transport and transhipments, synchromodality can increase their modal share by enabling the optimization of the entire logistics system and increasing flexibility (Ambra et al., 2019a).
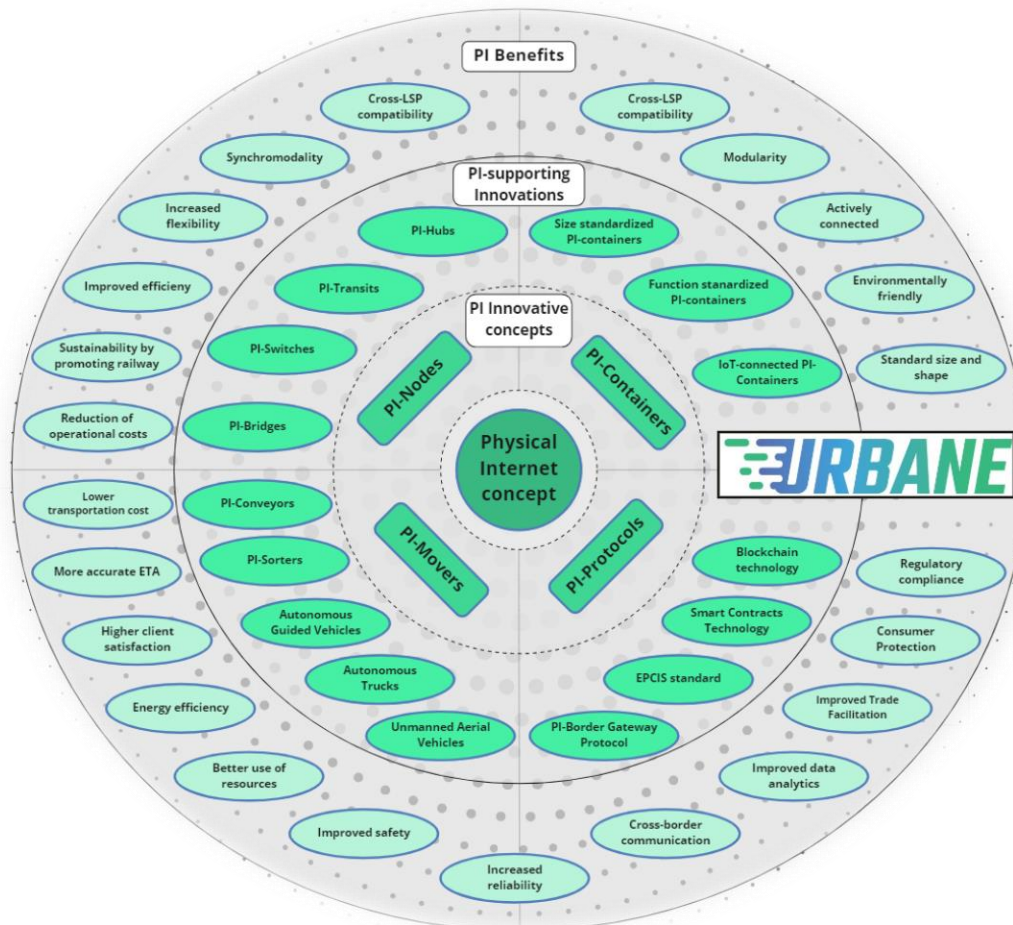
Figure 4: A collection of PI Innovative concepts, PI-supporting innovations, and expected benefits

3   Digital Twinning under the PaaS paradigm

Several definitions of Digital Twins (DTs) have been proposed in recent years (IBM, 2023; Kritzinger et al., 2018; World Wide Web Consortium (W3C), 2023). Despite the lack of a commonly accepted definition, they mostly agree that a DT is a *virtual representation of an object or system*. This is unsurprising, given that their origin lies in smart manufacturing (Kritzinger et al., 2018). Yet, in the domain of smart cities, as well as transport and logistics,

such an interpretation does not seem a good fit since the focus is not only on technology but also on the participation of different communities and stakeholders (Mylonas et al., 2021). In this context, the European Commission defined Local DTs as the "virtual representation of the city's or community's physical assets, processes, and systems that are connected to all the data related to them and the surrounding environment"[2]. Through the use of data analytics, AI, ML, and agent-based modelling they provide answers to case-relevant what-if scenarios. Such a solution was previously designed and developed in the context of the LEAD project[3] and is currently applied and extended in URBANE. In both projects, the DT is offered to the project's Living Labs as a Platform as a Service (PaaS) solution, providing several economic and practical benefits to the pilot cases since there is no need to build and maintain infrastructure, acquire licensing, and so on.

The ambition behind the URBANE DT is to support urban logistics communities with a ready-to-use solution that offers them dynamic data-driven modelling innovations and interventions with the ultimate purpose of empowering their policymaking. Significantly, the DT employs a plethora of different models - from AI models to social simulation, agent-based models developed within the project, but also models developed previously in LEAD – thus, developing a *Model Library* that can be reapplied and extended in several UCs within the project's Living Labs, but also in PI-relevant UCs outside of the realm of the URBANE project.
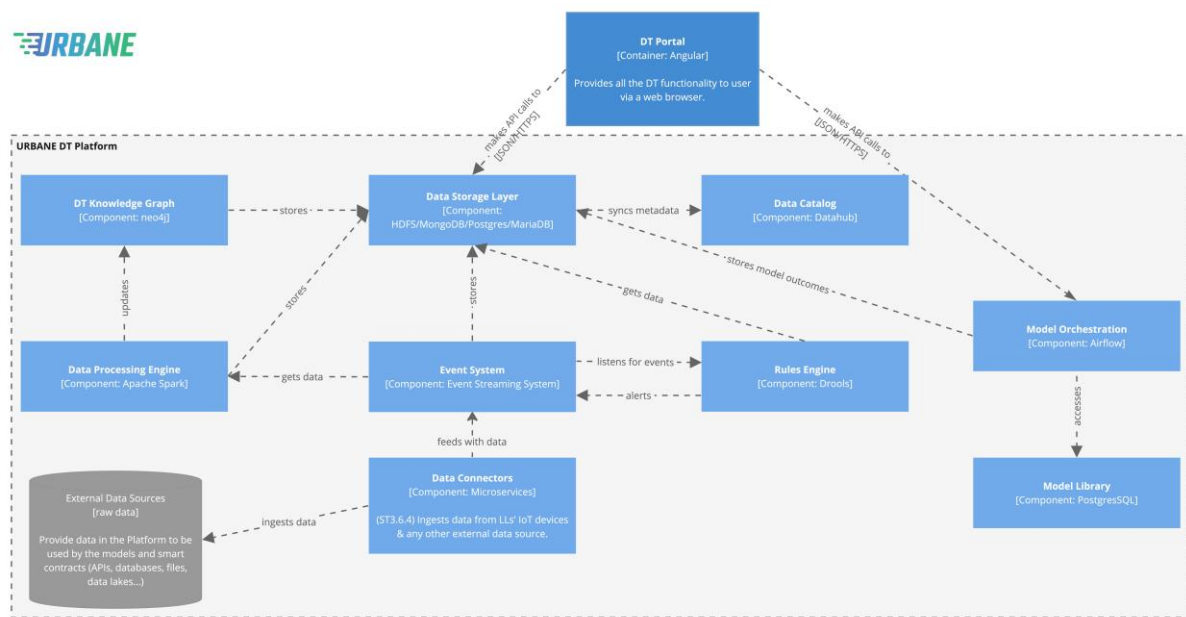
Figure 5: Component Diagram of URBANE Digital Twin

The high-level architecture of the DT consists of several key components as depicted in Figure 5. A feature of critical importance is the ingestion of relevant data from various external sources – either in real-time or in batch – through the dedicated *Data Connectors*. In this manner, the platform ingests raw data and afterward processes – by the *Data Processing* Engine - it and stores it to provide different what-if scenarios with real-life, suitable data. As already indicated, a key component of the DT is the *Model Library*; models are entered into the platform through a meticulous integration process – offered either as open-source components or through API communication – to ensure reusability and even extendibility of the models. On top of this, the

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[2] "Workshop - Local Digital Twins Technology", European Commission, https://digital-strategy.ec.europa.eu/en/events/workshop-local-digital-twins-technology
[3] Low-Emission Adaptive last mile logistics supporting 'on Demand economy' through digital twins (LEAD), https://www.leadproject.eu/

Model Orchestration component enables the dynamic creation of model workflows by the DT users. This functionality, enabled by Apache Airflow, empowers users to create their own what-if scenarios comprised of chains of different models – often one model output is used as input to another model – serving their own UCs. These functionalities are offered through a dedicated DT Portal that can be accessed through a web browser.

The following sections present a real-world application of Digital Twinning and last-mile logistics modelling, in which a model performs an estimation of Electric Delivery Vehicles (EDVs) fleet size to cover real-world parcel delivery demand. In more detail, the DT and the respective model have been used in two UCs:

- <u>Historical data analysis, based on monthly demand data:</u> Models are used to estimate EDV fleet size to assess the establishment of LSP's logistics services that focus either on missed and rescheduled deliveries or 'small' deliveries (i.e., lower volume orders), and,
- <u>Real-time DT:</u> Based on the available fleet size and specification, the DT and underlying model estimate the number of EDVs needed to cover demand on shorter time frames (i.e., daily horizon and dispatch windows within a day).

Based on these UCs, the LSPs can develop a techno-economic analysis of prospective services and/or calculate EDVs to be purchased/leased within different time horizons (i.e., months, days, and dispatch windows). The estimator model that has been developed and used in these UCs is based on a Capacitated Vehicle Routing Problem with Time-Windows (C-VRP-TW), LSP's parcel delivery data and routing based on the OpenTripPlanner engine and OpenStreetMap data. Through the developed DT solution, LSPs are empowered to move towards the 'electrification' of their fleet by acquiring quantified evidence of what is the number of electric delivery vehicles (specified by the maximum delivery range and capacity) required to cover a specific delivery demand over a timeframe (i.e., as indicated by input data to the DT). Not only that but the quantified evidence can be produced/re-produced by the LSPs themselves by utilizing the DT and underlying models under the PaaS framework, when needed. In URBANE, extensions of these UCs are under development, including the use of other innovative delivery vehicles, as well as the examination of as-is and to-be scenarios for their use.

During the last few years, research on DTs related to supply chain management, T&L, and the PI has increased (Barykin et al., 2020; Leung et al., 2022), though it is still in its infancy (Deepu & Ravi, 2021; Nguyen et al., 2022; Pan et al., 2021). Our work focuses on the development of a DT that focuses on last-mile logistics in urban areas and aims at improving the operation of parcel delivery, reducing costs but also emissions in a sustainable manner through PI-inspired forecasting and simulations applied to different scenarios within the project's Living Labs.

4 Blockchain-supported AI-enabled Smart Contracts and Decentralized Identity

Blockchain technology has the potential to play a significant role in the materialization of the PI paradigm by enabling secure and transparent data sharing across the entire logistics network while also supporting identity management towards a more user-centric approach. To this end, the URBANE Platform uses smart contracts to increase the transparency of interactions between T&L stakeholders and automate processes such as the movement of goods, payments, inspections, quality control, and last-mile infrastructure/resource sharing. The employment of AI-enabled smart contracts brings us a step closer to PI since it makes them even more intelligent and automated by analysing historical or live IoT data from sensors to trigger pre-defined actions, which were otherwise triggered by paper-based contracts.

The URBANE project integrates a blockchain-based service that employs AI to predict future demand in shared last-mile delivery lockers and automatically generate contracts between T&L stakeholders for a more fine-grained management of physical resources. The AI analytics of

the service predicts trends and incoming loads of shipments in the lockers that help LSPs adjust their operations, secure better pricing policies with their partners, and open up their privately owned infrastructure to competitors in a trusted way.

Another key functionality that is supported by blockchain technology in URBANE is the identity management of the platform's users, namely actors in the supply chain (e.g., carriers, shippers), but also administrators, and data analysts who wish to experiment with or develop data-driven services. Devices and systems are also using the same decentralized identity management mechanism to interact with the platform, since it follows legacy standards (i.e., OAuth 2.0 (Hardt., 2012), that make the integration straightforward. URBANE's identity management approach follows the SSI paradigm (Preukschat & Reed, 2021) that gives full control of the data to the user and enables GDPR[4] to the greater extent possible, by allowing the right of data erasure (to be forgotten) and the right of data portability.

Overall, the blockchain-based functionalities of the URBANE Platform enable the interoperability of stakeholders in the last-mile delivery, as it offers i) the ability for automated smart contracts between different organisations to eliminate ambiguities in case of disputes ii) increased transparency in the entire supply chain by allowing a trusted shared registry for data exchange and iii) secure and globally unique identities that follow the latest emerging standards i.e., DIDs[5] and VCs[6].

5 PaaS offerings and increased data sharing as contributors towards PI adoption

The PaaS model originated with the advent of cloud computing. According to the United States' National Institute of Standards and Technology (NIST) Definition of Cloud Computing (NIST SP 800-145), a cloud PaaS service is the capability provided to a consumer of the service to deploy consumer created or acquired applications using programming languages, libraries, tools, and services provided by the PaaS service provider. This definition provides a general overview of the PaaS service being developed in the URBANE project that has been described previously in this document.

Such platform services, facilitate migration to PI logistics operations in urban settings by providing LSPs the tools needed to develop and deploy scalable Logistics as a Service applications without having to worry about integration and dynamic management of sensor-enabled urban infrastructures that comprises the infrastructure as a Service layer of an urban cloud model. For example, a cargobike service provider performing last-mile delivery services within a city would be able to use the PaaS services to monitor the delivery performance of its workforce, predict failure to deliver situations due to congestion, accidents, or other delaying situations and design rerouting options to eliminate the delays. The service provider could also integrate with the PaaS blockchain and smart contracting services to create a smart contract model that, when the platform is notified of a successful delivery, the delivery person's account is credited, and a payment is executed.

With respect to the PI, a functional PaaS coupled with a true urban Infrastructure as a Service capability allows logistics operations to be managed in a manner mirroring how the digital Internet operates through cloud infrastructure. Shipments can be tracked in a distributed manner, infrastructures allocated and "scaled" based on flow demand, and pricing for usage can be allocated efficiently. The blockchain non-repudiation layer of the PaaS ensures that deliveries and other contracted events are documented and, if smart contracts are enabled, then automated bonus/malus, payments, and other operational actions can be executed in an automated manner. While the existence of a PaaS and IaaS structure are not required for

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[4] Regulation (EU) 2016/679, European Parliament, Council of 27 April 2016, http://data.europa.eu/eli/reg/2016/679/oj
[5] Decentralized Identifiers (DIDs) v1.0, World Wide Web Consortium (W3C), thtps://www.w3.org/TR/did-core/
[6] Verifiable Credentials Data Model v1.1, W3C, https://www.w3.org/TR/vc-data-model/

implementing either the PI or the digital Internet, as has been seen with the implementation of cloud services for the digital Internet, their availability eases the setup of innovative operational approaches and facilitates payment for only those services used.

6   Concluding remarks

The development of the DT and blockchain technologies has opened new opportunities for cities' transition to PI-inspired last mile logistics. To address the barriers to PI adoption, a comprehensive approach is necessary for PI projects on a Pan-European level. This approach should address the various challenges posed by technical complexity, lack of standardisation, upfront investment costs, regulatory, legal and cultural barriers. URBANE project's PaaS envisions to lift the PI adoption barriers by combining DT and blockchain technologies. In the current article, a presentation of the first results is given, including the main development directions for two of the core technological tools: *i)* DT platform as well as *ii)* the Blockchain-supported AI-enabled Smart Contracts and Decentralized Identity Management technologies. Numerous challenges remain ahead for the URBANE project to accelerate the adoption of the PI vision and bring emerging innovative logistics solutions to real-world application, including data sharing governance mechanisms, the introduction of automated vehicles and transforming logistics hubs to smart PI-nodes. However, we believe that these challenges can be overcome and that the results of the effort to overcome them will lead to positive outcomes for cities, citizens, LSPs, and the environment.

7   Acknowledgements

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The Urban Cloud: Linking city services, cloud computing, and the Physical Internet to achieve smart city objectives

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Conference Topic(s): last mile & city logistics

Physical Internet Roadmap ([Link]): Select the most relevant area for your paper: ⊠ PI Nodes, ⊠ PI Networks, ⊠ System of Logistics Networks, ⊠ Access and Adoption, ⊠ Governance.

Abstract

Urban logistics operations have become more complex and problematic for cities. The last mile delivery situation, driven by the growth in eCommerce purchases, is creating congestion and sustainability problems that cities must address if they are to meet the expectations of their citizens for a socially enjoyable and sustainable living space. This working paper explores the potential restructuring of how cities manage their infrastructure to achieve these objectives. Building on the fact that cities have increasingly built intelligence into their infrastructures through the installation of sensors, the paper examines the potential for reorganizing the management of this infrastructure using cloud computing three layers of Infrastructure, Platform, and Software as a Service architecture as a model.

1 Introduction

Cities are complex entities composed of multiple interacting networks of actors, systems, technologies, and regulations (Batty, 2013). As a structure built from the interaction of multiple networks, a city is not a planned construct, but an emergent concept reflecting the multitude of interactions between its underlying components (e.g., Fromm, 2004). Historically, the approach cities have taken to managing this complexity has been to organize functionally and, within function, to focus on either technical or geographic components of the function (Minett, 1975). Unfortunately, such a structure has encouraged the development of "silo" thinking, which ignores the interconnections of the various networks that operate within a city. As Christopher Alexander noted in the article that John Minett was responding to in his 1975 article, a city is not a tree, i.e., it is not a hierarchical construct that can be neatly laid out and managed as if what happens along branch 'x' has no impact on things going on along branch 'y' (Alexander, 1966). The complex interactions that people, organizations, services, etc. have within a city preclude this tidy tree like thinking (Jacobs, 1961).

Complexity makes the management of a city's infrastructure a difficult task. An urban street, for example, may have retailers located along it who need to be resupplied with goods for sale, parking for people to come by and shop, electricity to operate lights and internal systems,

sewage to provide for the comfort of employees and shoppers, telephone lines to make calls, Internet access to order supplies and replenish stocks, garbage collection to pick up waste and recyclables, gas for heating, street cleaning to entice shoppers to a neat shopping district, police and fire personnel to ensure safety, etc. The myriad of interacting systems operate to allow this retailer to provide services to their customers, rent to the building owner, pay its employees and taxes to the city. Numerous other sets of separate networks interact within the city to generate economic, social, educational, and artistic benefit for the city's citizens.

Overseeing the various services that are accessed by the entities that deliver services and benefits to the city's citizens are the city's public works department, the transportation department, the police and fire departments, the tax department, a building inspection department, a business license department, an education department, a social services department, a parks and recreation department, etc. In addition, water companies, electric companies, Internet service providers, gas companies and telephone companies all are also managing a set of services that allow these service entities to operate. And, of course, there is that logistics service provider who is being asked to replenish the stock of the retailer, deliver a package to the consumer, or deliver office supplies to the various city departments that enable the retailer to sell to the citizen who wishes to park their car in front of the retailer's shop and shop at the retailer.

As cities have grown the services that they are expected to deliver to their citizenry have also grown. As the example of the retailer indicates, these services, provided by numerous city functional departments and external commercial entities intersect, facilitate, and constrain the various recipients of the services in an emergent manner that no individual department or company can foresee or control. Given the city's inability to systemically control or understand what is happening at the operational level means that interventions are as likely to harm as they are to help in achieving higher level goals being set by citizens or regulatory authorities. Another approach to managing the operations of the city is required.

2   The Smart City

Several proposals have been put forward to try and address the problematic nature of managing a modern city (e.g., Batty, 2018). No single approach has gained more attention in the last fifty years than that encapsulated in the term "smart city."[1] Smart cities are defined in many ways (Dameri, 2013; Albino et al., 2015). For this paper we use a definition employed by the European Commission. This definition states that[2]:

> A smart city is a place where traditional networks and services are made more efficient with the use of digital solutions for the benefit of its inhabitants and business.

This definition recognizes that cities are composed of multiple networks that interact and that the purpose of applying digital technologies is to make these interactions more efficient so that citizens and businesses benefit. The smart city concept has evolved from its early days in the 1960s to a sophisticated view of citizen centric and ecosystem focused service deployment enabled through platforms, sensors, and artificial intelligence. This evolving viewpoint posits many benefits to citizens, society, commercial enterprises, and the environment. Unfortunately, analysis of the numerous projects that have been reported as part of smart city implementation

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[1] Note that the actual smart city concept, although not called a smart city, was probably in the minds of individuals in the early 1950s as can be seen in an article by Norbert Wiener in a December 1950 Life magazine article where he spoke of the city as a "communications net" (Kargon & Molella, 2004).

[2] Smart cities (europa.eu), accessed 15 April 2023.

efforts show that benefits have been limited (e.g., Lim et al., 2019). This fact is partially due to the primarily technical focus of these implementations, but also is a result of the relatively ad hoc nature of the implementations and their lacking integration into an overall smart city governance structure.

To date most smart city efforts have focused on applying technology to solve a particular problem. Classic examples of these efforts are the application of video cameras and sensors to control traffic flow, cameras and microphones to control and potentially predict crime, sensor deployments to measure pollutants, moisture levels, and noise levels, and RFID tags to allow vehicles access to roads and areas within the city (Law & Lynch, 2019). Some efforts have been undertaken to structure and integrate the various digital sensors that have been implemented to both better control the operations overseen through the sensors and to analyze the large datasets that result from real time sensing of city activities. Most of these efforts have focused on developing technical architectures that facilitate the interconnection and management of the multitude of sensors, cameras, IoT devices, and control systems that cities have implemented over the years to address various point problems in their operations (e.g., Miladinovic & Schefer-Wenzl, 2018; Haque et al., 2021).

While the primary effort for most smart cities has been in deploying technology to address problems in an ad hoc manner, some cities have recognized the problematic nature of this approach and implemented efforts to integrate their disparate systems. Cities such as Barcelona and London both have worked hard to address the integration of data flows and the management of the systems being controlled or monitored through their smart sensing infrastructures (Bibri & Krogstie, 2020). These cities use the data generated through the various sensors they have deployed to inform citizens about the state of the city and to manage various systems in a more integrated and efficient manner (Bibri & Krogstie, 2020). Unfortunately, even these two cities, given the efforts that they have put into both collecting and integrating their disparate data streams, have not rethought how they might utilize this information to leverage their infrastructures in a more effective manner. This fact can be seen by examining the architecture of Barcelona's smart city infrastructure (Sinaeepourfard et al., 2016).
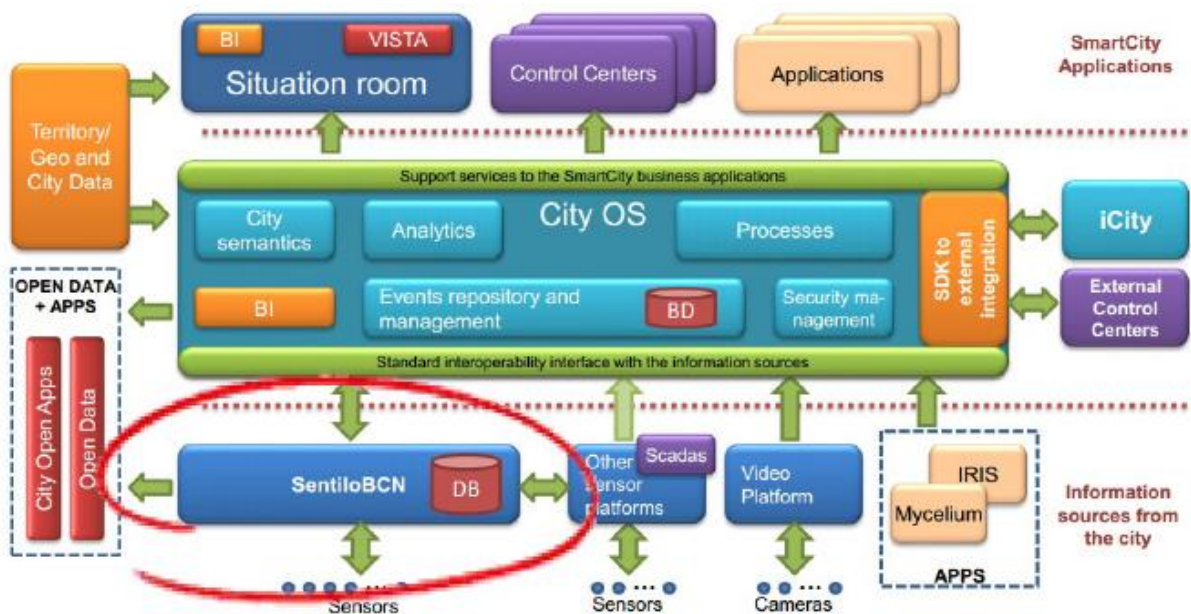

Figure 2-1 Barcelona Smart City IT Architecture (Sinaepourfard et al., 2016)

As noted in Sinaeepourfard et al. (2016), Barcelona developed its architecture with the goal in mind to better manage the disparate population of sensors it was deploying and integrate their

data for use in providing its citizens and businesses with more informative and beneficial services. The three-layer architecture follows the standard enterprise architecture approach of creating a data interaction layer to interact with sensors, a middleware layer to act as an integration and publish/subscribe layer, and an application layer upon which various management and citizen facing applications can be deployed. City departments use the platform to monitor the services under their control to ensure that their departmental goals for the city, its citizens, and businesses are being achieved. Using the IT platform thus developed to rethink how the city could manage the complexity of its infrastructure in a more wholistic manner was not a design element of the platform or its implementation.

3 The Evolution of Cloud Computing

While the smart city concept has been undergoing its evolution, advances in digital and communications technologies have revolutionized how distributed computing and application delivery are performed. The late 1990s and early 2000s model of server hosting in external locations began to have problems as the number of users began increasing, forcing new servers to be purchased as individual server capacity became constrained. Google found it could no longer manage its server farms in this manner and started developing operations around what it called "warehouse scale" computing (Barroso et al., 2009). This type of computing operation linked hypervisor (virtual machine) management techniques with virtual machines running on a type of "bare iron" processors that allowed processors to be shared and scaling to occur in a planned manner. This early approach to on-demand scalable computing would be called "cloud computing" later in 2006.[3]

Cloud computing's model of on demand scaling and pricing has enabled the abstraction of software application developers from having to worry about infrastructure support and management (Mell & Grance, 2012). Software as a Service applications have become commonplace and are providing distributed users with access to application services on an anytime/anywhere basis. In addition, cloud computing's three-layer architecture, providing Infrastructure as a Service for computing resources, Platform as a Service for application development, and Software as a Service as a hosting layer for applications has enabled developers to create innovative solutions for distributed business users (Mell & Grance, 2012).

The development of Infrastructure as a Service (IaaS) capabilities enabled the warehouse scale computing concept employed by Google to manage the extremely large workloads its search engine was attracting. It also helped Amazon to address its growing need to integrate and manage the diverse frontend and backend systems required to handle its global online retailing business. While Google focused on building out efficient infrastructure for itself, Amazon saw the potential for other global companies to use its infrastructure services and released its Simple Storage Service (S3) and Elastic Compute Cloud (EC2) in 2006. Amazon's commercialization of cloud services in 2006 created the market that is today recognized as cloud computing.

The key to the success of the cloud computing market has been its transformation of computer processing power from an individually onsite managed operation to a scalable utility in which a business pays for only what it uses. The ability of cloud computing companies to employ large datacenters composed of relatively inexpensive servers and allocate processing time dynamically across these servers utilizes technology that extends back to the late 1950s.

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[3] Eric Smith of Google is generally credited with using the term Cloud Computing first at conference in 2006. This credit is controversial as a University of Texas professor, Ramnath Chellappa, claims to have used the term in 1997.

In the late 1950s computer scientists began looking for ways to allow individual users to interact dynamically with the large and expensive computers available at the time. This need arose because computer users, primarily academics and developers, did not like waiting to run simple tests on programs that they were working on. Unable to interact in real time with the large computers available to them, they had to submit their programs to be run in sequential batches, which meant waiting long periods of time to see whether a simple algorithm or program change would run. Computer scientists at MIT developed a prototype time-sharing system in the early 1960s (Corbato et al., 1962). Concurrently with the research work going on at MIT, IBM began developing its own time-sharing system for its soon to be released System 360 (Adair et al., 1966). To make such a system work required development of a concept that has come to be known as a "virtual machine." This idea was required since the use of a single processor needed to be managed in such a manner that a computer program would believe it had sole access to the processor when in fact it was sharing the processor with many other programs.

Virtualization became a standard in shared computer systems in the years following its development. Users could now run their programs without worrying about having to manage all the intricacies of memory, loading, unloading, etc. However, virtualization was a process applied to a single processor, not to managing a host of processors running on different machines. Addressing this problem required a supervisory program for the operating system supervisor, a hypervisor. The first formal use of this term appears in an article by Popek & Goldberg (1974) where they introduce the concept of a virtual machine monitor, a hypervisor. The hypervisor, or virtual machine monitor, is the management technology that allows cloud service companies to abstract the physical hardware and operating systems they employ from users allowing users to focus on developing their applications and not worry about deployment or scaling.

IaaS services allow users to have access to scalable compute resources without having to manage the resources or worry about scaling. The ability to abstract users away from managing or worrying about the underlying physical technology has allowed the user community to increase its use of software for business operations while reducing its costs. Today there is little worry in most businesses about system response time or system crashes. The Quality of Service provided through IaaS services is significantly more reliable than on premise operations simply because of the scale and operational control that modern virtual machines and hypervisors provide in dynamically allocating compute resources to tasks. Failure of a compute resource is managed seamlessly and user applications continue to run as they are redeployed dynamically to run on other operating hardware.

4   The Physical Internet

While cloud computing was gaining traction in the computing world, the Physical Internet (PI) concept was also taking shape. The Physical Internet is an approach to mobility that uses the digital Internet as a metaphor (Montreuil, 2011). If every physical entity is instrumented with a real time trackable device, why can't these physical entities be managed on their trips from origin to destination like packets over the Internet? The Physical Internet concept is a particularly useful model when the entities being tracked are freight packages, which are very close conceptually to packets being sent over the Internet.

Using a PI model for addressing urban transportation issues, particularly urban logistics, has been shown to provide considerable benefits (Kim et al., 2021). The basis of the PI model is the collaborative sharing of logistics assets to improve logistics efficiency, effectiveness, and environmental impact. The PI has been demonstrated to lower overall costs in a network through efficiency improvements while also lower emissions (Pan et al., 2013). In the urban

context a PI structured logistics model would incorporate shared consolidation centers and microhubs ensuring that vehicle loads were optimized and that vehicle journey lengths were minimized (Kim et al., 2021). The use of low or no emission vehicles (electric vans, cargobikes, etc.) would further lower the emissions from logistics operations.

While the PI offers many advantages by increasing logistics efficiency, lowering costs and emissions, and potentially improving quality of service, it requires logistics service providers to collaborate in delivering their loads. In a highly competitive low margin business like logistics, this is a difficult hurdle for companies to overcome (e.g., Basso et al., 2019). In an interesting article by Fawcett et al. (2015) looking at why supply chain collaboration fails, the authors found that a series of relational resistors create friction that impedes and ultimately causes failure of collaborative efforts between supply chain participants. They created a model of the various resistors that cause failure that is quite informative and shown in the figure that follows.
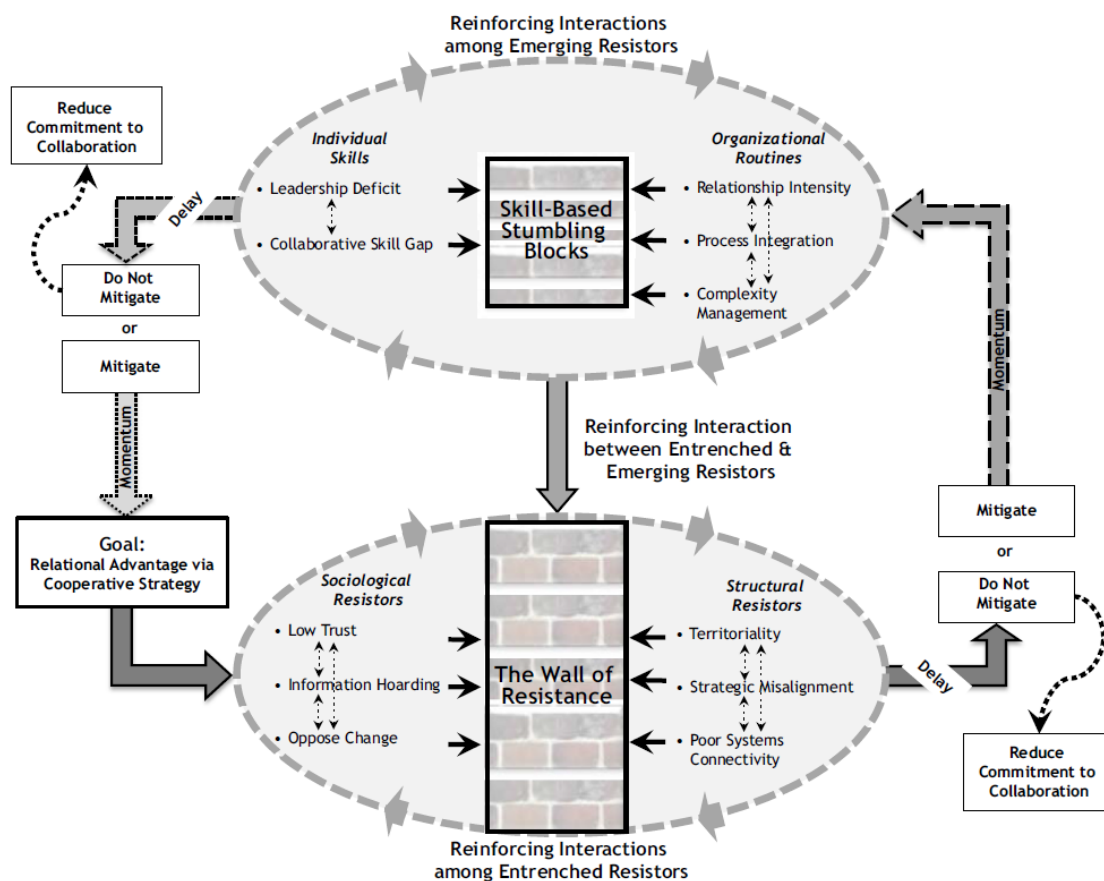
Figure 4-1: A Socio-Structural View of Resistors to Collaborative Capability (Fawcett et al., 2015)

The Fawcett et al. (2015) figure shows that resistance arises within two different groups of potential collaborators. The entrenched individuals see no reason to collaborate while the emerging resistors fail to get sufficient motivation from their leadership teams to overcome the friction caused by the entrenched resistors and the operational challenges that any new relationship brings with it. This study provides a very good overview of why, even when the benefits of collaboration are known, it is very difficult to get parties to collaborate. While it is not the intention of this paper to address the issues that get in the way of logistics collaboration, it is important to note that these issues do act to slow the implementation and adoption of the

PI, and similar issues create problems for city organizations to work in an integrated manner to deliver services to citizens and businesses (e.g., Pereira et al., 2017).

5   The Urban Cloud

The problems faced by cities as they attempt to achieve the vision of smart city operations can benefit from the linking of the cloud computing architecture framework discussed above with the Physical Internet construct. With respect to the cloud computing architecture, organizing smart cities around a model in which city infrastructure is managed as an on-demand service available to users could optimize the use of city infrastructure while eliminating overuse and congestion. In addition, building an urban "cloud" model for city services, where city platforms form a Platform as a Service layer upon which service providers (including the city itself) build applications to serve the city's citizens and businesses, would also enable cities to better realize the citizen centric service objective at the heart of the smart city concept.

The Internet provides an example of how urban cloud services, operating to manage a Physical Internet in which delivery and pickup of shipments within a city are consolidated and deliveries are optimized, could improve the utilization of city infrastructure, and benefit the city through more efficient logistics operations. Just as businesses use the Internet to access cloud-based services, cities employing an urban cloud model could deliver Logistics as a Service to their constituencies with the physical execution performed according to Physical Internet principles.

5.1   Urban Infrastructure as a Service

Managing city infrastructure as a service requires some clarification. Unlike the infrastructure models developed for cloud computing in which operations on silicon can be "virtualized" so that computing resources can be dynamically shared, and failure of infrastructure gracefully handled, it is very difficult to virtualize a vehicle occupying a curbside parking space so that another vehicle can also occupy that space. However, a city can dynamically manage and control the linear areas along its curbs using cameras or sensors. Using data collected in real time, the city can dynamically assign loading and unloading space to both passenger vehicles and logistics vehicles. It can enforce this assignment process by dispatching enforcement personnel to ticket offenders or by requiring all local vehicles to carry a sensor that identifies the vehicle and that can be used to automatically ticket the vehicle for offences. Certain issues with privacy would need to be addressed, although most cities require owners to register their vehicles to park in the city today, so adding a sensor requirement may not be as problematic as it may seem.

By abstracting the infrastructure through an IaaS system, the city would provide convenience to its citizens, businesses, and logistics operators. These users would no longer have to seek out open areas for parking, dropping off, or picking up items. They could schedule the abstract space through applications built on top of the IaaS services and be assured that they could use the space for the duration that they have scheduled it. These users could also be forewarned about issues with particular areas that they are interested in using through both predictive capabilities of the city's PaaS services and be given dynamic alternatives.

Beyond dynamic management of curb space, the Infrastructure as a Service model would allow cities to control access to areas that are congested by dynamically blocking access or controlling access flow based on congestion. Integrating this flow control with curbside parking management would reduce emissions and circling by both commercial and citizen drivers as they look for open parking space. Additionally, cities would have the potential to dynamically allocate open space areas to mobile consolidation hubs or parcel lockers based on demand. This capability would further reduce travel times for both logistics delivery services and customers

as the distribution hubs and pickup points would be positioned as close to the demand locations as possible.

By dynamically managing its Infrastructure as a Service, a city not only is able to manage a scarce resource more efficiently and effectively, but it can also optimize its return on investment in that resource. Today cities generally charge fixed fees for parking and access. By being able to charge for actual use, and by employing demand based variable usage fees, cities can optimize the revenue they receive from the use of expensive and limited city resources. These fees can then be employed to better maintain or increase capacities thereby improving both citizen welfare and business economics.

It should be noted that while this paper focuses on a certain subset of a city's transportation infrastructure, the concept of urban Infrastructure as a Service is not limited to transportation. Cities have many different infrastructure components interacting in systems that support their citizens and businesses (e.g., sewers, water, communications, electricity, Internet, etc.). There is no reason that these types of infrastructure could not also be managed via an IaaS system as they are also highly instrumented today via different control systems and interact with transportation infrastructure in numerous ways.

5.2   Urban Platform as a Service

To develop services that would make use of an Urban Infrastructure as a Service requires the aggregation of sensor data from different urban systems. It also requires tools to make sense of the data being received and to develop new services that can be delivered to businesses and citizens. In an Internet cloud environment these tools and collection services are provided through the cloud providers Platform as a Service (PaaS) layer. For the urban environment such a layer would link to the sensors embedded in the city's infrastructure, integrate these data as required, feed management systems for controlling the infrastructure, link to digital twins for predicting future use and making decisions, and connect to strong non-repudiation monitors to ensure that events are properly logged and inevitable conflicts are resolved through clear establishment of what occurred, when it occurred, and who was responsible for the occurrence.

Employing a PaaS system for integration of data flows and management decision making increases the resilience of the city to disruptions. The PaaS services provide real time access to what is happening in the city's infrastructure. Failures are noted as they happen and, through the use of digital twin projections, city operators can determine the likely set of issues that such failures might cause. This information can be used to make informed decisions concerning what to do, how to minimize impacts, and, just as importantly, how to correct the failure. As cities face more stress due to increasing populations and environmental degradation, the ability to respond quickly becomes increasingly important. The structuring of a city's infrastructure technologies using the IaaS and PaaS models could help in addressing these rapid response needs.

5.3   Urban X as a Service

The urban PaaS would provide tools to developers, internal and external, to develop additional services that could take advantage of the city's infrastructure and be deployed through the PaaS. An example might be an urban Logistics as a Service (LaaS) model that implements on demand delivery of food or groceries for businesses within the community. A last mile delivery service could also be built as a LaaS service where consumers or business requiring delivery of goods could link to the delivery process and direct both the timing and location of delivery or drop off that would be most convenient for them. By connecting through the city sponsored LaaS service the city would be able to dynamically manage logistics flows and ensure that unintended

problems did not arise. The city's Mobility as a Service operation could also employ tools from the PaaS to provide citizens with on demand mobility based on IaaS feeds that optimized their pickup and transport experience. Many other services could be developed such as Parking as a Service, Meetings as a Service, etc. All these services would provide citizens with more transparent access to city services and would help to improve the quality of delivery of these services to them.

6 Conclusion

Linking the Urban Cloud concept to city-wide logistics operations employing the Physical Internet model has the potential to create a controlled Logistics as a Service approach to city logistics operations. Such an approach, delivered through the on-demand scalability of the city's Infrastructure as a Service model and built on top of the city's Platform as a Service development platform, could lead to the elimination of logistics congestion and environmental problems that currently cause problems for city administrators and their constituencies.

This paper explores the potential for organizing city services in a cloud-like manner to achieve the smart city vision, optimizing the use of shared resources (city infrastructures). It examines how an Urban Cloud could be constructed in a three-layer model like Internet based cloud services. Using the Urban Cloud model as a foundation, the paper examines the development of a Logistics as a Service model built using the Urban Cloud's platform services, managed by digital twin services embedded in the platform, and employing its Infrastructure as a Service enabled by edge-based sensor technologies to control last mile delivery of parcels, accounting for interoperability, security, resilience and sustainability. The benefits of such an approach are discussed and the limitations of the model are identified. Finally, recommendations for how a city might move forward in the development of its own Urban Cloud are presented.

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Scan4Transport: Connecting the transport unit to its digital twin

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Physical Internet Roadmap (Link): ☒ *System of Logistics Networks,* ☒ *Access and Adoption*

Abstract

The transport and logistics industry has long struggled with ensuring that operators could always effectively and efficiently handle the transport units at hand. Three challenges especially hampered the industry:

1. *Transport units are often handled by several operators from source to destination. Many operators are SME with low IT capabilities.*

2. *Connectivity to an IT system is often not feasible and thus access to remote data not possible.*

3. *Proprietary approaches by large LSP makes things worse for the SME.*

Scan4Transport[1] (S4T) is a global standard for encoding transport data in a 2D barcode on a Logistics Label attached to Transport Units, supporting organisations across the entire transport chain from seller to buyer.

The 2D barcode:

1. *contains the minimum information available for the (field) operator even in case there is no connection with a remote host system.*

2. *may be read with modern standard mobile phones that all operators (including SME) will have with them.*

3. *is globally standardized independent from any shipper, carrier, receiver, LSP or other stakeholder*

Any operator working with several/many other operators can suffice with a single application to interpret the 2D barcode and be able to handle the transport unit effectively and efficiently

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[1] https://www.gs1.org/industries/transport-and-logistics/scan4transport

Introduction

Most of the businesses across the supply chain use different systems, each with their own proprietary standard ("language") for encoding data into barcodes on the labels affixed to Transport Units and sharing information (e.g. transport instructions and status notifications). Subsequently, connecting the different systems ("learning and translating the different languages") and the cost of automating processes to capture data across supply chains is often prohibitive, especially for small and medium sized enterprises (SME). This causes manual processes, duplicated effort, cost and freight visibility delays/gaps for companies across the supply chain as freight is often handled by multiple logistic service providers in the journey from Seller to Buyer.

The transport and logistics industry has long struggled with ensuring that operators out in the field as well as those in logistics centers could always effectively and efficiently handle the transport units at hand. Three challenges especially hampered the industry:

1. The Freight Transport Industry is extremely fragmented with 40,000 Logistic Service Providers in Australia alone and millions around the world to support the delivery of different types of freight (e.g. bulk, satchels, parcels, pallets, ugly freight, etc), to different locations (e.g. metro, regional, interstate, international), via different service levels (e.g. standard, overnight, same day express, etc). The industry has a very high proportion of small and medium sized (SME) operators with little or no information technology capability. Larger Logistic Service Providers (LSP) often rely on large numbers of SME for last mile delivery or first mile collection of transport units.

2. GS1 estimates 50% of the Earths land mass does not support reliable or affordable connectivity with remote host systems. E.g., in Australia over two thirds of the land mass does not have such connectivity. This means that in many cases it is not feasible for the field operator to connect to a remote system to retrieve the relevant information for the transport unit based on some identifier on the transport unit.

3. Large LSP tended to develop their own proprietary approach to alleviate the problems mentioned above. That often makes things worse for the SME working for several large LSP. E.g., when these SME make delivery rounds carrying transport units from several of these LSP, the SME needs to carry specific scanning equipment from each of them and even the recipient of the transport units needs to confirm delivery on multiple LSP devices in case the delivery involves transport units from different large LSP.

However, emerging expectations and even requirements from customers (more specifically consumers in e-commerce context) related to flexibility, last-minute changes and accurate real-time capture of actual events occuring with the transport unit (and its contents) also necessitate a review of the current "traditional" ways of working in transport and logistics.

The figure 1 below indicates the most important issues identified by stakeholders involved in the development of the Scan4Transport standard.

81% Improve interoperability	**Lack of interoperability** – Many parties in the supply chain have different systems with their own proprietary format ("language") for encoding transport data into barcodes on the Transport Label and sharing information (e.g. transport instructions and status notifications).
86% Improve efficiency	**Inefficiency** – Each party in the supply chain needs to develop and maintain the different barcode formats found across the supply chain within their systems. Relabelling and manual processes resulting from the different formats are other consequences impacting the efficiency of these businesses.
81% Improve resilience	**Poor resilience** – When electronic transport instructions have not been exchanged prior to the freight being handled, the movement of freight is often impacted until the instructions have been sourced or manually processed.
76% Improve freight visibility	**Freight visibility challenges** – There are often visibility gaps or delays when Supply Chains rely on information being passed in a daisy-chain style from party to party along the supply chain or not all systems in the supply chain are connected.

Figure 1: Key transport challenges, GS1

One key requirement to be able to implement the Physical Internet (PI) concepts is that transport units are unambiguously identifiable and data about the transport units is always available for the operator physically handling the transport unit at all times.

In "traditional" transport and logistics networks, many transport units do **not** carry a globally unambiguous identifier (let alone that it is available in machine-readable format e.g., in a barcode and/or RFID tag). As already pointed out above, an operator may be able to scan the identifier from the transport unit, but still not be able to do anything useful with it because there is no connection with any host system that contains the data related to the transport unit. We will address that challenge in Chapter 1.

Traditionally, transport and logistics works based on data that is already fixed/static at the moment the sales order between seller and buyer is made. E.g., delivery point is already agreed between seller and buyer then. There is an emerging trend that last mile delivery carriers offer opportunities to the final recipient to interact with the carrier to arrange the "hand-over" between the carrier and the recipient. In general, the seller is not informed about those arrangements. We cover the general topic of dynamic interaction with stakeholder systems in Chapter 2.

Scan4Transport (S4T) is a global standard for encoding transport data in a 2D barcode on a Logistics Label attached to Transport Units of any size and dimensions. The standard supports companies and organisations across the transport process including first mile, line haul, sorting processes and last mile activities and enables them to keep pace with the growing needs of their customers. The S4T standard builds on long-established and well-proven standards from ISO, GS1 and other standardisation bodies.

A large group of stakeholders from diverse backgrounds have contributed to the development of the Scan4Transport standard as well as to the implementation of the standard.

Some of those are LSP like DHL, New Zealand Post, Australia Post, VT Freight Express, Correios Brazil and solution providers Leopard Systems, Avery Dennison, SICK, MixMove as well as cargo owners e.g., CHEP.

The content of the 2D barcode when structured according to the S4T standard may be generated by any stakeholder and any other stakeholder following the S4T standard can then accurately scan and process the contents of the 2D barcode without any confusion about interpretation of any element in the 2D barcode contents.

This achieves the ultimate objective defined in the <u>European Interoperability Framework</u> (EIF) of the European Commission: <u>"Ensure that what is sent is what is understood"</u>.

1   Making Structured Data available on the Transport Unit

One of the primary objectives of the Scan4Tranport standard is to make sure that the operator handling the transport unit always has at least the minimum data available to execute the next step in the journey of the transport unit from seller to buyer. Achieving that basic objective enables the first three goals mentioned in figure 1.

The Scan4Transport standard ensures access to minimum required data on the transport unit in the following ways:

1. The 2D barcode contains the minimum information available for the (field) operator even in case there is no connection with a remote host system or if there has been no prior electronic information exchange related to the transport unit.
   This provides much increased resilience, reliability and accuracy for those operations.

2. The 2D barcode may be read with modern standard mobile phones that most/all operators (even the SME) will have with them at all times. This means that even the least sophisticated operators (in terms of IT capability) will be able to be included in the information exchange network.

3. The data structures in the 2D barcode are globally standardized independent from any seller, shipper, carrier, buyer, receiver, logistic service provider or other stakeholder. Therefore, any operator working with several/many other operators can suffice with a single application to interpret the 2D barcode and be able to handle the transport unit effectively and efficiently.

NOTE: In an e-commerce context, many of the transport units will be handled/delivered by so-called designated operators (in plain language: National Post organisations). Postal operators deliver more transport units than any other transport service provider. They also deliver to less populated areas that other logistic service providers choose not to service. Therefore, it would a lot of sense from the Physical Internet perspective if the transport and logistics networks operated by the Designated Operators and other Supply Chain and T&L stakeholders would be much better integrated than they are today. Interoperability may be improved by making the minimum data available in a well described and structured format on the transport unit such that even when the transport unit changes hands between carriers (be they designated operators or non-postal service providers) the next operator is able to handle the transport unit (even if there is no electronic interface between them). The UPU (Universal Postal Union) is currently going through a process to decide if (and if so, how) the UPU will facilitate better integration of the postal networks with the wider Supply

Chain T&L networks. It is foreseen that the UPU will make their decision on their Extraordinary Congress in October 2023.

The sample list of participants in the development of the S4T standard includes organisations that are designated operators as well as other LSP. The S4T standard enables them to exchange transport units if they so desire. Currently not all participants listed exchange transport units with all other participants listed.

1.1 What kinds of information can the 2D barcode provide?

1. The globally unique identifier for the transport unit.
    This is a mandatory data-element. Without it the S4T standard cannot deliver its full potential.

2. Basic data about the transport unit
    Weight, dimensions, volume, returnable asset identifier (e.g., for roll-cage, pallet or container) as appropriate.

3. Trade and Transport Reference identifiers
    Identifier for the Trade Transaction (shipment) and Transport Contract (consignment) as appropriate.

4. Ship-to / Return-to information
    Structured address data, geo-coordinates, identifier for the ship-to location, contact details as appropriate.

5. Handling instructions
    Dangerous Goods flag, delivery window, Signature required as approrpiate.

6. A Digital Link (URL / URI)
    This enable the operator to access remote information in case Internet connectivity is available. We will cover this in more detail in Chapter 2.

The list of data-elements is not exhaustive. It merely indicates the information that is most commonly used in daily operations in freight transport. Here is an example of what the content of the 2D barcode could look like.

"https://example.com/00/3952110010013000121?4300=GS1+AISBL&4302=Avenue+Louise+326&4305=Bruxelles&4307=BE&420=1050&403=123%2B1021JK%2B0320%2B12%0B&s4t"

This example contains (in sequence) Digital Link, Transport Unit Identifier, structured delivery address, and handling instructions. (&s4t indicates the barcode content follows the Scan4Transport standard).

The data-elements in the 2D barcode are individually identifiable based on their Application Identifier (or AI). Application Identifiers (or Data Identifiers) have been used for half a century in barcodes to ensure consistent interpretation of data-elements in barcodes.

E.g., the transport unit identifier highlighted in green consists of the AI "00" followed by the value of the identifier "3952110010013000121" (a so-called SSCC or Serial Shipping Container Code compliant with ISO/IEC 15459-1).

Similarly, application identifier "4300" indicates the value that follows is the name of the Ship-to / Deliver-to organisation, whereas AI "420" precedes the postal code of the Ship-to location. GS1 provides a very comprehensive list of Application Identifiers on their website.

The most popular 2D barcode types today that may also be used for the Scan4Transport approach are:

Figure 2: Sample 2D barcode types for Scan4Transport

The standard also supports "special" characters like é, è, ö, ü, ã, ç, Σ, Ω as well as other Latin and non-Latin characters. This means the S4T standard can be used in countries all over the world.

NOTE: According to "Addressing the Unaddressed" there are approximately one **billion** people in the world who do not have a "functional" postal address, mainly living in developing countries. In addition there are also developed countries where the addressing systems do not provide a very precise way to find a physical location. In rural areas buildings may be many miles apart. In Japan, house/block-numbers on the same street are not (always) in sequential order (e.g., number 26 may be in between number 4 and 8). Making efficient and effective deliveries to locations that do not provide precise positioning information requires the use of geographical coordinates. The Scan4Transport standard supports including geocoordinates in the 2D barcode. Modern satellite navigation systems (as available on pretty much all mobile phones) are able to use those geocoordinates to direct the (SME) operator to the right location without fail.

1.2 Improving Interoperability

While shippers commonly use 5 or more Logistic Service Providers, larger shippers rely on 50-100 Logistic Service Providers to meet their transport needs. The number of Logistic Service Providers explodes when the subcontractors involved in the movement of freight are included. These subcontractors are very often SME.

Because the data required to effectively handle the transport unit is in the 2D barcode on the unit, an operator can get that data from the unit with a SINGLE scan using a SINGLE application completely independent from the stakeholder that created the 2D barcode in the first place. In effect, all stakeholders capable of generating and/or scanning/working with the Scan4Transport 2D barcode have become interoperable in line with the main objective of the European Interoperability Framework.

Looking at the SME operator delivering transport units from several large LSP, he can now use his own mobile phone (instead of several LSP devices) **and** the recipient of the transport units also needs to sign off on a SINGLE device only (the SME operators mobile phone). Therefore, this also has a significant impact on Customer/Consumer Experience.

We need to reiterate here that the vast majority of LSP are SME who have (very) low IT capability. They will however generally have mobile phones that are capable of scanning 2D barcodes (at least a QR-code). They may install a SINGLE application (from any solution provider) that will interpret the Scan4Transport 2D barcode and present the information to the operator so the operator can effectively and correctly execute the next step in the journey of the transport unit from Seller to Buyer.

1.3 Improving Efficiency

Having the data available on the transport unit in a standardised and fully structured format, eliminates the need for manual data capture in those cases where information is not available for the operator. Elimination of that manual work (being able to capture all required data in a single scan) ensures that the operator can execute his/her transport task much more quickly. It also ensures that the data captured is 100% accurate and the operator (and clients and partners) no longer need to waste time on correcting errors due to manual data capture. The efficiency manifests both in speed of execution and reduction of time spent on non-value-added activities.

The improved interoperability mentioned above also has a significant impact on efficiency (or rather utilisation of T&L resources). Because more stakeholders LSP, Shippers etcetera can work well with more LSP (even the very small ones) it becomes feasible to consolidate more freight flows with a single (SME) LSP, especially in sparsely populated areas but also in very densely and regulated/constricted areas (such as inner cities). This increases the utilisation of the transport execution resources in those cases and provides a significant boost to the efficiency of those operations. In addition, that increased efficiency may reduce undiserable effects of transport execution and increase quality of living.

Utilisation and efficiency are also increased because the (SME) operator may use the geocoordinates (if available in the 2D barcode) to navigate to the desired location in the quickest way and avoiding going to the wrong place/s before going to the right one (thus freeing up more time for other transportation acitivies).

1.4 Improving Resilience

From a Physical Internet perspective the improvement in resileince (combined with the improvement in interoperability) may be the most interesting aspect of Scan4Transport. We already indicated that having the minimum data available on the transport unit means that it is not technically necessary to have electronic information exchanges in advance of the physical hand-over of the transport unit to a next service provider.

That means that in case of disruptions in transport and logistics networks, a service provider may decide then and there to engage with a service provier (other than the one originally planned) to make sure the transport unit can continue on its journey to the Buyer despite the disruption in the network.

In fact, the combination of resilience and interoperability enables supply chain stakeholders to delay making firm decisions on how exactly a transport unit may be transported on the next leg right up to "the last minute before" the transport unit really needs to start on that next leg. At that point in time, the stakeholder may have much more information available regarding the actual freight and transport mix and where the individual transport units need to go than will be available in the currently customary up-front planning processes. Based on that last minute information, the stakeholder may make better decisions on how to route the individual transport units over the various next legs and service providers even when there are no disruptions in the T&L networks. Note that this is also exactly the way that routers in the Electronic Internet route packets through the network.

2   Enabling dynamic interaction with stakeholder systems

The above chapter deals with the use cases where the operator may **not** have access to remote systems. In this chapter we will cover use cases where the operator **does** have connectivity with the Internet and may access one, several or in principle **any** remote IT system.

There are three logical groups of IT systems that the operator may connect with

1. their own;

2. those operated by the Seller of the goods contained in the transport unit

3. third party system/s, which includes other LSP systems

NOTE: They may access any combination of these three groups of systems. E.g., the SME operator may **not** have its own IT systems, but they may want/need to access IT systems of the Seller and/or the LSP they may be handling the transport unit for.

In the paragraphs below we will dive a little deeper into how the S4T standards enable these connections.

2.1   Operator accessing own IT system.

For accessing your own systems you do **not** need to have any URL or URI present in the 2D barcode (you know where to access your own system). In general, in this case, the device used by the operator will run its own app(lication).

That app will have interpreted the content of the 2D barcode and used that information within the context of that app. The app will then connect and communicate with the operators own remote IT systems using their own proprietary protocols, formats etcetera.

This internal communications topic is outside the scope of this paper.

2.2   Operator accessing the Seller's IT system.

The operator may also need to access the Seller's system. Here are a few use cases where that makes sense:

- The Buyer has contacted the Seller (e.g., on the Sellers webshop) that the delivery needs to be *rescheduled* to another (later/earlier) date and time but still at the same delivery location.

- The Buyer may also *change the location* of the delivery.

- The operator needs to *confirm delivery directly to the Sellers* IT systems. This will often be the case where an SME is doing the ultimate delivery to the Buyer.

To support all of these use cases, the seller may create a 2D barcode with this sample content: https://TransportUnit.Seller.com/00/395211001013000121? 4300=GS1+AISBL&4302=Avenue+Louise+326&4305=Bruxelles&4307=BE&420=1050&4 03=123%2B1021JK%2B0320%2B12%0B&s4t

The value <TransportUnit.Seller.com> is merely an illustration of the purpose of the URL. The Seller will have to provide an application on that URL that is able to interact with the transport operator. That application will then need to interpret the 00/395211001013000121 part of the URL and "connect" the front-end application with the relevant records in the Sellers back-end IT systems. Once that has been done, the front-end application may offer a menu of options via the front-end to the transport service provider. It could offer to provide the latest delivery information known to the Seller (e.g., changed dates and/or locations,

contact details and so on). The Sellers application could also offer an option for the transport operator to confirm delivery of the specific transport unit. This feature to be able to easily connect any transport or logistic service provider to the Sellers IT system is potentially the most powerful aspect of the Scan4Transport to realise the ideas and concepts of the Physical Internet and to put the Seller (owner of the goods in the transport units) more in control of what happens with those goods on their journey from Seller to Buyer.

2.3   Operator accessing third party IT system.

There are also several use cases where the operator may want or need to access a system from a third party. Here are some examples:

- The operator needs to _confirm delivery to the larger LSP_ IT systems. This will often be the case where an SME is doing the ultimate delivery to the Buyer on behalf of a larger LSP who operates (advanced) IT systems. This is a common use case in the Scan4Transport pilots.

- The operator wants to look up opening hours, contact details, geo coordinates or other details related to the location e.g., based on the Global Location Number (GLN) for the Ship-to location).

In case the SME transport operator needs to confirm delivery directly to the large LSP system, the scenario runs very much the same as described above for the Sellers IT systems. However, the URL in the 2D barcode would have to point to the application operated by the large LSP. That LSP application would then offer the approiate functionality to the SME operator (including the option to confirm delivery and/or exceptions for the delivery e.g., failed delivery).

We highlighted that a GLN for the location may be included in the 2D barcode. The application running on the transport operators device (or the Web applications operated by the Seller or the larger LSP) may use that GLN to access Data Linked to the GLN anywhere on the Web. This concept is often referred to as "Linked Data".

Let's assume a delivery has to be made to GS1 New Zealand Auckland office (which is identified with GLN = 9429300016329). The New Zealand government operates a free Web-service that will provide information about New Zealand business and locations based on the GLN. In this example you may directly acces the location information using the below URL https://www.nzbn.govt.nz/mynzbn/opndetails/9429000000000/9429300016329/ (9429000000000 identifies GS1 New Zealand as the organisation associated with this location).

Alternatively (and even more powerful), the GLN may be used to access Webservices (e.g., operated by GS1 or other parties) that may be accessed to find out basic data about the location and may also provide **multiple** different links to more information (Linked Data) for the location. In the below demonstration Web-application screenshot you see a map of where the GS1 NZ offices in Auckland are (https://www.portmasterdata.com/id/9429300016329).

Bottom right you will aso see a table with different Linked Data targets. The bottom one connects directly to the records for GS1 NZ Auckland in the New Zealand Location Registry.

These Links To Other Sources Of Data can already be posted to a global service operated by GS1. They may then be retrieved by any application that can then present them to its users (very much like the demonstration application does in the screenshot below).
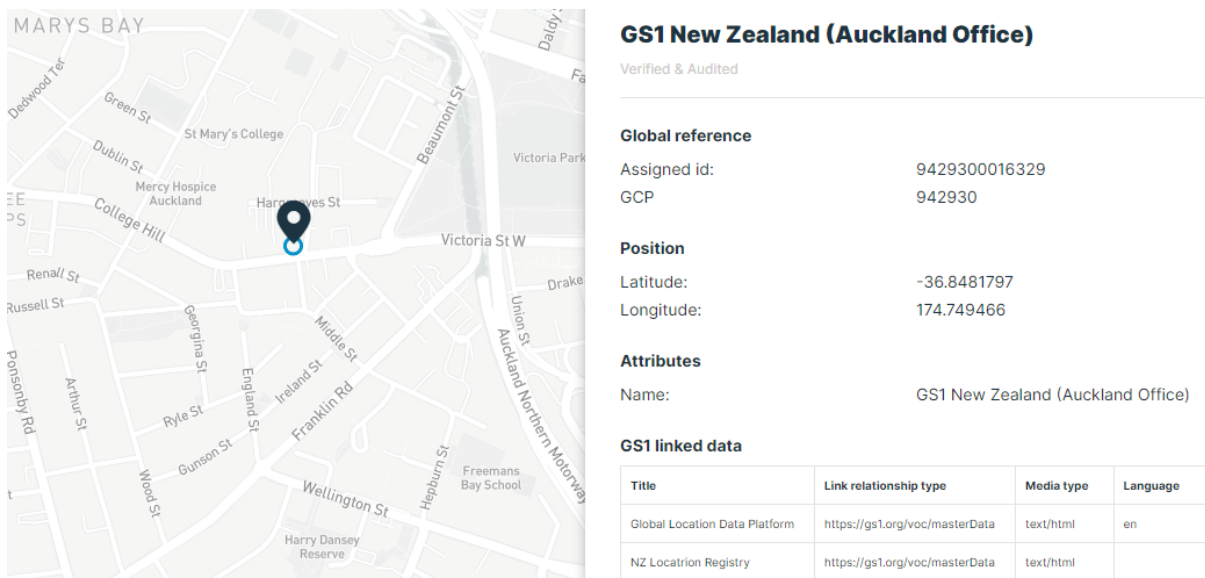
Figure 3: Linking to Other Sources of Data for locations

Using this Links To Other Sources Of Data (L2SD) approach, any application that supports the GLN as location (or organisation) identifier may make its presence known to the world by posting its L2SD links to the global service. Any other application may then retrieve those L2SD records to connect to applications that can provide more information about the GLN.

3   In Conclusion

The Scan4Transport standard delivers many benefits for the Transport & Logistics industry and the realization of the Physical Internet:

- Improves first and last mile processes through the capture of essential information relating to the transport task from the barcode on the transport label (e.g., when the freight is handled and scanned before the electronic instructions have been received).

- Improved efficiency and interoperability across industry through a standard label across the entire supply chain. The same 2D barcode may be used at any stage in the journey of the transport unit.

- Enhances delivery accuracy by encoding Ship-to GEO locations (e.g., Construction sites, rural address, gates to terminals / ports / airports, which do not have a clear/granular street address).

- Where connections to the Internet are available Links To Other Sources Of Data enable access to the latest information for the transport unit e.g., delivery location or delivery date and time may have changed since the transport unit and label have been created. It also enables that stakeholders handling the transport units may provide feedback into the primary source application e.g., confirmation of delivery.

These lead to smoother processes and greater customer satisfaction.

The results of the pilot implementations of Scan4Transport standards have been documented in a [report][2] and a [video][3] that are available on the Web.

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[2]   https://www.gs1.org/sites/gs1/files/s4t-pilot-report-v1-1.pdf
[3]   https://youtu.be/MIscdZQP0xA

Prerequisites for Data Sharing and Realizing Off-peak Deliveries

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Abstract: *Off-Peak is an efficient way to transport goods to dense urban environments where congestion and lack of space have a major impact on the productivity of the delivery. Battery Electric Vehicles are quiet and have opened the possibilities for freight deliveries in cities at night. One challenge is that the deliveries must be possible to make without having staff at night to receive the delivery. In the HITS (Sustainable & Integrated Urban Transport System) project, we have accomplished a successful test and proven that unmanned off-peak deliveries can start to be implemented for many applications and can reduce delivery time by 30 percent. One-time encrypted digital smart lock solutions enable the right goods, from the right truck, at the right time, in the right location to get access to, e.g., restaurants after closing hours. In order for off-peak deliveries in a "Physical Internet"-setup to work, data needs to be shared between the actors. One part of the project has studied the prerequisites for data sharing to enable a trustful collaboration between different stakeholders in general. Important factors are the willingness to apply data-driven decision making and trust between the different actors within a supply chain.*

Keywords: *off-peak deliveries; urban freight; freight efficiency; night-time distribution; unmanned delivery; connected goods, data sharing*

Conference Topic(s): *Distributed intelligence last mile & city logistics*

Physical Internet Roadmap: *System of Logistics Networks,*

1 Introduction

The logistics system in urban environments is stressed. Freight forwarders are forced to meet customers' increased expectations for speed and flexibility by deploying more vehicles, each with a smaller load capacity. This development further amplifies the difficult challenges of congestion and sustainability in cities and it often leads to unnecessarily long lead times and imprecise deliveries. HITS project is a Stockholm-based multi-stakeholder collaboration with the mission to develop transport-efficient solutions that provide cleaner and safer cities.

Off Peak is an efficient way to transport goods to dense urban environments where congestion and lack of space have a major impact on the productivity of the delivery. Battery Electric Vehicles (BEV) are quiet and have opened the possibilities for freight deliveries in cities at night. It also offers an opportunity for transport companies to use the vehicles 24/7 at lower total cost. This also means that demand for BEVs may increase.

One challenge is that the deliveries must be possible to make without having staff at night to receive the delivery. In the HITS project, we have proven that unmanned off-peak solutions can be implemented for many applications and thereby reducing delivery times by 30 percent. One-time encrypted digital smart lock solutions enable the right goods, from the right truck, at the right time, in the right location to get access to e.g. restaurants after closing hours.

In order for off-peak deliveries on a "Physical Internet"-setup to work, data need to be shared between the actors. One part of the HITS project has studied the prerequisites for data sharing to enable a trustful collaboration between different stakeholders. The prerequisites for data sharing are in this study applied in unmanned off-peak deliveries, with the purpose to evaluate strengths and challenges of the current solution and to identify needs for further investigations.

2   Methodology and Research Process

In the literature on urban logistics, off-peak deliveries are often mentioned as a promising concept with substantial potential for reducing environmental impacts, congestion and costs. However, there are some conflicting goals that must be addressed. Verlinde (2015) exemplifies, e.g., noise pollution at night, increased labour costs, and liability issues as areas that need to be addressed in which conflicting interests of the stakeholders involved must be addressed and balanced. The author further points out that the negative effects might not easily be overcome. The conflicting interests of different stakeholders in the city, i.e., trade and industry, society, and public policy-makers must be involved in this process.

The design thinking process, involving workshops and stakeholder engagement, has been a very efficient method in structuring problem framing. Unlike traditional linear methods for problem-solving, Design Thinking is an iterative and insight-driven process where testing and pivoting from the original ideas to new ideas, are fundamental. It is a process designed to help us shift focus from HOW to solve something to rather understanding WHAT problem to solve.

After the initial workshops in the design thinking process with the aim of identifying and understanding the stakeholders' needs and challenges, a demonstration of unmanned off-peak deliveries to 4 restaurants in the shipper HAVI logistics system was carried out in the centre of Stockholm City.

2.1   Design thinking

Design Thinking (Stickdorn M & Schneider J, 2012) is a people-centred approach to innovation that, with the help of design methodology, ensures that the right customer value is met. Design Thinking uses design as a process to understanding and integrating people's needs, technology opportunities and goals and requirements for successful business value. By dividing the work into the phases Empathize, Define, Ideate, Prototype and Test in an iterative process, one focuses on the solution of the right problems, enables innovation, and ensures the value and relevance of the solutions that are developed. By working in a solution-oriented and agile way, the design process of tests/prototypes (e.g., "proof of concepts") close to customers helps the working group to understand customer values and quickly gather insights from operations and actual situations.

As Design Thinking is often used to solve complex problems, the design process can also be used to drive the transformation of businesses and organisations. The goal is still to create customer value, but new customer behaviour and the solutions may force the organisations to act differently. The design in that case delivers results by changing organizational behaviours, which in turn change customer behaviours.

2.2   Literature review - data sharing

The overview on data sharing presented in section 3 is mainly based on literature reviews, where not stated otherwise. A broad literature search was conducted in several libraries, incl. Google scholar, IEEE Xplore, ScienceDirect, and SCOPUS. The term "data sharing" was combined with different versions of "eco-system", "mobility" and "transport". Due to the rapid

development within this field, mainly articles published in the last ten years have been considered. Web-searches have also been conducted, with similar search terms, to catch commercial trends that might not yet be published in scientific papers. The work presented here does not intend to give a full overview of this field, but rather to extract relevant material within this area.

2.3 Practical input - data sharing

The synthesis of relevant factors for data sharing is partly based on the author's (A. Hultåker's) almost 15 years of practical data sharing between departments within the automotive manufacturer company Scania. Much of that work has been conducted in ways similar to Design Thinking. The results are either undocumented, or cannot be shared in detail outside of Scania for confidential reasons.

3 Data sharing

Today, much of the collaboration between transport actors relies on digital data sharing, such as purchase orders or transportation orders. The recent boost in e-commerce has further increased these types of digital collaboration. Still, much of the data sharing covers only the bare minimum to keep the business going, and sometimes specific actors are left out of the sharing. Data sharing, data load, and data quality has become even more crucial as an increasing number of services are automated, for example by applying artificial intelligence. This creates advantages both from a system and unit perspective, but can also create disadvantages for those who are not included in the data sharing.

3.1 Research and regulations on data sharing

Research on data sharing is a fairly new field (Deloitte et al., 2018). And the same goes for regulations and policy making concerning data sharing and data usage. The rapid digitalisation in the last 10-15 years has been a major driving factor, and further spurred by growing e-commerce during the Covid-pandemics (World Economic Forum, 2021). During this period, the EU authorities have been striving to regulate the field to ensure customer privacy, fair competition, and yet a competitive data market through e.g. the General Data Protection Regulation (GDPR, 2016), the Open Data directive (2019) and the up-coming Data Act (EU Commission, 2022).

Most of the research so far has been done on open data sharing, often related to governmental data (Barbossa et al., 2014, and Ubaldi, 2013) and, for example, within the domains of transportation (Karpenko et al., 2018) or energy (Diran et al., 2020). The Open Data Institute (2023) gives a good overview of different types of data access. This work mainly deals with restricted data sharing. The actors and use cases that HITS have looked at are mainly group-based or named access, of various sizes, and provided on commercial grounds or by a governmental organisation.

3.2 Barriers for data sharing

It is important to understand what barriers exist against data sharing in order to determine which mechanisms that need be in place for it to work. Barriers might be perceived or real. IDC (2017) has identified three classes of barriers:

- **Cultural and organizational barriers:** e.g. no perceived potential benefits, lack of trust, fear of competition

- **Legal and regulatory barriers:** e.g. restrictions on data location, restrictions/ uncertainty about lawful grounds to use or share data, uncertainty about data ownership and data access
- **Technical and operational barriers:** e.g. lack of data interoperability, lack of standards, high costs of data curation to adapt it for sharing

As is clear from the listed barriers above, there is no individual factor hindering data sharing. However, some barriers can probably be explained by the fact that this field is rather new and thus undergoing changes, still setting standards as well as best practices, deciding on policies and regulations. At the same time, the closely related areas of software and technical platforms also undergo rapid development.

3.3 Data sharing eco-systems

To enable the potential benefits of sharing data, the barriers listed above need to be overcome. As there are a multitude of barriers, the solutions must fit together. An emerging view is that data sharing in eco-systems will evolve, where the different parts work in union. Nischak et al. (2017) states that three components are essential for any digital business ecosystem: value exchange, resources and actors.

Olivera et al. (2019) as well as Runeson et al.(2021) provide extensive overviews of the data sharing eco-system, both their definition and their development, although mainly concerning open data. Here the compiled definition by Runeson et al. (2021) is used to describe the data sharing eco-system as a complex socio-technical network consisting of two major components:

- A community of actors, which base their relations to each other on a common interest (Zuiderwijk et al., 2014)
- Supported by an underpinning technological platform (Jansen, 2020)

A data sharing eco-system is further something that enables the actors to:

- Process the data (Oliveira et al., 2019)
- Create value, foster innovation, or support new businesses (Oliveira et al., 2019)
- Collaborate on the data and boundary resources (Jansen, 2020)

3.4 Factors required for fully functional data sharing

The consultancy company Everis (2018) has, on behalf of the EU Commission, presented a thorough investigation on data sharing between companies in Europe and concludes that there are five key features of a thriving data-driven economy; **datasets, trust, infrastructure, security, and skills**. The authors argue that these are necessary factors also for establishing and maintaining functional data sharing between individual actors in networks. They are thus not just needed on an overall economic level, but needed for each data sharing initiative.

However, for individual cases of data sharing, there are three more factors that we also deem necessary; **business value, regulatory foundation, and meta data**.

Business value is needed for any healthy business relationship. Without a clear incentive for business, it will be hard to justify or engage in data sharing (Nischak et al. 2017). Although it might not necessarily be needed for a governmental data sharing initiative, it might bring about other values (Martens, 2020) such as co-loaded deliveries to pre-schools, thus increasing safety

and reducing pollution as demonstrated by other partners in the HITS project (Södertörnskommunerna, 2023).

The importance of regulatory foundation is obvious when one considers the amount of regulations and policies in this field that the European commission and other legislative bodies have put forward during the last 10 years. Uncertainty regarding GDPR compliance is very common when e.g. position data from connected vehicles is discussed. Needless to say, any lasting business relationship needs to abide by the laws. Andersson (2022) elaborates in the report *Regulations for data sharing in city logistics: current situation analysis* on e.g. how companies can set up individual agreements regarding data sharing as grounds for data exchange.

Finally, meta data is usually overlooked in this context. The main reason for this is that most studies are done from the perspective of the data supplier, or from the perspective of the intermediate tech platform perspective. There seems to be very few studies done from the perspective of data users. Meta data issues are often addressed initially, simply by describing the general content and context of the data. However, most IT systems will sooner or later contain anomaly data and change both content and context over time. It is then crucial that the down-stream data receivers are also informed about any changes.

Reflecting on the barriers for data sharing presented in 3.2, one can see that the factors presented here correspond well to the barriers.

The eight factors can be said to form a data sharing eco-system, as defined in 3.3. Where the common interest of the actors is realised through finding business value, having a solid regulatory foundation, trust, and maintaining security. Runeson et al. (2021) points out the need for an underlying technical platform. In reality, when multiple actors are involved, there are usually several different platforms involved, between which data are transferred in some manner, today often via API:s (Application Programming Interface) as well as additional technical tools to process the data. API:s has the further advantage of establishing a sort of data contract, thus establishing the content and forms for the data, solving the meta data issue as well.

Usually all eight factors are needed. However, which factors are more or less important vary depending on the use case. Although the three factors, data, business value, and regulatory foundation, play a specific role as a starting point for any data sharing.

There is also an interdependence between the factors. For example an increased security level might take the edge off a potential distrust situation. It should be noted that infrastructure, security, and skills go very much hand-in-hand, although skills can also refer to curation of data and skills in solving the legal grounds for data sharing.

Some of the factors have to do with the internal culture of a company, e.g., trust, while some of the factors, most notably infrastructure, security, and skills can be obtained from external partners.

Finally, established data sharing has a potential to bring about new or added services for the actors, ranging from everyday tasks such as planning of staff, facilitating detection of deviations, to more advanced services such as improved route planning. In HITS we have

demonstrated that off-peak deliveries are enabled through data sharing between the involved actors, and that the business venture can be further fine-tuned by analysing the obtained data.

4 Off-Peak

With the introduction of electric distribution vehicles, the problem with noise from vehicles in urban environments practically disappears and if the transport companies can shift to off-peak distribution, the transport efficiency and cost can be reduced at the same time as congestion at peak hours can be eased. Previous studies have shown that off-peak solutions can reduce the delivery time by at least 30 percent and increase the delivery precision (on-time) to almost 100 percent (Sanchez-Diaz I, Georen P & Brolinson M, 2017) (Holguín-Veras, J Marquis, R., & Brom, M., 2012).

However, although the concept is very promising, using electric distribution vehicles off-peak for deliveries does not solve all problems. Many challenges still need to be addressed, e.g., silent handling of material, safety issues and finding values and incentives for all involved stakeholders. Having personnel to receive goods at night is an unacceptably high cost for many businesses (Holguín-Veras, J Marquis, R., & Brom, M., 2012). The insights from previous research and the initial analyses in this project showed that unmanned reception of deliveries is a prerequisite for scaling up off-peak distribution.

4.1 Internet of Logistics

The first key element was to digitalize individual goods by giving them e-identities and thus allowing tracing. This was enabled by using the international logistic communication standard called "Internet of Logistics" (IoL). This industry standard was developed in a collaboration between LogTrade Technology, Ericsson, IBM, and many more. The purpose was to find a way to break data silos and provide easy and secured access to a shared data platform. If everyone integrates with IoL, they don't have to integrate with each other, thus solving the data connectivity problem as described above. This data sharing platform can be used to create different applications needed for company specific services based on the common shared data.

4.2 Off-Peak pilot

The second step of the research process was to prototype a system that connected goods to the vehicle and further, to a digital lock at a restaurant. Every assignment can be tracked and its location, whether inside pallets, containers or trailers, can be defined. Shipping notes and proof of deliveries are digitized and securing the right assignments are in the right place at the right time and any possible deviation is logged - which increases the security and trust between the operators and the receivers. The key to achieving this was to use IoL as a standard communication and integration platform which enabled all different actors and data sources to connect and communicate with each other without the need to set up individual integrations. The principles as well as the technical details are described in Figure 1.

The collected data can be analysed to create different machine learning models that can look into optimising both from a complete system perspective but also look deeper into a more efficient and time-saving route management and vehicle run-time.

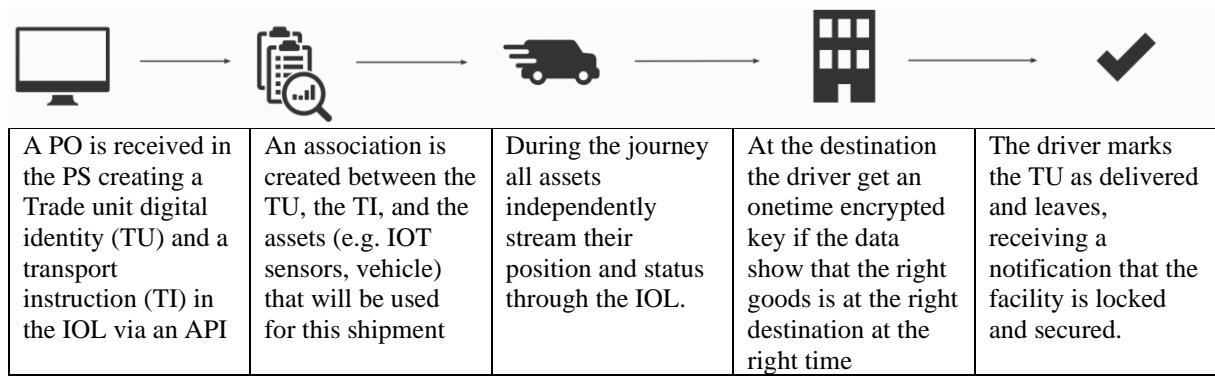| A PO is received in the PS creating a Trade unit digital identity (TU) and a transport instruction (TI) in the IOL via an API	An association is created between the TU, the TI, and the assets (e.g. IOT sensors, vehicle) that will be used for this shipment	During the journey all assets independently stream their position and status through the IOL.	At the destination the driver get an onetime encrypted key if the data show that the right goods is at the right destination at the right time	The driver marks the TU as delivered and leaves, receiving a notification that the facility is locked and secured.

Figure 1: The process from receiving a Purchase Order (PO) in the planning system (PS) to completing the delivering and securing the facility is described in the picture.

The final step was to test the concept in real logistics operations in HAVIs' delivery system to evaluate the functionality in real life. HAVI delivered off-peak (22.00 – 06.00) to 4 restaurants in the Stockholm City area during a time period of 1+1 month. The tests were successful and showed that the concept works and that it can be used in scale. However, during the implementation of unmanned deliveries, inefficiencies and obstacles became evident. Although the vehicle is silent, there is still a risk of noise from the handling equipment and accidental slamming of doors etc. The off-loading of the truck into the restaurant took between 50 to 80 minutes during the first weeks, as the drivers were uncertain about the process and also there was insufficient communication between the drivers and the restaurants about where to put the goods. The restaurant had not prepared sufficient space in the fridges, so the drivers needed to reorganise goods to find space for the goods. There were also physical obstructions e.g., pallets and garbage cans that needed to be removed. When the drivers knew exactly where to place the goods, the off-loading time was reduced to about 30 minutes. The drivers were very pleased to work night-time as they felt less stress. For safety reasons, HAVI used two people for the off-peak delivery. This is a cost that is necessary but not justified for serving only 4 restaurants with off-peak solutions. However, initial calculations of the business model indicate that for a larger delivery system with more restaurants and delivery points, this investment in security for the drivers and the goods is justified.

The results showed that the delivery time savings were at least 30 percent (some weeks even up to 40 percent), which confirms the results from previous tests. The use of BEVs eliminates emissions to air in the city, except for particles from tyres and road usage. The recipients were also pleased with the system as they did not have to unpack the goods in the morning when there were customers in the restaurant. They could instead focus on giving them their full attention and good service. Another key finding of the pilot is that it can be used to further optimize route planning in order to increase the number of shipments.

5 Analysis

An additional step in the off-peak pilot is to evaluate the strengths and challenges of the current solution based on pre-requisites for data sharing. In Table 1 below we map the data sharing factors towards the current off-peak set-up. The mapping clearly shows that all factors have been addressed within the pilot project. However, there still remain some challenges, mainly concerning physical security and business value. Compatibility with pre-existing IT-systems (i.e. IT legacy) is a factor that should have been addressed early in the pilot, to try to prevent additional workarounds.

Table 1: Mapping of strengths and challenges for the data sharing within the pilot project.

Factors	Issues
Data	- Exists, incl. e.g., shipping notes - Shared through secure IoL communication standard for data interoperability - Is stored and can be used for analytics to further develop the business case
Business value	- Incentives for supplier and carrier to decrease congestion and be able to sell "green deliveries". Also incentives for receivers as they could reduce the number of man hours at the restaurants as goods would be delivered inside by the carriers. - Still challenges with silent handling of material, driver safety issues and finding values and thus incentives for all involved stakeholders
Regulatory foundation	- Based on business-to-business contracts - Temporarily permits for night time deliveries had to be requested and requires silent delivery - Involving security service to make sure that security fulfils insurance requirements - Data ownership structure setup between supplier, carrier and recipient.
Trust	- Existing stakeholder relationships since many years - Clear data ownership as shipper and carrier were the same company - Smart lock solution and logs increases trust
Infrastructure	- Data exchange, logging, and analysis were done through Logtrade IoL platform. - But parts of pre-existing IT-system not compatible with API:s, had to build work around solution - Has to equip the facilities with digital locks and additional security systems
Security	- The goods, trucks, and drivers each have unique authentication through different API sources. - One-time encrypted digital smart lock solutions, as well as logging of all event provides secure IT-solution - Driver and goods safety needs to be further addressed
Meta data	- Using API:s for data transfer with an agreed content and form
Skills	- Combining traditional delivery with IT competence, competence on digital locks and security service. - Recurrent training sessions for all parties involved.

Within the HITS project, we have shown that unmanned reception of off-peak deliveries is possible in bilateral business-to-business relations. We have also explored the prerequisites for data sharing in this context, as data sharing is a necessity for the off-peak deliveries. One area that we want to further explore is if, and how, data sharing can help enhance consolidated off-peak deliveries from several retailers to multiple recipients in a city.

6 Conclusions

The successful test with unmanned off-peak deliveries is an important step toward realizing a sustainable urban distribution system and it confirms previous research that the transport efficiency (number of deliveries per hour) can be enhanced by about 30 percent. The main contribution is that this can be achieved without high labour cost on the receiver side. It can be implemented based on technologies and services that already exist. The key success factor has to do with the data sharing model and how mature and structured the data behind those models are.

The focus needs to be a system perspective rather than on individual data systems. Other factors that play important roles are the willingness to apply data-driven decision making trust between the different actors within a supply chain. We can also see that the speed at which these types of software-based services are being released into the market forces the regulatory actors to adapt to new ways and should ultimately work side by side with the suppliers/carriers to make the move towards more efficient ways of getting goods in and out of urban areas.

However, there are still many obstacles to overcome before unmanned off-peak deliveries can be implemented on a large scale. An important issue is to further update the regulatory policy issues that today hinder large-scale off-peak distribution with BEVs. The new electric battery trucks can, especially if equipped with geofence technology, open many more opportunities for safe and sustainable urban distribution opportunities. This way of connecting specific goods to deliveries creates possibilities to do more accurate CO_2 calculations on the individual deliveries. We also see a need to further investigate security issues for personnel working at night-time, business models and whether there are cost savings to be made in the system to understand how upscaling can be done. This implies investigating if, e.g., different suitable distribution routes or selection of cargo categories offer better profit margins than others. We need to understand how a transformation from today's test operations to a large-scale introduction can be implemented where the values and value streams of different actors can be analysed so that a realistic implementation plan can be set over time.

7 Acknowledgements

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Modeling and optimization of an omnichannel retailing problem

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Abstract: *In this paper, we focus on a problem faced by an omnichannel retailer that operates multiple stores and a fulfillment center. The retailer sells products to customers over a selling horizon of the period through online and physical channels. This study aims to determine the joint tactical and operational decisions on fulfillment optimization and inventory management services in an integrated model. The multi-period horizon in our model allows more realistic planning, where various decisions can be taken at different periods. Besides, our model considers the lost-demand sale to reflect the actual sale. The proposed model helps omnichannel retailers to have an integrated tool for inventory management and fulfillment service with real-time monitoring the inventory levels across locations.*

Keywords: *Omnichannel retailer, Optimization, Inventory Management, Replenishment, fulfillment.*

Conference Topic(s): *logistics and supply networks; omnichannel & e-commerce logistics.*

Physical Internet Roadmap (*Link*): *Select the most relevant area for your paper:* ☐ *PI Nodes,* ☐ *PI Networks,* ☒ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

1 Introduction

The world of retailing has expanded dramatically in the past few decades. The digital channel finds its way through all stages of the customer shopping journey because it provides a more convenient way of shopping, a wider choice of items, and the ability to access more information about items through customer reviews (Verhoef, 2021). Consequently, a growing number of retailers have started to integrate their traditional physical sales with online channels, moving towards omnichannel retailing to leverage their physical store channels(Bayram & Cesaret, 2021).

There are various definitions of omnichannel retailing and the understanding of the concept still varies. In general, definitions exhibit distinct features in the channel organization of the omnichannel, as discussed below:

1. Needs the consistent and fully integrated information, services, and process at any moment of its operation (Bayram & Cesaret, 2021; Bieberstein, 2015; Cummins et al., 2016; Fairchild, 2014; Fernie & Sparks, 2004a; Galipoglu et al., 2018; Kozlenkova et al., 2015a; Rigby, 2011; Saghiri et al., 2018; Wollenburg et al., 2018; Yrjölä et al., 2018a).
2. Includes customer touchpoints (Chauhan & Sarabhai, 2019; Cortiñas et al., 2019; Cummins et al., 2016; Heuchert et al., 2018; Pawar & Sarmah, 2015; Picot-Coupey et al., 2016; Verhoef et al., 2015; Yrjölä et al., 2018b, 2018a); any direct or indirect

      communication or contact with the prospect customers, which is not necessarily an interaction (Mirsch et al., 2016; Pawar & Sarmah, 2015b).

3. Eliminates borders between channels and manages them as an integrated channel (Heuchert et al., 2018; Hübner et al., 2016; Melacini & Tappia, 2018; Menrad, 2020; Pawar & Sarmah, 2015b; Picot-Coupey et al., 2016; Trenz et al., 2020; Verhoef et al., 2015).

4. Provides a seamless shopping experience for customers (Abrudan et al., 2020; Hole et al., 2019; Jiu, 2022; Kozlenkova et al., 2015b; Menrad, 2020; Mosquera et al., 2017).

In this study, we define omnichannel retailing (Abrudan et al., 2020) a seamless shopping experience through fully integrated distribution and communication channels (Fairchild, 2014), allowing customers to purchase and return products from anywhere and allows retailers to fulfill orders from anywhere by eliminating borders between different channels (inspired by the definitions of (Bayram & Cesaret, 2021)). Performing the logistic operations in an omnichannel retailing network is not a simple task. This activity significantly increases the complexity in terms of *fulfillment planning*, *inventory management, and delivery services.*

An omnichannel retailer has the flexibility to fulfill online orders from a physical store (*Ship-From-Store (SFS) strategy*), fulfillment center, or their combinations (Difrancesco et al., 2021). Using stores to fulfill online orders is the most adopted strategy among omnichannel retailers (Bayram & Cesaret, 2021). Appropriately, a ship-from-store strategy needs the lowest initial investment (Gallagher & Vella-Brodrick, 2008), increases online sales by avoiding frustrating online stock-outs (Jiu, 2022b), and improves customer value and experience (Difrancesco et al., 2021). On the other hand, using store inventory increases the risk of stock-outs (Bendoly, 2004) and the risk of dissatisfaction and disloyalty of customers who can't find items in-store (Goedhart et al., 2022). To overcome this challenge and benefit from the advantages of different fulfillment strategies, this study focuses on the combined ship-from-store as well as fulfillment facilities.

A suitable inventory system would order the just-right size and take into account factors such as the ordering cost, the holding cost, the shortage cost, etc. (Shenoy & Rosas, 2018). Retailers need to decide how to retain their stocks across the channels to prevent risks of running out of stock and stockouts. Excessive stock levels may result in increasing storage, labor, and insurance costs and causing revenue loss and quality reduction depending on the type of product. On the other hand, the lack of inventory can lead to an inability to meet customer demand, lost sales, and customer dissatisfaction (Kilimci et al., 2019).

In recent years due to the busy lifestyle, many customers prefer products to be shipped to them as fast as possible. Most recently, the need for the home delivery service has a dramatic raise during the COVID-19 pandemic as a result of social distancing. The delivery process is an important part of the order fulfillment problem (Ishfaq & Raja, 2018). Shipping products to customers is affected by different factors such as distance, various service options, number of customers, weight, and volume of products per order.

Research in the domain of omnichannel retailing has seen various literature reviews and research studies. De Borba (2020) used a systematic literature review to identify barriers in omnichannel retailing. They categorized barriers in operations and inventory activities that need to be considered by future studies. Mahvedan and Joshi (2022) reviewed the research literature on omnichannel retailing over the period 2013–2020. They outlined that developing logistics, inventory optimization, operations, and endless combinations of fulfillment, delivery, customer service, and return logistics are important areas for retailers to focus on.

Bayram & Cesaret, (2021) investigated dynamic fulfillment decisions in which online orders can be shipped either from an online fulfillment center or from one of the stores. They construct a heuristic policy that maximizes the retailer's total profit. Difrancesco et al., (2021) study a fulfillment policy for both online and walk-in demand using store inventory under a variety of sources of uncertainty. The authors combine the simulation approach with exploratory modeling analysis to test various fulfillment policies in a variety of scenarios of analysis. Jiu, (2022b) study a joint replenishment, allocation, and fulfillment problem faced by an o-tailer. They formulate the problem as a two-stage approach, first deciding the replenishment links and then computing the appropriate quantities for replenishment and fulfillment. They proposed a two-phase approach to solving the problem.

The inventory control systems have Several variants in literature. Popular combinations include (1) continuous Review, Fixed Order Quantity (s, Q) System, (2) continuous Review, Order-Up-to-Level (s, S) System (3) Periodic Review, Order-Up-to-Level (T, S) System. The latter is the focus of our model. In periodic Review, Order-Up-to-Level (T, S) System the inventory level of items is reviewed at predetermined, fixed points in time. That is decisions are taken in at time $T, 2T, \ldots$.

This study aims to consider the tactical and operational decisions on the optimal amounts of inventory and replenishment, and the fulfillment location for an omnichannel retailer with the objective of maximizing the total revenue over a finite horizon.

We formulate the problem as an integer linear programming problem and examine the viability of the proposed model using a numerical example, inspired by an Australian omnichannel retailer.

The rest of the paper is organized as follows. In Section 2, the problem description and mathematical formulation of an omnichannel problem are described. The solution approach and computational results are described in Section 3. Section 4 presents a numerical study. Finally, the conclusion and future outlines are provided in Section 5.

2 Problem description

2.1. Problem statement

Figure 2 shows the structure of the omnichannel retailing network, where solid lines represent customers visiting stores and dashed lines represent products delivered to customers. The notations in the figure will be used in the mathematical modeling.

The network is divided into a number of *local zones* and hence customer locations. Each zone includes exactly one store. Customers are classified by their shopping channels and physical/delivery addresses. With respect to the shopping channel, the retailer deals with two types of customers: (i) walk-in customers, who physically come to the store and collect products from a store themselves, and (ii) online customers, who place orders through the retailer's website or mobile app (Govindarajan et al., 2021). Customers buying product(s) online would have the option of selecting the delivery service, with products directly shipped to their location, called *home delivery*, or collecting orders from a local store called *click-and-collect (C&C).*

C&C customers are defined as a part of online customers where the payment and purchase accrue at the online channel, but the pick-up happens at a nominated store, meaning that customers cross-buy (buy online and pick up in-store) (Jara et al., 2018). We emphasize that with the introduction of C&C, the retailer requires an integrated information system to provide customers with immediate access to the real-time inventory information at each store (Gallino & Moreno, 2019). In another word, the actual stock availability is promptly updated once a C&C order is processed by an employee or a walk-in customer makes a purchase in the store.

The entire fulfillment process of walk-in customers only is taken care of at the corresponding store in the local zone. We assume that customers who face a stock-out don't switch to other stores, and it is because of the long distance between stores. Therefore, the unfulfilled in-store demand of one store cannot be fulfilled by other stores. This assumption is in line with research in Bayram & Cesaret, (2021), and Jiu, (2022b). The retailer needs to decide from which location (a store or an FC) fulfills online orders. We stress that the fulfillment process in a fulfillment center is more efficient than in a store (Gallino & Moreno, 2019). The flowchart of fulfilling online orders is shown in Figure 1.

In this research, we study omnichannel retail operations to determine the decisions on fulfillment optimization and inventory management in an integrated model. In particular, the retailer determines the amount of inventory replenishment at selected times, the inventory policy at each store, and the fulfillment of the online orders for different selling channels.
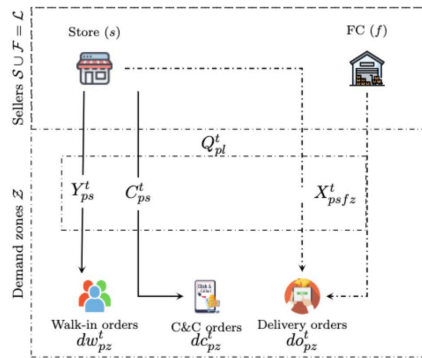

Figure 1: Structure of an omnichannel retail network

Assumptions used in the mathematical model have listed below:

- Unfulfilled demand of walk-in and click-and-collect customers for products that are out of stock is immediately lost.
- Customers don't switch between selling channels or stores in the case of stockout. That is, a) an online customer will not intend to buy products physically in store, and b) a walk-in customer does not choose delivery but collects product(s) from the store.
- All stores support walk-in, click-and-collect, and online demand.
- The replenishment occurs weekly.
- The actual inventory availability is changed in real time, meaning that the retailer has an integrated information system.

2.2. Mathematical model

Notations:

Consider a retailer selling products $p \in \mathcal{P} = \{1, \dots, P\}$ to customers in different demand zones $z \in \mathcal{Z} = \{1, \dots, Z\}$ over a finite planning horizon of periods $t \in \mathcal{T} = \{1, \dots, T\}$ (a period could represent a day for example). Let $s \in \mathcal{S} = \{1, \dots, S\}$ denotes the set of stores and $f \in \mathcal{F} = \{1, \dots, F\}$ denote the set of fulfillment centers respectively, and $\mathcal{L} = \mathcal{S} \cup \mathcal{F}$ represent the set of all seller locations. So, a seller or seller location refers to a store or a fulfillment center. For the complete list of notations, please see Table 1.

Table 1: Notations

Notation	Definition
$\mathcal{S}$	Set of stores ($s \in \mathcal{S}$)
$\mathcal{F}$	Set of fulfillment centers ($f \in \mathcal{F}$)
l	Set of sellers ($\mathcal{L} = \mathcal{S} \cup \mathcal{F}$)
$\mathcal{P}$	Set of products ($p \in \mathcal{P}$)
$\mathcal{T}$	Set of time periods ($t \in \mathcal{T}$)
$\mathcal{Z}$	Set of zones ($z \in \mathcal{Z}$)

Parameters:

do_{pz}^{t}	The online (home delivery) demand of zone z for product p at period t,
dw_{ps}^{t}	The walk-in demand of store s for product p at period t,
dc_{ps}^{t}	The click-and-collect demand of store s for product p at period t,
i_{p}	The retailer price of product p,
ch_{plz}	The cost of delivering product p from the seller l to a customer in zone z,

cf_{ps}	The walk-in fulfilment cost of product p at store s,
cr_{pl}	The replenishment cost of product p in seller l,
co_{pl}	Holding cost of product p in seller l,
$\bar{u}_l$	The inventory capacity of seller l,
$\bar{k}_{lz}$	The capacity of transportation vehicle from seller l to customers in zone z,
lo_{pz}	Lost sale penalty cost for online customers in zone z for product p,
lw_{ps}	Lost sale penalty cost for walk-in customers in store s for product $p \in \mathcal{P}$.

Variables:

X_{plz}^t	The amount of product p ship to online customers in zone z from seller l at period t,
Y_{ps}^t	The amount of product p sold to walk-in customers in store s at period t,
C_{ps}^t	The amount of product p sold for click-and-collect orders in store s at period t,
I_{pl}^t	Inventory level of product p at location l at the beginning of period t,
R_{pl}^t	Replenishment amount of product p at location l in period t,
Q_{pl}^t	The total sale of product p at location l at period t.

Before proceeding with the definitions, we describe the order of events during a period. The start inventory for product p in each period t at seller l is I_{pl}^t. Online and walk-in demands arrive over periods. Walk-in demands are immediately satisfied if the inventory level is positive, otherwise, they are lost. Online demand and the click-and-collect orders could be satisfied from either a store or by the fulfillment center (the pick-up location for click-and-collect orders is still the store). At the beginning of each period, the amount of product p replenished at seller l is denoted by R_{pl}^t.

The amount of sale for sellers: Let X_{plz}^t denote a decision variable representing the amount of product p shipped from seller l to satisfy the online demand of customers in zone z at time period t while Y_{ps}^t is the amount of the product used to fulfill the walk-in customers from the store s. Besides, C_{ps}^t represents the amount of the product for C&C orders. For ease of exposition, we substitute the total sale for the seller l for product p at time t by Q_{pl}^t as

$$Q_{pl}^t = \begin{cases} \sum_{z \in Z} X_{psz}^t + Y_{ps}^t + C_{ps}^t, & \forall t \in \mathcal{T}, p \in \mathcal{P}, s \in \mathcal{S}, \\ \sum_{z \in Z} X_{plz}^t & \forall t \in \mathcal{T}, p \in \mathcal{P}, l \in \mathcal{F}, \end{cases} \tag{1}$$

for store s and fulfillment center f, respectively.

The start inventory level for sellers: The replenished products arrive immediately and will only be available to serve the demand that occurs during the same period. The start inventory ($I_{pl}^t > 0$) is determined on the basis of the amount of total sale (fulfillment), replenishment amount, and the leftover inventory from the previous period $t-1$. We apply an order-up-to-level system, that is the start inventory raises to I_{pl}^t at the beginning of each period with zero lead time (Poormoaied, 2022). So,

$$I_{pl}^t = I_{pl}^{t-1} + R_{pl}^{t-1} - Q_{pl}^{t-1} \quad \forall t \in \mathcal{T}, p \in \mathcal{P}, l \in \mathcal{L}. \tag{2}$$

Unlike the fulfillment which occurs daily, the replenishment occurs weekly. So, we set $R_{pl}^t = 0 \ \forall t$ if $rem(t, 7) \neq 0$.

Supply constraint: To guarantee that the amount of products used by each seller to fulfill demands doesn't exceed the available inventory, we impose

$$Q_{pl}^t \leq R_{pl}^t + I_{pl}^t \quad \forall t \in \mathcal{T}, p \in \mathcal{P}, l \in \mathcal{L}. \tag{3}$$

Capacity constraints: In our study, each seller has a limited storage capacity and so transportation vehicles are. To respect the capacity constraints, we have:

$$R_{pl}^t + I_{pl}^t \leq \bar{u}_{pl} \quad \forall t \in \mathcal{T}, p \in \mathcal{P}, l \in \mathcal{L}, \tag{4}$$

$$\sum_{p \in \mathcal{P}} X_{plz}^t \leq \bar{k}_{lz} \quad \forall t \in \mathcal{T}, p \in \mathcal{P}, l \in \mathcal{L}, z \in \mathcal{Z}. \tag{5}$$

Fulfillment constraint: Let do_{pz}^t denote the online demand of zone z for product p at period t. The demand for the walk-in and click-and-collect customers from local store s is presented by dw_{ps}^t and dc_{ps}^t, respectively. Then the fulfillment constraints are

$$\sum_{l \in \mathcal{L}} X_{plz}^t \leq do_{pz}^t \quad \forall t \in \mathcal{T}, p \in \mathcal{P}, z \in \mathcal{Z}, \tag{6}$$

$$Y_{ps}^t \leq dw_{ps}^t \quad \forall t \in \mathcal{T}, p \in \mathcal{P}, s \in \mathcal{S}, \tag{7}$$

$$C_{ps}^t \leq dc_{ps}^t \quad \forall t \in \mathcal{T}, p \in \mathcal{P}, s \in \mathcal{S}, \tag{8}$$

which ensure that the sale is subject to the demand.

7

Income: The total cumulative profit from physical and online sales is

$$A_{0p} = \sum_{t \in \mathcal{T}} \sum_{p \in \mathcal{P}} \sum_{l \in \mathcal{L}} i_p^t \, Q_{pl}^t. \tag{9}$$

The holding costs: Leftover products remaining at the end of each time period incur a holding cost, and the unit cost is co_{pl}. This cost could represent the total of the costs of capital tied up, fulfillment center, space, insurance, taxes, and so on. In our setting, the holding cost is assessed only on inventory left at the end of a period and carries over to the next period. The total holding cost is presented by

$$A_{1c} = \sum_{t \in \mathcal{T}} \sum_{p \in \mathcal{P}} \sum_{l \in \mathcal{L}} co_{pl} \, I_{pl}^t. \tag{10}$$

Unsatisfied demand cost: Retailers policy prohibits deliberately planning for shortages of any of its products. However, a shortage of products occasionally crops up. Consequently, the amount of the product required (demand) exceeds the available stock. Unfulfilled demand for products that are out of stock is immediately lost and incurs penalty costs.

$$A_{2\_1c} = \sum_{t \in \mathcal{T}} \sum_{p \in \mathcal{P}} \sum_{z \in Z} lo_{pz} \left(do_{pz}^t - \sum_{l \in \mathcal{L}} X_{plz}^t \right), \tag{11}$$

$$A_{2\_2c} = \sum_{t \in \mathcal{T}} \sum_{p \in \mathcal{P}} \sum_{l \in \mathcal{L}} lw_{ps}^t \left(dw_{ps}^t + dc_{ps}^t - Y_{ps}^t - C_{ps}^t \right). \tag{12}$$

The replenishment cost: The retailer pays cr_{pl} unit variable cost for replenishing product p for seller l. The replenishment cost is given by

$$A_{3c} = \sum_{t \in \mathcal{T}} \sum_{p \in \mathcal{P}} \sum_{l \in \mathcal{L}} cr_{pl} \, R_{pl}^t. \tag{13}$$

The total handling cost: The handling cost for online demand of zone z associated with preparing and shipping product p for seller l is given by ch_{plz}. The handling cost for online orders is calculated by

$$A_{4c} = \sum_{t \in \mathcal{T}} \sum_{p \in \mathcal{P}} \sum_{l \in \mathcal{L}} \sum_{z \in Z} ch_{pls} X_{plz}^t \tag{14}$$

The store fulfillment cost: The unit cost cf_{ps} for fulfilling the demand of walk-in and click-and-collect orders including rent, overhead, labor, etc. are associated with products type, stores, and periods, that is the cost of store s for product p. So, the total store fulfillment cost is given by

$$A_{5c} = \sum_{t\in\mathcal{T}} \sum_{p\in\mathcal{P}} \sum_{s\in\mathcal{S}} cf_{ps}\left(Y_{ps}^t + Z_{ps}^t\right). \tag{15}$$

Non-negativity constraints are

$$I_{pl}^t, R_{pl}^t, Q_{pl}^t, X_{plz}^t, Y_{ps}^t, Z_{ps}^t \geq 0 \qquad \forall t \in \mathcal{T}, p \in \mathcal{P}, l \in \mathcal{L} \tag{16}$$

The objective is given as

$$Max\left(A_{0p} - A_{1c} - A_{2_{1c}} - A_{2_{2c}} - A_{3c} - A_{4c} - A_{5c}\right). \tag{17}$$

4 Numerical experiments

This section presents a case study, explains the set of parameters, how the data was generated, and discusses the numerical results.

Data Generation:

The time horizon $\mathcal{T}$ is fixed to 14 time periods (days). The replenishment schedule of each seller was set to be at the beginning of each week, and during weeks there is no replenishment opportunity. The start inventory level is set as 120 and 250 per product for each store and fulfillment center, respectively. The walk-in, online, and click-and-collect demand for each customer zone was generated randomly as $U_d[1,100], U_d[1,60], U_d[1,35]$, respectively.

The available transportation and storage capacity for each store were estimated 1.2 higher than the total mean (walk-in, click-and-collect, and online) demand of a zone (7,74) while for the fulfillment center was 1.2 higher than the online mean demand of all zones (56,56).

The other values for the settings and parameters are present in Table 2.

Table 1: Instance generation parameters

Parameters	Store	Fulfillment center
Price per product: $40		
Replenishment charge per price	8%	8%
Holding charge per price	8%	8%
Handling charge per price	Vary per distance [2.5,7] Increase per distance for other zones	Vary per distance [2.5,7] Increase per distance for other zones
Lost sale cost per price	50%	50%
Walk-in fulfilment cost per price	15%	-

The demand distribution for the walk-in, click-and-collect, and delivery orders for product 1 at time 2 is presented in Figure 2. The figure shows the demand and commutative demand for zone 1 over time.
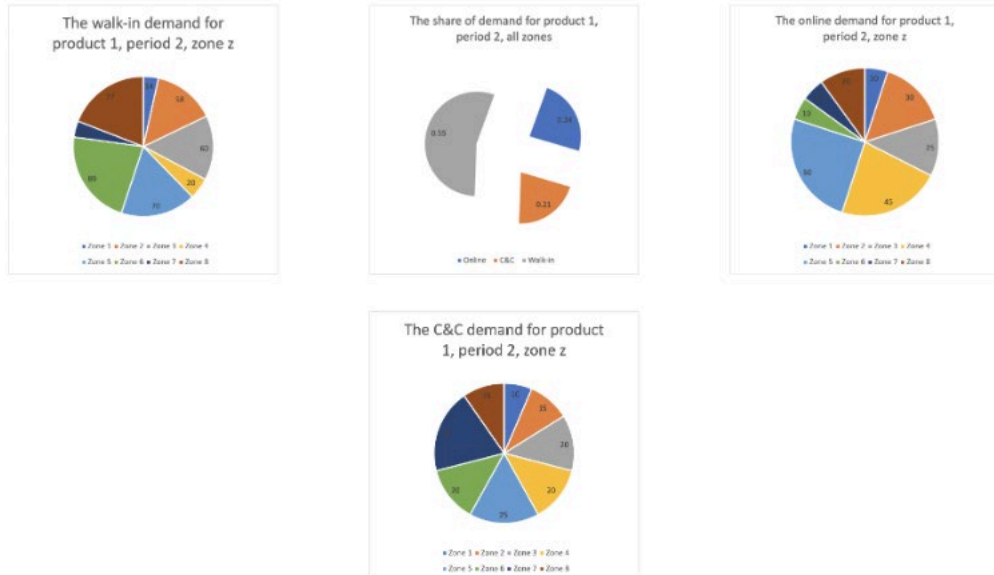
Figure 2: Demand distribution for product 1 at time 2

Solution approach and computation result:

All experiments were carried out on a PC with Intel Corei7, CPU 2.6 GHz, 16 GB of RAM, using a Gurobi solver version 11.5. The maximization problem for the deterministic model was solved in 0.002323 second with 3418 variables and 1204 constraints and the objective value is $636221.5. The most important results are presented as follows.

Start inventory: The start inventory levels of the fulfillment center and store 1 are shown in Figure 3. The beginning inventory levels for the sellers are raised to the highest point at the replenishment date and then continue to fall between two replenishment times. Because here we assume full knowledge of demand, the inventory level drops to zero immediately prior to the second replenishment. In practice, one could set the safety stock to non-zero.

Figure 3: Start inventory for the FC and store 1 over time.

The total online sale: The online sale for stores in comparison to the online sale of the fulfillment center is presented in Figure 4. The figure shows that the total online sale for stores is higher than the fulfillment center. Although the handling cost for the FC is less than a store, this cost increase on the distance and it is more profitable if the online orders are served by the stores at the same zones, however establishing more fulfillment centers and a close distance from customer zones, may improve the objective value.

Figure 4: Start inventory for the FC and stores for product 1 over time
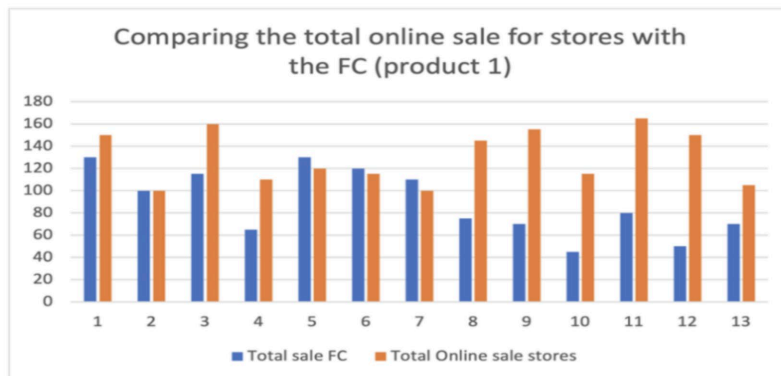
The results are also drawn based on changes in demand as depicted in Figure 5. The results shows that the objective function is highly positively correlated with the customer demand. However, we expect when the demand is much higher and hence the penalty of unfulfillment increases, the objective function value will stop increasing eventually.
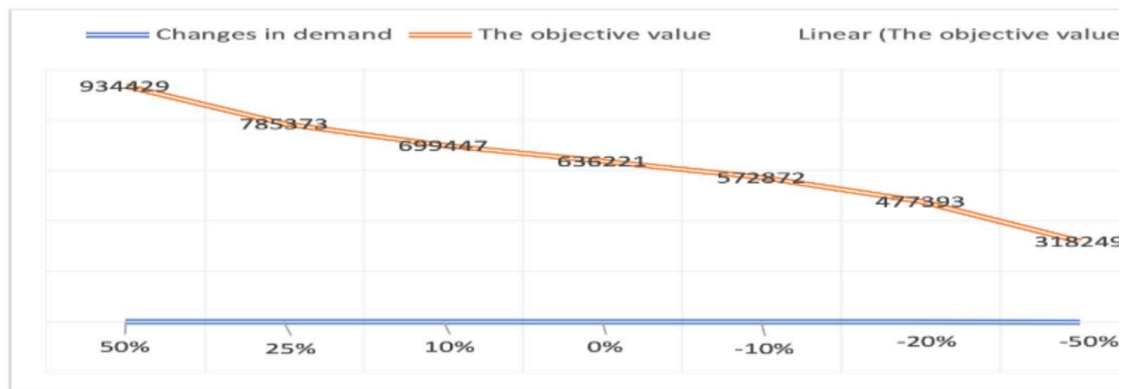
Figure 5: The relationship between demand and objective function

5 Conclusion

This study investigated a capacitated omnichannel retailing problem to integrate tactical and strategic decisions on inventory management and fulfilment optimization. By examining the results, some insights which abide by the market rules and the unique structure of the problem were drawn. This work comes with many limitations and hence offers a large number of future directions. For example, the deterministic setting is not realistic, and the stochastic demand should be considered. Another future direction is to consider a large, connected network with collaboration of partner stores. Partnering with other retailers and leveraging their store location and capacity can provide a great potential for improving delivery efficiency, fulfillment level and customer satisfactory.

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Data Sharing in the Physical Internet: A Capability-Based Approach for Trustless Logistic Networks

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Abstract

Physical Internet (π) promises a more sustainable logistics network through hyperconnectivity between companies and high automatization. However, many logistic companies are reluctant to enter such a network, as they fear sharing sensitive commercial data with competitors and/or a central orchestrator. Therefore, we introduce a fixed set of 'capabilities' (services a specific company offers) which allow for the flexibility and exactness to define logistic companies. Based on these capabilities, we propose a decentralized scheme wherein 1) logistic companies only need to share these 'capabilities' openly with the network and 2) the logistic network is modelled based on these capabilities and routing algorithms can be applied. We tested this concept both by applying it in an ABM model based on real data and by in-depth interviews with potential participants for a real-life test. The approach shows promising preliminary results on both tests, although more research is needed to confirm these findings.

1 Introduction

Physical Internet (π) is, as it is inspired by the Digital Internet, conceived as an interconnected network of networks. Montreuil et al. (2012) describe it as such: "The Physical Internet enables to shift from private supply networks to an Open Global Supply Web-enabling the physical equivalents of Intranets, Virtual Private Networks, Cloud Computing and Cloud Storage". Indeed, collaboration is a key element in improving the efficiency of supply chains as a whole and logistics specifically (e.g., Audy et al., 2012; Ha et al., 2011), increasing both profitability and sustainability of the chain. From the earliest research on Physical Internet, the advantages of flow travel, transportation and supply chain inventory were made clear. Even without a modal shift, a division by four in logistics generated CO_2 emissions was predicted. (Ballot et al., 2011). Despite these results, only a few real-life collaborations between transport companies exist (Basso et al., 2019), with many citing a lack of trust as a relevant impeding factor.

With the Physical Internet Living Lab project (PILL), we aim to implement a real-life application of the Physical Internet, allowing competing companies to work together in a trusted environment, without the need for a central orchestrator. For our test case, we focus on ISO containers moving to and from the Port of Antwerp-Bruges (PoAB) towards the hinterland. This setting is ideal for testing the application of the Physical Internet in practice for two

reasons. First, ISO containers are already standardized. This makes it easy for them to be handled by different entities during a route, allowing for the dynamic routing envisioned in Physical Internet. In addition, the hinterland of the Port of Antwerp-Bruges offers a very dense network with different logistic actors and different modes of transport available. Congestion issues for road traffic - both in the port and on the surrounding highways - increase the potential for alternative modes to be used. Although we focus on container traffic, we aim to develop a framework that can easily be expanded to other locations or flows.

In accordance with the prevalent view in literature, we conceptualize Physical Internet as a decentralized and interoperable network of software clients that allows collaboration and data sharing across the entire network of logistics nodes. The benefits of our holistic approach are best demonstrated by using it for route planning, which is considered a primary concern for the Physical Internet. In our case, we consider routes as a combination of different (uni- or multimodal) transport legs, with or without temporary storage (offering different options both in space and in time). As a test case, we developed a tool that will be tested in real life by 10 companies and in a fictional setting by an additional 7 companies in the Flanders region in April (first iteration) and September (second iteration) 2023. Seemingly similar route planning tools have been developed by logistic communities, logistic companies and ports over the past few years. However, they all offered a centralized solution, which created distrust amongst (smaller) players afraid of losing independency from the platform. Also, they offered either a system where only fixed schedules could be consulted (without booking logic) or a system where capacity needed to be shared. The first offered too little advantage, and the second required too much sensitive data to be shared. These concerns were confirmed by our advisory board members.

In the remainder of this document, we will first explore the relevant literature on horizontal collaboration in freight transport and the levels of data-sharing and trust this implies. Next, we will introduce our proposed solution in section 3. We will show that this solution could provide solutions with both from a modelling/route-finding point of view and a human, privacy-sensitive point of view in section 4. We will end with our main conclusions in section 5, including some avenues for further research and the limitations of our study.

2 Literature

Horizontal collaboration in freight transport has been applied in the industry for some time (see Saenz et al. (2015) for some examples). In academia, the field is relatively young. Pan et al. (2019) conducted a thorough review of the existing literature and found 6 solutions for horizontal collaboration and 7 implementation issues considered. Interestingly, Physical Internet is the only horizontal collaboration solution to take a decentralized approach, whereas the others either imply fixed relationships between partners or a neutral platform or orchestrator. Another interesting conclusion is that communication between collaborating companies is an aspect that has not yet received significant attention, while these aspects were found to be crucial for efficient collaboration (Min et al., 2005). When evaluating the opportunities and impediments of horizontal cooperation, Cruijssen et al.(2007) found that, although SMEs clearly agree with the opportunities of collaboration (increased productivity, reduced costs, larger contracts, ...) the issue of finding suitable partners and the fear of unfair division of gains (especially when dealing with a larger partner) are holding them back. Similarly, Plasch et al. (2021) found that transport companies saw the potential benefits of collaboration in Physical Internet, but stressed the importance of trust to do so. They suggest

the factor needed to provide this trust is a 'central orchestrator' or 'trustee', suggesting a certain level of centralization within Physical Internet.

Centralized data sharing is a widely suggested strategy for interconnectivity in literature, which involves storing all data at or sharing it through a single platform (e.g. Baumgrass et al., 2015, Maneengam & Udomsakdigool, 2021, Maneengam & Udomsakdigool, 2020). However, this approach has limitations, as it poses potential threats to data integrity, privacy, and other weaknesses (Rejeb et al., 2019). This can hamper adoption due to a lack of trust and reluctance to share data and the complexity of collecting and processing high volumes of data (Hopman et al., 2022). In contrast, recent research suggests that decentralization is a future trend in logistics collaboration (Pan et al., 2019a; Simmer et al., 2017). Decentralization avoids the potential for organizations that control the data to grow too powerful and exploit their position against the general interest of the network. Hopman et al., (2022) analyzed the effects of different levels of centralization on 2 case studies by using an ABM simulation with real data. They found that a high level of decentralization was beneficial in the case of container hinterland transport by road as it allowed for flexible adaptation to changing circumstances. This confirms the validity of our case as a real-life test for the Physical Internet.

When bringing the concept from theory to practice, we have to take into account that the concept of Physical Internet implies a form of collaboration between logistic companies that is both flexible and extensive (Hofman & Dalmolen, 2019). Extensive collaboration requires a high level of trust between the companies involved. However, trust building requires that both parties show they have the 'ability to perform to promise', which implies both the commitment and the skill/assets to fulfil the promises made (Fawcett et al., 2012). This is a process that needs time and effort and requires accepting a certain level of vulnerability (Wieland & Wallenburg, 2013). In a fast-changing context such as Physical Internet, where the aim is to create ad hoc collaborations to optimize and/or flexibly reroute shipments, these investments cannot be made for each potential party. Therefore, to bring the optimization potential of Physical Internet to reality, a framework that allows for extensive data sharing while still protecting each company's commercial privacy is needed. This aspect has received less attention in research so far, despite the importance of information exchange in horizontal collaboration, especially when evolving to (near-to)-real-time optimizations envisioned in Physical Internet (Pan et al., 2019).

In the larger part of the studied literature, the Physical Internet is assumed to be fully functional (within the considered network boundaries), and decisions are made automatically and on the spot. Indeed, Treiblmaier et al. (2016) noted that there is a tendency to look at Physical Internet as a final state that either exists or not. However, participation in a fully automated $\pi-$network requires a high level of trust in Physical Internet, especially when implementing the system in a multi-company environment without previous collaboration. As such, we state there is a need to focus on intermediate steps towards Physical Internet. Therefore, we aim at a short-term implementation of a minimal Physical Internet network involving different companies to build this trust. To achieve this goal, we decided to consider the human (or business) as the deciding agent. This approach increases the confidence of the users as they remain in control. With this decision comes the consequence that the concepts used need to be people-readable, while still being machine-readable (to allow for route-finding). Also, as there is no baseline trust in the proposed system, we need to reduce the amount of information to be shared to a minimum, while still providing enough information to allow for efficient route-finding. Therefore, our approach has been designed not to require the exchange of such sensitive data, as the shared information only pertains to the services provided by logistics companies.

To achieve our goal, we build upon the notion of π-nodes proposed by Montreuil et al., (2010). They define π-nodes as "locations expressly designed to perform operations on π-containers […]. Generically, the π-nodes are locations that are interconnected to the logistic activities". They defined 9 different types of π-nodes, each with its own specific definitions. Translating to more common logistic terminology, these are hubs, terminals, warehouses etc., that are part of the π-network. While many papers cite this paper referring to the general concept of Physical Internet, only a limited number specifically look at π-nodes. Furthermore, those who do, focus on the development and optimization of a specific type of node: Oktaei et al. (2014) and Gardanne & Meller (2012) optimize a road-road transit node, Ballot et al. (2012), Walha et al. (2014) and Chargui et al. (2020) do the same for a road-rail hub. We found no papers that explore the different types of nodes from a more conceptual view.

The contribution of our work is twofold.

(1) This paper presents a novel approach to formally describe logistics networks in terms of the capabilities that π-nodes are offering to the network. This allows a formal way of routing discovery and optimization as a foundation for a true collaborative Physical Internet;

(2) We propose a fully decentralized network of π-clients relying on the sharing of capabilities only, without the need for sharing capacities. Both the decentral nature of the network and the limited requirements for information sharing address the trust-related concerns that have hampered the adoption of earlier collaboration networks.

3   A network defined by capabilities

This study employs a formal approach to analyze the π-network, which is conceived as a system of π-nodes differentiated by the services they provide. With this approach, we achieve several objectives. Firstly, it enables the construction of a decentralized network structure, facilitating a more democratic distribution of power and control. At the same time, the approach limits the amount of sensitive data that needs to be shared between nodes, enhancing privacy and security and e further ensuring trust. Finally, it provides a relevant framework for routing in the Physical Internet, which can help improve efficiency, reduce costs and increase sustainability in the logistics industry.

Decentralization

In accordance with Hens et al., (2011) we propose an event-based decentralized orchestration, which allows for decoupling in space and time and increases scalability. In this approach, changes to the network are published as an event, leaving it up to the receiver to react (or not). We apply this event-based decentralization in two ways:

- Updates of the network state: every member of the network publishes its service offerings defined in terms of π-capabilities to all other members the network. Receivers can decide if this information is relevant for their local copy of the network and if so, make adaptions. This approach avoids the need for constant updates prompted by irrelevant parts of the network (e.g. a change in railway schedules to a region where a producer has no clients, or a low water level alert when no waterway trips are planned)
- Capacity requests: once a potential route is calculated, the requesting company sends a capacity request to the involved transport companies and/or node operators. This is a 1-

on-1 communication, thus limiting the sharing of sensitive information to the partners directly involved.

Using this approach, we avoid sharing sensitive commercial information openly with the network. The only information required to share, is information most of the logistic companies already share openly on their websites. Given its intentionally limited footprint, this information can also be efficiently distributed across the network via established peer-to-peer technologies (e.g. Benet, 2014; Weil et al., 2006) We posit that this approach can effectively scale to large logistics networks, including dense European intermodal hinterland networks. To further ensure such scalability, we can employ cut-off parameters that serve to limit the amount of local data required for route discovery.

Capabilities

However, the definition for each capability is not always clear, and the information is labor-intensive to retrieve for a large set of companies. To make route planning possible in this context, we need a standardized way to communicate these service offerings to the network. We propose the term 'capability' for these service offerings. However, contrary to their approach of predefining specific types of nodes, we propose to define nodes by the set of capabilities they offer. This way of working allows for high flexibility in design nodes with different capabilities (as is the case in reality), while still profiting from the clear definitions offered by these capabilities. To define the capabilities, the types of nodes defined by Montreuil et al., (2010) served as our main inspiration.

Using these concepts, we have modelled the Port of Antwerp-Bruges hinterland logistics network for container transport using an ABM, replicating the real-life network operated by our advisory board members and their partners. This enabled us to validate the completeness and soundness of our approach. We also used the ABM to identify which capabilities were indeed necessary and which should be adapted or could be ignored in this setting. We came to, resulting in the following list of relevant capabilities for our case:

- Transit (M): The transfer of carriers, such as container trailers, between inbound and outbound vehicles, with optimization as the primary consideration.
- Store (A): The storage of π-containers during a route, full or empty, under agreed-upon conditions (e.g. maximum time and cost).
- Gateway (Γ): A point of entry or exit for containers in the π-network to or from different parts of the network, typically lower or higher-level networks. Container terminals that serve as gateways to hinterland networks are examples of this.
- Depot (Δ): The temporary storage of unused containers after a route is ended.
- Composer (Ω): The composition of smaller containers into larger ones or vice versa.
- Hub (Φ): The unimodal or intermodal transition from incoming movers to outgoing movers between different logistics parties.
- Service provider (Σ): capable of fulfilling a service. These services can be considered as 'wildcard' capabilities that need to be defined in the model, such as cleaning, weighing etc. This is an extension of the aforementioned paper.

Other capabilities introduced by Montreuil et al. (2010), such as π-Switch and π-Sorter, remain relevant but have been kept out of our early models for the purpose of limiting complexity. By introducing a fixed set of clearly defined capabilities, any logistics company can be defined by

the set of capabilities they offer and the location at which they are offered. This way, the proposed framework offers a level of abstraction in the network that ensures both flexibility and exactness. Flexibility is needed to incorporate the diverse nature of actual logistic companies without loss of information. Exactness is needed to allow for correct modelling of the network and for the routing algorithms to function.

Routing

By combining the π-nodes with their π-capabilities with a set of π-transporters along the edges between them, a network is created in which routes can be found.. Consider a routing function

$$P_c(s, n) \rightarrow s', n'$$

with routing constraints c allows for transitioning from a starting state s and a π-node n to a new state s' and node n'. In our experimental model for hinterland logistics of ISO containers, a routing state is defined in terms of the container state and the mover state as follows:

$$s = \begin{cases} \text{Container state} & \text{(full or empty)} \\ \text{Container location} & \text{(a } \pi\text{-node)} \\ \text{Container ready} & \text{(a point in time)} \\ \\ \text{Mover id} & \text{(a } \pi\text{-mover)} \\ \text{Mover modality} & \text{(road, rail or inland waterway)} \\ \text{Mover state} & \text{(with our without container)} \\ \text{Mover location} & \text{(a } \pi\text{-node or a } \pi\text{-vertex} \end{cases}$$

The container ready time is the point in time when the container will be ready. It represents the latest departure time of the container from its current node, which may be determined by the storage limitations of the node or the departure schedule of the next mover.

The routing constraints are defined as follows:

$$c = \begin{cases} \text{order type} & \text{(import or export)} \\ \text{pick-up location} & \text{(a } \pi\text{-node)} \\ \text{drop-off location} & \text{(a } \pi\text{-node)} \\ \text{composer location} & \text{(a } \pi\text{-node)} \\ \text{composition time window} & \text{(a start and end time)} \\ \text{earliest pick-up} & \text{(a point in time)} \\ \text{latest drop-off} & \text{(a point in time)} \end{cases}$$

For instance, after retrieving an empty shipping container from a depot, the transition

$$P_c(s, n) \rightarrow s', n$$

from a pick-up location node n with capability Δ (depot) may transition the mover state from *without container* to *with container* (i.e., a pick-up transition), whereas the location remains the same. Although the set of valid states and transition functions may vary between different types of π-networks, such as urban logistics and parcel delivery networks, the same basic approach for defining valid transitions can be used to drive the routing algorithm.

4 Testing the theory

4.1 Building a routing algorithm

The decentral network allows clients to synchronize with the evolving network state. Routing can then be done locally on the replicated network state. Different routing algorithms can be applied by different companies, using the same network information. To prove efficient routing could be achieved using our proposed concept, we developed a first version of such a routing algorithm. Existing research on routing algorithms for Physical Internet is limited. Sarraj *et al.* (2014) use an A* algorithm to route containers in their multimodal logistic network. On a unimodal network of a small scale, Fazili *et al.* (2017) use a mixed integer programming (MIP) method to search the optimal routes. For scalability and interpretable purposes, we used an A*-based routing algorithm, adapted to allow for the decentralized information sharing and our capability scheme: Physical Internet A* (PIA*). The nodes and transport means among them are translated into the vertices and edges on a directed graph in the model. A shortest-path algorithm is then devised to find routes for containers.

We define the following terms:

- A vertex is defined by container location, container state (empty or full) and timestamp. Note that this information is part of the container state defined in the previous chapter.
- An edge represents a set of states and transitions that move a container between two different locations, in time, by a particular mover.
- A route combines a set of vertices and edges, which transports the container from its origin to the destination before a specified time. It is represented by a sequence of valid transitions between states, as explained in section 3.

Figure 1: Pseudo code of PIA*

Algorithm 1: Pseudo code of PIA*

Input: NetworkState{Vertices, Edges}, Container, LatestDeliveryTime
Output: Set of routes

1 R ← set of incomplete routes;
2 C ← set of complete routes;
3 R.add(initial route which contains only the original vertex) ;
4 **while** *C.size() < the desired number of routes to find* **OR** *R.size() > 0* **do**
5   i ← the top route in R;
6   Remove i from R;
7   F ← all the feasible routes by expanding on the last node to all of its adjacent nodes (a direct edge in-between exists);
8   R.addAll(F);
9   **for** *each route in R* **do**
10   Calculate actual + estimated cost;
11   **if** *the last node is the destination* **then**
12   Move the route from R to C;
13   **end**
14   **end**
15   Rank R by cost ascending;
16 **end**
17 **return** C in the order of cost;

Figure 1 shows the calculation steps performed in the routing algorithm. The routes are then presented to the decision maker and ranked depending on their overall performance. This performance is calculated by a weighted function of different aspects of a solution, such as distance, monetary cost, duration and greenhouse gas (GHG) emissions. The input parameters

for this cost function are normalized by scaling, based on their known respective maximum values.

In order to validate the capability-based routing, we used an Agent-Based Model (ABM). This type of model has been used by several authors, to mimic the decentralized tendency of Physical Internet by modelling each decision-making unit as an individual entity (e.g. Sarraj et al., 2014, Sallez et al., 2016, Walha et al., 2016). Walha et al., 2016). In our setting, the decision-making units were the expeditors (requesting a route and selecting a preferred route), the node and transport operators (accepting or declining a request) and the movers (moving containers and experiencing disruptions). We were able to run various simulations on a set of scenarios, thanks to the data received from PILL's partners. Example data to be utilized include historical demand based on containers entering/exiting terminals; schedules for trains and barges and their free capacity; origin and destination of containers transported by road and historical data on driving times between different nodes (TomTom); historical road disruptions based on disruption data from the Flemish Agency of Road and Traffic (AWV) road measurements.

With this exercise, we proved that routing of containers can indeed be achieved using our proposed concept and returns valid routes. In the next step, we will use this ABM model to test and measure the benefits of the proposed "capability sharing" versus the conventional "capacity sharing" reservation mechanism by simulating how the two processes behave given the same logistics flow. Besides the quality of the routes and speed of calculation, we will also evaluate the level of commercial privacy obtained in each instance. A similar exercise has been done with an alternative routing algorithm, also developed within the PILL project and returned good results on all measures (Sun et al., n.d.).

4.2   Stakeholder interviews

After constructing the first version of the application, we are conducting a round of open interviews with a diverse set of logistics stakeholders to introduce them to the concept and ask for their participation (25 have been completed so far). Additionally, another 10 semi-structured follow-up interviews were conducted (up until publication date) to go through the functionalities of the route planner for targeted feedback. The interview guideline and a coded overview of participants can be found in the annex to this paper. Only elements relevant for the topic of the current paper are discussed in the text. An additional paper is planned to discuss the overall results of the real-life test after its completion.

The majority of interviewees were positive about the concept of a decentralized network, regardless of the necessity to share data with competitors. Many stakeholders have already warmed up to the idea or are even considering decentralized applications of their own.

"*I was already convinced that this is the way forward.* [G3]"

"*I was actually contemplating a similar concept a few years ago*. [T4]"

Only two interviewees mentioned their concern about sharing information with their competitors. The main concerns that did pop up were related to the cyber security of an open platform and collaboration with parties without a former contract. The former is a technology challenge, the second requires more attention in follow-up projects. In an industry where collaboration with a new partner still requires significant administrative efforts, how can a platform enable these "digital handshakes" to facilitate open collaboration?

By introducing the concept of capabilities, the data requirements of our proposal are sufficiently limited to not deter even more hesitant stakeholders. They evaluated the fact that actual sensitive data (like real-time capacity) is only shared anonymously and on a 1-on-1 basis to finalize bookings as a strong point of the proposal. This duality of data sharing (open and 1on1) was generally considered sufficient.

When discussing the general definitions of the capabilities, most stakeholders said to find them clear. The only exception was [N8], who had difficulties with the distinction between Depot and Storage. We can therefore conclude that the general description was well received by our stakeholders. In further testing, we will verify if they are fully able to combine these capabilities to define their own nodes. However, two interviewees had difficulties interpreting the concept of 'nodes' as such. 'Locations' was suggested as a more understandable word.

5 Conclusions

We have presented a scalable decentral π-system that provides logistics service users with the ability to explore alternative logistics routes and solutions without the involvement of third parties that may exert control over the network. We have intentionally limited the scope to hinterland container logistics using a limited set of capabilities for clarity reasons. Adding more capabilities to the mix may offer more flexibility and optimizations in routing. Further study is needed to explore the full potential of the decentral capability-based network. Looking beyond hinterland networks and shipping containers can extend the benefits of our approach to other transportation methods, such as (break)bulk transportation. Additionally, one can look at modelling more local logistics (sub)networks such as urban logistics and parcel delivery networks, leveraging the abstraction layers Physical Internet offers or rather larger intercontinental transportation networks using air cargo and ocean vessels.

The system provides data security by (1) storing data locally and (2) limiting the amount of (sensitive) data to be shared by separating "capability" from "capacity". Validation of the concept with potential users confirmed that they find this approach both comprehensible and trustworthy. Some remarks were made as to the naming of the different capabilities, but all agreed the general framework is promising. Follow-up interviews will be conducted after the real-life testing to ensure stakeholder support remains.

We showed that the route discovery algorithm, which is founded on a formal definition of logistics node capabilities, is feasible and can be applied in a decentralized system and capability framework. Further testing will be done to compare the performance of this algorithm to existing algorithms, comparing the level of privacy, quality of the routes and speed of calculation.

Moreover, beyond operational use, the system can also be utilized for simulation purposes. Such a model may facilitate the assessment of potential network changes, including the addition of inland terminals, the implementation of additional scheduled services for trains and barges, the establishment of inland container stores and depots, and the relocation of production and storage facilities. The ABM infrastructure can also be used to assess the effectiveness of routing algorithms or to simulate the impact of disruptions of critical infrastructure in dense logistics networks.

Additionally, an important remaining question regarding the adoption of Physical Internet as we present it, it is the need to attain a critical mass. The mere promise of more optimal logistics planning in itself will not drive the necessary adoption, as these benefits will only fully develop when enough participants join the network. However, standards-based peer-to-peer data exchange, which facilitates a much-needed digital transformation in logistics, could offer the added value that is needed. We encourage to study and develop interoperability standards in the context of the different supply chain processes that facilitate collaboration across the decentralized π-network. In turn, this will drive the adoption needed for obtaining the critical mass to interconnect the Physical Internet.

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7 Annexes

7.1 Annex 1: List of interviewees

Code	Transporter	Node Operator	Expeditor	Cargo Owner	Governance Roles	Policy Roles
T1E1	x		x			
T2E2	x		x			
T3	x					
T4	x					
T5	x					
T6	x					
T7N1	x	x				
N2		x				
N3		x				
N4		x				
N5		x				
N6		x				
N7		x				
N8		x				
E3			x			
E4			x			
E5			x			
C1				x		
C2				x		
OE1*			x			
OG1*					x	
OG2*					x	
G3					x	
OP1*						x1

* Sector organizations

- Logistic roles:
    - o Transporter: responsible for the actual movements of goods
    - o Node operator: responsible for the operations within a π -node
    - o The Cargo owner (shipper or consignee): party currently responsible for the cargo
    - o The Expeditor: responsible for the planning of the route cargo takes
    - o The Asset owner: is the entity that owns the specific assets (containers)
- Policy roles: governing the physical network and rules applied to the physical cargo
- Governance roles: governing the digital network and rules applied to data

7.2 Annex 2: Interview Guideline

The interviews were set up in two steps:

- A first open interview in which the concept of Physical Internet was explained and the potential participant was asked whether they were interested
- A second semi-structured interview in which the tool was explained and evaluated in detail. For this second interview, the following guideline was used:

Goal of test:

- Validate the data sharing model
- Validate the key flows of the platform

Research questions:

- Does our data model allows for the current way of working of the stakeholders?
- Is there a difference between the requirements for the different stakeholder types (forwarders, terminals, transporters)
- Do transporters feel comfortable sharing this data?
- Is the data in the wizards correct for
  - o Adding a node, capability, transport
  - o Create a booking
  - o Confirming a route

Add a node

- Look at the nodes table, complete the wizard to add a location
- Is anything missing in adding the location?
- Is longitude / lattitude relevant?

Add a capability

- Complete the wizard to add a capability
- Are the capability categories clear and complete?
- What costs would you add and how?
- Do you feel comfortable adding this?
- Are all the steps clear?
- Is any data missing?

Add a transport

- Complete the wizard to add a transport
- Does it make sense to add a pool name?
- Are the container categories correct?
- How would you add your timetable
- Is the way to add a schedule clear?
- How would you add cost?
- Is anything missing?

Create a route

- Fill in the flow for booking a route
- Is any data missing?
- Who determines this data?

Overview routes

- Review the page with the routes, look at a detail of a route and book a route
- Is this enough information to book a route?
- Would you remove any of the routes of change the order?
- Do you mind that it's anonymous?

Capacity check

- Look at the route request table, check the detail of a route and confirm or cancel the route
- Do you have enough information to make a decision?
- Could you answer this right after seeing the request or is there a planning moment to wait for?
- How frequent would you be able to confirm/refuse a request per day?

7.3   Annex 3Algorithm 1: Pseudo code of PIA*

Assessing the Performance of Urban Distribution Networks

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Abstract:

Due to increasing concerns regarding rising emissions, urban congestion and financial costs it is important to develop and identify appropriate performance measures that can be used to aid the design of improved urban distribution networks. The Physical Internet (PI) concept involves transforming independent logistics networks into open and shared networks for improving sustainability. This involves designing new networks that are based on utilising multiple transport modes and transfer points. There is a need to compare the performance of typical urban freight networks with collaborative networks that involve shared use of warehouses and freight vehicles. This paper presents an assessment of several criteria that can be used to quantify the performance of freight and logistics networks in cities. Multi-criteria analysis is conducted for common urban goods networks including retail swaps and retail distribution.

The analysis contained in this paper can be used to assist network planners and designers to identify the most appropriate criteria to aid the design of future urban freight networks for achieving net zero emissions. Such measures can provide direction for fleet managers, urban freight planners as well as communities.

Keywords: Network Design, Collaborative Freight Networks, Network Performance Measures

Conference Topic(s): distributed intelligence last mile & city logistics; logistics and supply networks

Physical Internet Roadmap: ☐ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.

1 Introduction

Hyperconnected City Logistics (HCL) combines concepts from the Physical Internet and City Logistics (Crainic and Montrieul, 2016). The aim of HCL is to create more collaborative and integrated distribution networks to address sustainability issues. Sharing vehicles and warehouses can reduce the distance travelled by freight vehicles that can reduce operating costs, emissions and energy consumption as well as noise and congestion. However exchanging goods involves additional costs such as unloading and unloading goods as well as storage and vehicle wait times. There is a need to understand more about the trade-offs between transport and transfer/storage costs to assist in promoting HCL.

Major cities in Australia generate a substantial volume of freight movement and are characterised by some of the largest metropolitan areas in the world, with low population densities and limited transport infrastructure. Increasing urban congestion, coupled with increased levels of home deliveries from eCommerce, has created significant sustainability challenges for Australian urban freight systems. This worsening congestion is expected to cost Australian cities $37.3 billion by 2030 (Bureau of Infrastructure, 2015), while Australia's urban freight volumes are predicted to increase by up to 60% before 2040 (Transport and Infrastructure Council, 2021).

Australian governments are committed to reducing emissions with the aim of achieving net zero emissions. However, to attain environmental goals, new initiatives for transforming urban freight movement towards the use of more shared vehicles and storage facilities is required. This will require a radical transformation of existing urban freight systems into real-time based collaborative networks, which will subsequently reduce vehicle emissions, noise levels, and increase system efficiency.

There is a need to identify appropriate performance measures for urban freight networks considering a range of stakeholders and to combine them to provide measurable goals for designing more open and collaborative urban distribution systems. This paper describes a range of performance that can be used to assess the sustainability of urban distribution networks. Case studies involving retail swaps and retail distribution networks are presented.

2 Network performance measures

Vehicles performing urban distribution tasks typically undertake routes or tours visiting more than 1 customer before returning to the depot or distribution centre. Tonne kilometres (TKM) is a measure of freight demand, calculated as the product of the weight of goods transported by the distance between origins and destinations. There are a number of common measures of performance for urban distribution networks, including number of vehicles used by type and vehicles kilometres travelled by vehicles (VKT). However other network measures can provide useful information for addressing sustainability issues, including:
(i)   Efficiency (TKM/VKT) (ITF, 2018)
(ii) Load Factors (proportion of capacity of vehicles: weight or volume used over all legs on routes)(McKinnon, 2000)
(iii) Work (product of load carried by distance travelled for all legs on routes)
(iv) Laden (percentage of distance travelled with goods in vehicles on routes) (McKinnon, 2000)
(v)   MNAD (average number of arrivals and departures at receivers)

City Logistics considers that benefits and costs for various stakeholders including shippers, carriers, receivers, administrators and residents (Taniguchi and Thompson, 2015). Therefore, it is important to estimate vehicle operating costs for carriers as well as social and environmental costs. It is common to only consider the transport costs of distributing costs in urban freight networks. However, logistics costs incorporate storage and transport costs that include costs of transferring goods between vehicles.

2.1 Financial costs

Vehicle operating costs (VOC) for carriers are the financial costs of operating a delivery vehicle. Key components of VOC models include time based and distance-based costs. Common types of vehicles used include walkers with a trolley, cargo bikes, e-cargo bikes, vans, e-vans and trucks. The main attributes for determining the costs for each mode of transport are wages, purchase price, energy costs, vehicle registration costs, maintenance and repair costs. Usage rates directly impact the lifespan of each mode of transport.
Non-motorised vehicles such as walkers with trolleys as well as cargo bikes and e-cargo bikes typically have the lowest cost rates per hour with wages for walkers and rider constituting the majority of these. Vans are costlier to operate than e-vans when they have high use due to lower costs of electricity than diesel. Trucks are the most expensive to operate but have the greatest capacity. The differential in speeds between modes renders motorised vehicles more efficient when customer densities are low.

2.2 Social and Environmental Costs

Air quality impacts from urban distribution networks are influenced by the emissions produced per vehicle kilometre of freight vehicles as well as the vehicle kilometres travelled. Emissions per vehicle kilometre depends on characteristics of vehicles such as the mode of transport, type of fuel, vehicle engine emission standards and load capacity as well as the operating conditions such as travel speed and the weight of the goods being carried. Vehicle kilometres travelled depends on the nature of the distribution networks such as the location of depots and customers as well as the demand for goods to be transported. Rates ($/km) have been determined from public health and economic studies for estimating the air pollution, noise, accidents, congestion and infrastructure costs for vehicle types (Kin and Macharis, 2015).

2.3 Exposure metrics

A selection of thirty eight freight measurements and metrics was presented Hassall, (2008). Two types of measures were defined, Type 1: that deals with community observations of a growing freight task. This involves such metrics and truck numbers, truck lengths and truck trips that could be used to estimate accidents and freight noise. Type II metrics are compiled from another set of metrics notably those that impact more specifically on road infrastructure such as tonne-kilometres, gross vehicle mass, axle loadings and total tonnes carried.

2.4 Reliability

Generally speaking, an urban distribution system is more reliable when there are fewer product transfers. Unreliability can be estimated by the number of transfers made (Zhang and Thompson, 2021). The trade-off between VKT and the number of transfers was highlighted in Zhang and Thompson (2021). However, costs associated with transferring goods at stores were not considered apart from vehicle related costs.

2.5 Transfer and Storage Costs

Personnel and administration costs consisting of management expenses as well as operational staff costs were found to account for the majority of expenses at a urban consolidation centre (Aljohani and Thompson, 2021). Equipment and facility costs were shown to be significant. However, Sydney's Courier Hub has minimal personnel and administration costs (Stokoe, 2017). Forklift and hub lease costs should also be considered (Thompson et al., 2020).

3 Retail Swaps

A common problem in urban areas in swapping goods between retail stores where there is a small amount of goods moving between individual stores to satisfy customer requirements where there is stock shortages at some locations. This type of network is also common for deliveries between local post offices or B2B networks particularly with parcel lockers. Such networks are characterised by having multiple common origins and destinations requiring services operating from many to many nodes.
A simple network will be used to illustrate how various measures of performance can be used to assess common networks. This network is based on distributing 500kg of electrical goods

between retail shops. Transhipment is possible at each store and each van has a load capacity of 2000kg. A number of feasible distribution configurations have been defined (Figure 1).

(a) 5V4S (b) 4V1S (c) 4V4S
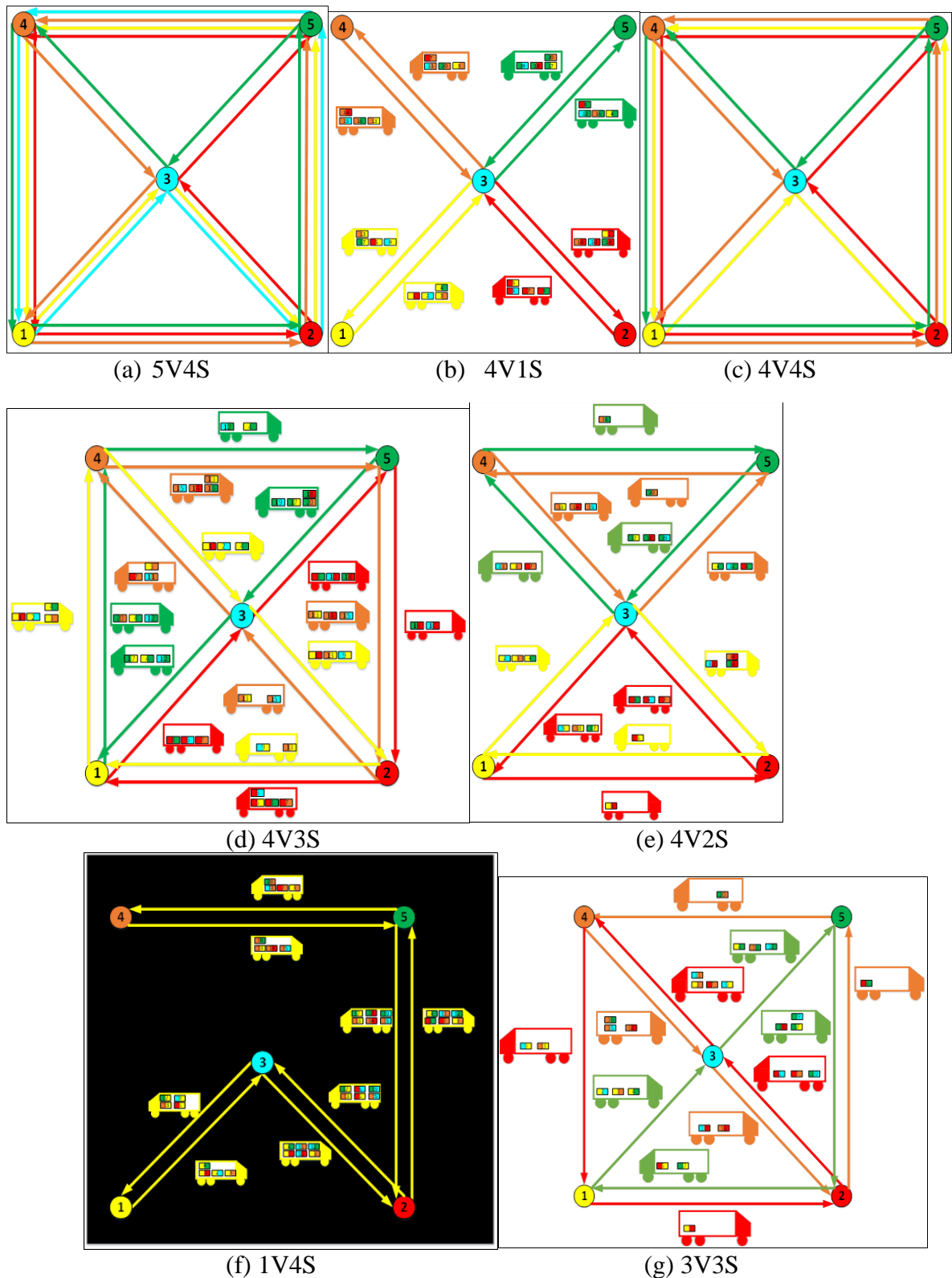
(d) 4V3S (e) 4V2S

(f) 1V4S (g) 3V3S

Figure 1 Swap Networks

For each configuration considered a number of performance measure were derived including Vehicle Kilometres of Travel (VKT), Network Efficiency (NE), Load Factor – weight (LF(w)), Number of Swaps (# Swaps), Number of Vehicles Used (NVs) and Mean Number of Arrivals and Departures at stores (MNAD). Figure 2 illustrates the relative performance of the network configurations for each criteria.
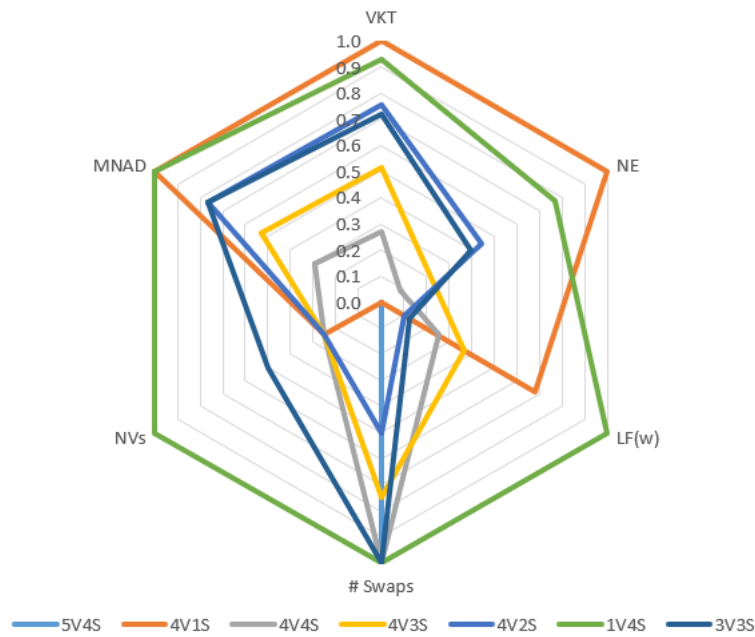
Figure 2 Performance of Network Configurations

Criteria were assigned to 3 key stakeholders, carriers, receivers and administrators (Table 1). Several weightings for the stakeholders were considered to identify the performance of the network configurations (Table 2).

Table 1 Stakeholders and Criteria

Stakeholder	Criteria	
Carriers	Load Factor – weight (LF(w))	Number of Vehicles (NVs)
Receivers	# Swaps	Mean Number of Arrivals and Departures (MNAD)
Administrators	Vehicle Kilometres of Travel (VKT)	Network Efficiency (NE)

Table 2 Rankings of Network Configurations considering stakeholders

Stakeholder weighting	5V4S	4V1S	4V4S	4V3S	4V2S	1V4S	3V3S
Uniform	6	2	5	5	4	**1**	3
Administrator only	6	**1**	5	4	3	2	3
Carrier only	5	2	3	3	4	**1**	3

The single vehicle network configuration has the highest ranking when stakeholders and their assigned criteria are consider equal. However, when administrators are only considered, 4 vehicles visiting 1 store is the highest ranking network. The network with all stores operating their own vehicle (5V4S) consistently achieves a low ranking.

4 Retail Distribution Networks

Distribution systems in many metropolitan regions are characterised by shippers operating their own vehicle fleets, distributing only their goods to common customers on a regular basis. Within specific sectors such as retail there is an opportunity to combine distribution networks to reduce the distance travelled by delivery vehicles from warehouses to major retail outlets. This can result in substantial savings in distances travelled by vehicles leading to reduction in emissions from freight vehicles.

Suppliers who are own account or not-for profit carriers can operate collaborative distribution networks by sharing vehicles and warehouse space. This involves suppliers integrating their networks with other suppliers and carriers requiring coordination.

Distributing goods in a large metropolitan area such as Melbourne is challenging as there are typically a low density of customers, with some customers being located a considerable distance (over 50 kilometres) from warehouses or distribution centres. The benefits of collaborative urban freight networks can be illustrated by considering how several suppliers distribute goods to common retail outlets within the metropolitan area of Melbourne. When suppliers operate independent distribution networks, daily routes can be optimised to service stores in each area (Figure 3).

Figure 3 Independent Network Routes

In urban areas the distances involved in TKM and actual distances are quite different due (Figures 4 & 5; Table 3).
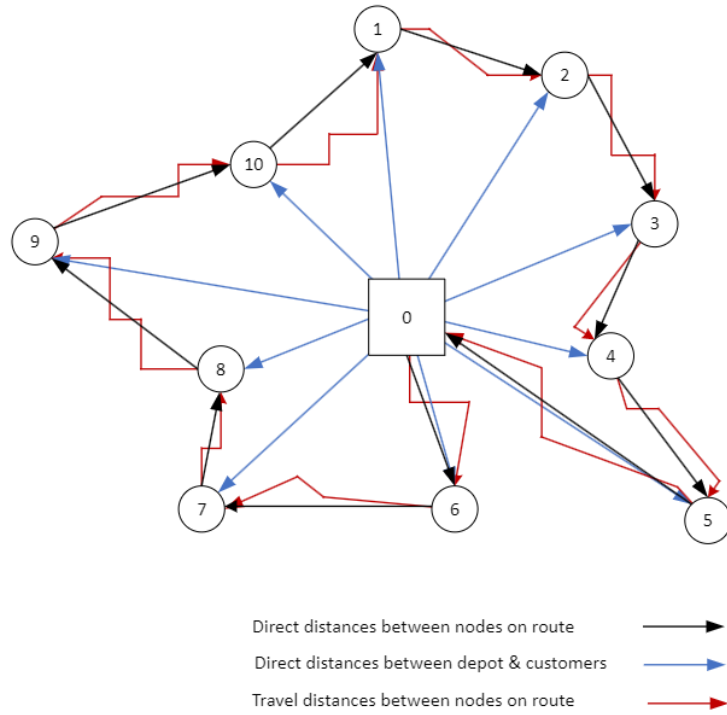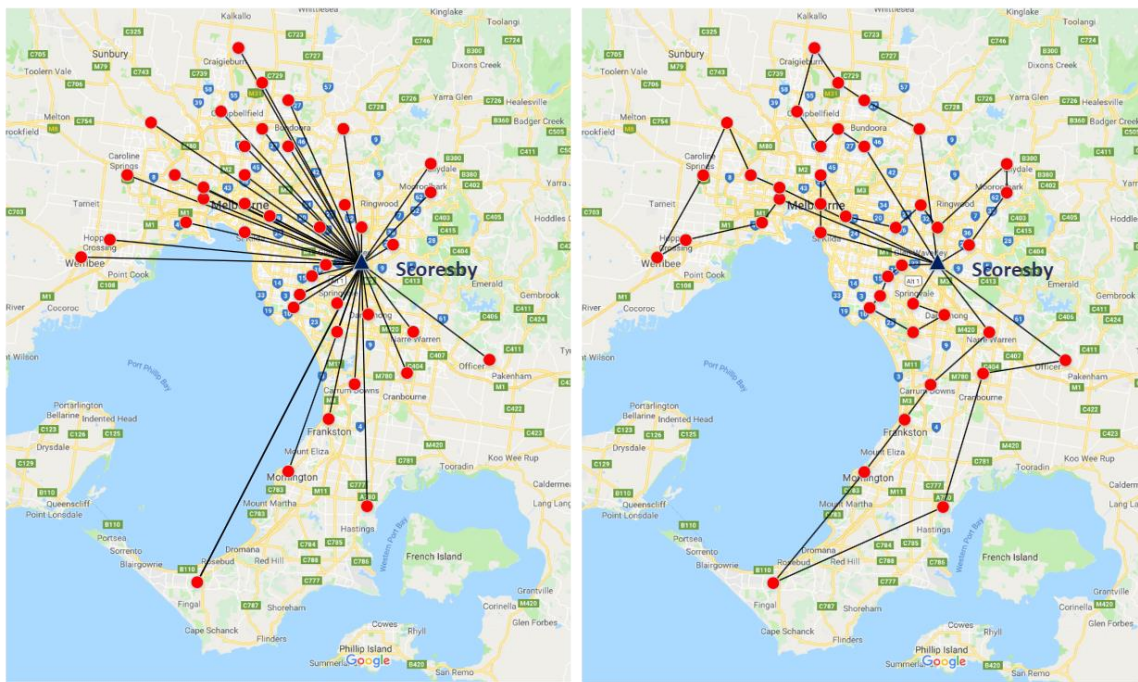
Figure 4 Distances in urban distribution networks

(a) Direct Distances   (b) Vehicle Routes

Figure 5 TKM and Vehicle Routes from the Scoresby warehouse

Table 3 Independent Network Performance

	Scoresby Supplier	All Suppliers
Direct Distance (from Warehouse to all stores)	858.4 km	4449.6 km
Tonne Kilometres (from Warehouse to all stores)	175.9 t km	800.1 t km
Total Travel Distance (from Warehouse on vehicle routes to all stores)	568.6 km	2899.5 km
Network Efficiency	0.31 t	0.28 t

With the collaborative network, suppliers are allocated to areas (Figure 6). One supplier is selected for the location to exchange goods between suppliers where goods with destinations near other suppliers are transferred to these suppliers. Specialised optimisation procedures were developed to determine the best supplier to transfer the goods to design the collaborative distribution network. The shared network allows delivery routes from suppliers to be developed with higher utilisation and substantially lower vehicle travel distances. A sizeable reduction (77.9%) in the distance travelled were estimated for a retail distribution network using existing warehouses and delivery vehicles. This would lead to a similar reduction in emissions from freight vehicles. Shorter local routes from warehouses to customers can be more suitable for electric trucks or vans. The collaborative network has a significantly higher network efficiency (1.25) compared with the independent networks (0.28).

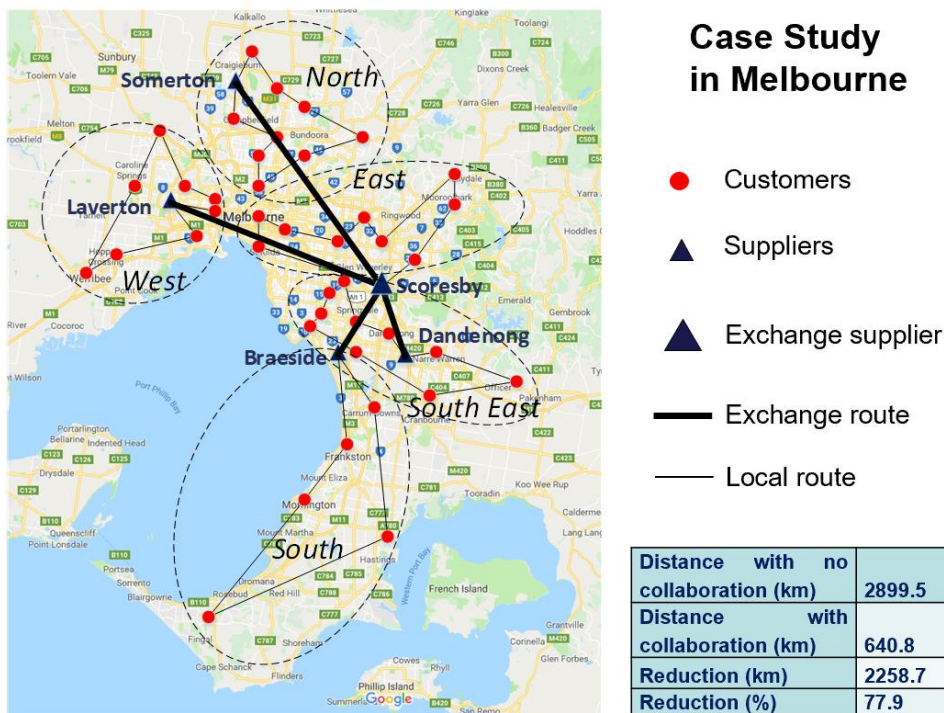| Distance with no collaboration (km)	2899.5
Distance with collaboration (km)	640.8
Reduction (km)	2258.7
Reduction (%)	77.9

Figure 6 Collaborative Retail Distribution Networks

5 Conclusions

The distribution of goods within metropolitan areas is currently dominated by independent networks that are designed to minimise the transport costs for individual networks. Integrating networks can dramatically reduce transport costs but leads to increased transfer and storage

costs. This paper highlights the need to consider a range of stakeholders and performance measures to promote more collaborative distribution networks.

A set of network performance measures relating to various stakeholders were defined. The relative performance of traditional and PI networks was illustrated. The need to consider transfer and storage costs in transformed networks was demonstrated. Sharing warehouses and storage space within retail stores would require additional resources to manage facilities and would be more disruptive to shippers and receivers.

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Dynamic resource deployment in hyperconnected parcel logistic hub networks

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Abstract: With the development of e-commerce, one of the major challenges for many parcel logistics companies has revealed to be designing reliable and flexible scheduling and deployment approaches and algorithms to meet uncertainties of parcel arrivals and resource availability in logistic hubs. In this paper, we want to present models to spatiotemporally adjust the available resource, like workforce and robots, across hyperconnected logistic hub networks using a rolling horizon approach. In most traditional parcel logistic hubs, workers are hired to enable the sorting, consolidation, transshipment, and crossdocking of parcels, and most resource scheduling is periodic (e.g., daily) and limited to single facility, thus the number of required resources in each hub is constrained to meet the peak demand with high variance. We here propose dynamic resource scheduling and deployment mechanisms, that are fed with updated data with sensors and dynamically updated parcel arrival predictions at hubs.

Keywords: Physical Internet; Hyperconnected Parcel Logistic Hubs; Dynamic Resource deployment; Dynamic Workforce Scheduling.

1. Introduction

The increasing global urbanization and the surge of e-commerce underline the necessity for inventive, sustainable, and economically viable strategies in designing, managing, and operating urban logistics systems. Resource allocation in parcel logistic hubs refers to the strategic assignment and scheduling of resources like workforces, robots, and equipment in the logistic networks to achieve the desired service level in the most efficient and effective manner possible. Recently, the COVID-19 pandemic also reveals the significance of designing reliable and flexible resource deployment approaches with swift adjustments for handling the uncertainties and dynamic conditions of unpredictable parcel delivery demands as well as resources availability in logistic hubs.

The shift scheduling problem can be divided into two broad categories based on the type of workload they consider: task-coverage problems and workload-coverage problems [1]. The parcel hub scheduling problem (PHSP) is a scheduling problem that occurs in the parcel delivery industry. Those problems involve allocating resources over time to perform tasks as part of a process, such as sorting, unloading inbound trucks and loading outbound trucks [2]. Smart supply chains incorporate more objects embedded with sensors and better communication technology, along with intelligent decision making and automation capabilities, offer opportunities for cost reduction and improved efficiency [3]. The technologies allow logistics companies to monitor their resources in real-time, detect potential issues early, and make data-driven decisions to optimize resource allocation. Moreover, picking robots, also

known as autonomous mobile robots (AMRs), are recently used in the logistic hubs to enhance efficiency, minimize errors, and boost productivity. Since these robots do not have the same physical and mental limitations as humans and can be programmed to respond quickly to real-time changes, they create an opportunity for dynamic resource scheduling and allocation problems. In the past few decades, dynamic scheduling problems have also attracted widespread attention in the literature [4,5,6], including completely reactive scheduling, predictive-reactive scheduling, and robust scheduling problems, which focus on making timely decisions considering real-time system status with uncertainties.

The Physical Internet (PI) was introduced by Montreuil [7] as 'an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols', and thus defines a new opportunity for supply chain design and operations, enabling seamless open asset sharing and flow consolidation [8]. In the context of urban logistics, the PI is realized through a multi-tier urban logistics web that is composed of hyperconnected logistic hubs. These hubs enable the sorting, consolidation, transshipment, and crossdocking of goods. The multi-tier structure consists of access hubs that interconnect unit zones, local hubs that interconnect local cells, and gateway hubs that interconnect urban areas [9,10]. This structure also presents an opportunity for moving workers across these hubs. Some of the hubs are in proximity but on different planes in the network, resulting in different arrival patterns and workforce demand peaks throughout the day. For example, the arrival time of parcels at access hubs depends on customers' pick-up requirements, while the arrival time of parcels at gateway hubs is dependent on transport truck schedules, subway, or train timetables.

In this paper, we propose a dynamic resource deployment system in parcel logistic hubs to match predicted demand with shifts in real-time using heuristic rules to respond quickly to changes of predicted arrivals at hubs and provide guidance for centralized resource assignment. Shifts are scheduled to cover the predicted workloads at hubs and online scheduling problems are solved dynamically based on real-time status including the assigned shifts as well as future tasks. We also rely on a rolling horizon approach to address the presence of uncertainty, which decompose the effect of lookahead into the informational and a processual component [11]. A reactive scheduling method that iteratively solves the deterministic problem by moving forward the optimization horizon in every iteration is proposed; assuming that the status of the system is updated as soon as the different uncertain parameters become known, the schedule can be optimized for the new resulting scenario [12]. We believe that this is the first work that shows the feasibility, efficiency and reliability of the proposed dynamic resource scheduling and allocation system for hyperconnected logistics hubs considering parcels' dynamically predicted arrival time and maximum dwell time in real-world logistics networks.

2. Methodology

2.1 Model preparatory techniques

2.1.1 Demand analysis among multi-tier parcel logistic hubs

To share resources spatial-temporarily in hyperconnected logistics hub networks, data analysis on daily workloads is necessary to identify a set of hubs, which are geographically close and easily accessible to each other, but differ in their demand patterns over time. Methods such as covariance matrix and correlation matrix can be utilized to examine the similarity among several time series demands. Both matrices provide information on the relationships between different time series, with the covariance matrix showing the level of covariance and the correlation matrix showing the strength and direction of the linear relationship. Positive values in the matrices indicate that the time series tend to move together, while negative values indicate that they tend to move in opposite directions. As shown in Figure 1, we select three hubs whose

time series demands have comparatively small correlations, which means it is possible that resources could be shared among them over time to perform tasks with demand peaks.
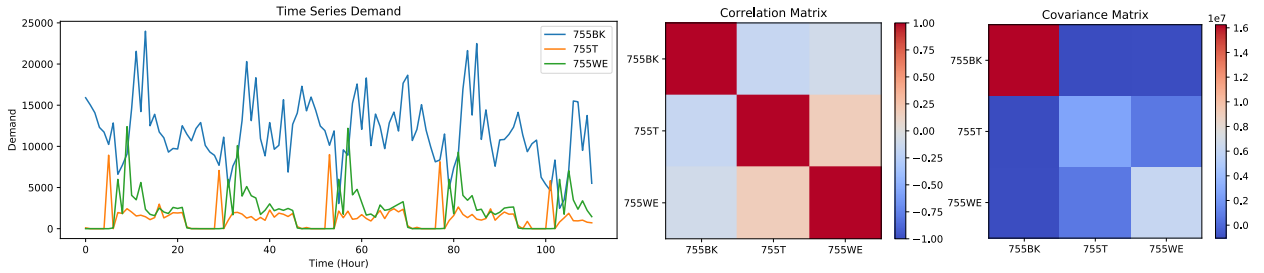

Figure 1: Demand analysis for three hubs in the network

2.1.2 Shift pattern generation

We assume that resources in the system can be classified into four states, namely "in work," "in idle," "in transit," and "off duty" to address the issue of resource allocation in hyperconnected parcel logistic hubs. A combination of the four states, each with a starting and ending time point, constitutes a shift pattern. Different resources may have distinct limitations for shifting patterns, such as maximum working time, idle time, or total time on duty. For example, the workforce may be restricted to an 8-hour workday, while picking robots require recharging after a full working shift. As a result, potential shifting patterns within the planning horizon can be generated for each resource type based on their specific time constraints.

Shift scheduling patterns generation offers several advantages. Firstly, it makes the proposed allocation system flexible enough to accommodate different types of resources. Secondly, it saves time for the subsequent algorithms.

2.2 Dynamic resource deployment and scheduling assignment system

We assume that workload predictions for hubs within hyperconnected logistic networks are provided and can be updated every ϵ minutes. Due to limited capabilities in solving scheduling problems for large logistics networks that contain hundreds of hubs, we propose a reactive scheduling model utilizing a rolling horizon approach to iteratively generate continuous shifts and shift combinations. Additionally, unlike traditional scheduling problems for single logistic hubs, we consider the possibility of labor working sequentially at multiple nearby hubs during daily shifts. The flowchart depicting our developed methodology can be found in Figure 2. Our dynamic resource scheduling and deployment system offers two key benefits: shift assignments within hubs are made while considering maximum dwell time, and resource deployment across hubs is made while considering traveling costs. The overall objective is to cover hub workloads while minimizing costs and associated penalties such as late parcels.
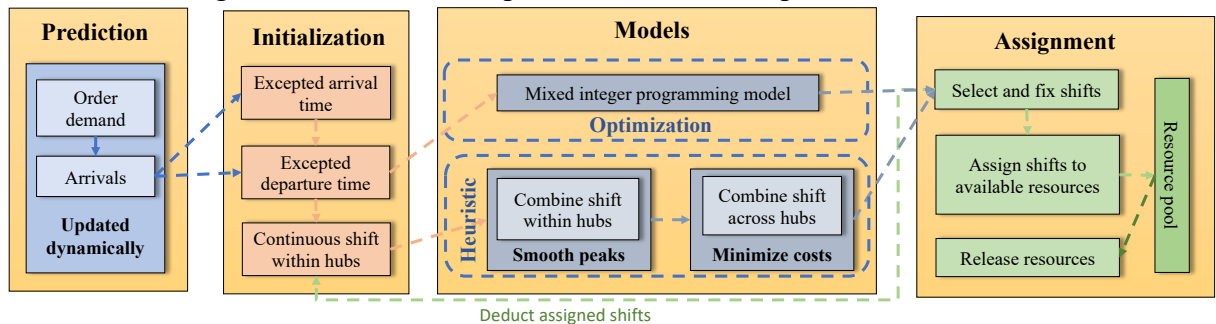

Figure 2: Flowchart of the developed dynamic resource scheduling and deployment system

2.2.1 Smoothing demand peaks

The dwell time of parcels at logistics hubs refers to the amount of time that a package or shipment spends at a hub or sorting center before it is dispatched to its next destination. The duration of this dwell time can vary depending on several factors, including the shipping service selected, the schedule of the following transportation method and the size and weight of the package. The duration of parcels' dwell time at a logistic hub is closely linked to the level of demand and the allocation of resources at the facility. Essentially, if the departure time for parcels is predetermined by the chosen service level, it may be possible to optimize resource usage by prioritizing emergency shipments and handling less urgent packages later.

An Integer Programming (IP) model can be used to demonstrate the idea. The optimization problem involves allocating resources to shift scheduling patterns in order to reduce overall scheduling costs and minimize lateness penalties. The objective is to flatten demand peaks, considering the parcels' dwell time at logistic hubs. Let I indicates the set of resources, S indicates the set of all possible shifting patterns and T indicates the set of time units in the planning horizon. For every shift pattern $s \in S$, according to the number of working and waiting time units in the shift pattern, we define C_s as the payment if a resource be assigned the shift pattern s. Specially, a shift with no working time units would cost 0. We define $x_{i,s}$ equals to 1 if the resource i is assigned to the shift pattern s, and 0 otherwise. Integer variables y_t and z_t is defined to be the number of parcels being processed and late at time unit t. We also assume that parcels' dwell time at the hub is pre-decided and could not be changed, therefore, we could calculate the number of parcels need departure the hub according to their arrival time, we define A_t and D_t to be the number of parcels arrive and need to depart the hub at time unit t. We assume parcels could be processed by a resource with the working efficiency λ. Then, the problem can be formulated as follows:

$$Min \sum_i \sum_s C_s x_{i,s} + +\delta \sum_t z_t \tag{1}$$

s.t.

$$\sum_s x_{i,s} = 1 \qquad \forall i \in I \tag{2}$$

$$y_t \leq \lambda \times \sum_{s:t \in Q_s} x_{i,s} \qquad \forall t \in T \tag{3}$$

$$\sum_{0 \leq c \leq t} y_c \leq \sum_{0 \leq c \leq t} A_c \qquad \forall t \in T \tag{4}$$

$$z_t \geq \sum_{0 \leq c \leq t} y_c - \sum_{0 \leq c \leq t} D_c \qquad \forall t \in T \tag{5}$$

Objective (1) minimize the sum of total shifting cost and the lateness penalty. Constraint (2) ensures that every resource is assigned to one shift pattern while constraints (3) – (5) are put in place to guarantee that the number of processed parcels never exceeds the number of arrived parcels at any given time, and that the number of late parcels equals the number of parcels that need to depart minus the number of processed parcels. This optimization model works well within one hub but could not incorporate shared resources among multiple hubs. Also, the optimization model could not return a near optimal solution for a large-scale resource allocation problem of hyperconnected logistic networks within limited time.

2.2.2 Heuristic algorithms for large-scale multi-hub resource allocations

Our approach for optimizing workforce allocation and smoothing demand peaks involves using dynamically updated workload predictions to initialize shifts with the maximum possible length at each hub. Algorithm 1 is used to estimate resource demand in each time unit, based on predicted parcel arrivals and assumed working efficiency. The list $x = [x_0, x_1, x_2, \dots, x_n]$

indicates current the labor demand in each time unit that need to be assigned shift patterns. Additionally, we select the most cost-effective shift scheduling pattern components with possibly maximum working time during this step.

Algorithm 1: Initialization with labor demand and efficient shifts

Input: a list of integers x representing resource demand, the maximum working hour ρ, the length of the list n

Output: a list of tuples representing initialized shifts

$start \leftarrow 0$;
$shifts \leftarrow \emptyset$;
while $start < n$ **do**
  if $x[start] = 0$ **then**
    $start \leftarrow start + 1$;
  end
  $x[start] \leftarrow x[start] - 1$;
  $end \leftarrow start + 1$;
  /* find the shift with the maximum possible length*/
  while $end < n$ *and* $x[end] > 0$ *and* $end - start \leq \rho$ **do**
    $x[end] \leftarrow x[end] - 1$;
    $end \leftarrow end + 1$;
    $shifts \leftarrow shifts \cup \{(start, end)\}$;
  end
  $start \leftarrow end$;
end
return $shifts$;

Our model assumes a specified maximum dwell time ζ for each parcel at the hub, during which it can be processed and prepared for departure. This allows us to combine shorter shifts into longer ones, without resulting in workforce demand peaks. To accomplish this, we use Algorithm 2 is used to identify potential scheduling pattern components based on demand predictions, and utilize the dwell time to smooth out demand peaks, so as to find the minimized number of shifts and maximized shift total length.

Algorithm 2: Within Hubs: Combine Scheduling Pattern Components with Minimized Number of Shifts and Maximized Shift Length

Input: a list of integers x representing resource demand, the maximum working hour ρ, a list of tuples representing possible shifts $shifts$

Output: a list of tuples representing combined shifts

$Combined \leftarrow \emptyset$;
for $shift$ *in* $shifts$ **do**
  if $shift[end] - shift[start] = \rho$ **then**
    $Combined$.append($shift$);
    $x[shift[start] : shift[end]] \leftarrow x[shift[start] : shift[end]] - 1$;
  end
end
$start \leftarrow 0$;
while $start < n$ **do**
  if $x[start] = 0$ **then**
    $start \leftarrow start + 1$;
    continue;
  end
  $end \leftarrow start + 1$;
  while $end < n$ *and* $end - start < \rho$ **do**
    Find next non-zero hour and add to shift;
    if $x[end] = 0$ *and* $x[end - 1] \neq 0$ **then**
      /* **smooth labor demand by moving count to next time unit** */;
      Move count from $end - 1$ to end;
    end
    $end \leftarrow end + 1$;
  end
  $Combined \leftarrow Combined \cup \{shifts\}$;
  $x[shift[start] : shift[end]] \leftarrow x[shift[start] : shift[end]] - 1$;
  $start \leftarrow end$;
end
return $Combined$;

Algorithm 3 is utilized to merge shifts across nearby hubs, considering both transportation modes and cost. The algorithm operates by considering shifting components at different hubs and greedily combining them, provided that their shift hours do not overlap, and transportation time falls within the specified requirements. We continue merging shifts between hubs until the cost of traveling becomes greater than the cost of utilizing a new resource.

Algorithm 3: Across hubs: Combine Scheduling Pattern Components with Minimized Travelling Cost

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Input: a list of hub pairs H, the maximum working hour ρ
Output: a list of tuples representing combined shifts

$Combined \leftarrow \emptyset$;
for $hub\ in\ H$ **do**
    for $shifts\ in\ hub$ **do**
        if $shift\ hours\ do\ not\ overlap\ and\ moving\ time \leq shifts\ gap \leq$
        $maximum\ gap\ and\ total\ working\ time \leq \rho$ **then**
            $Combined \leftarrow Combined \cup \{shifts\}$;
            Remove $shifts$ from hub;
        end
    end
end
return $Combined$;

Finally, we select and assign shift patterns to available candidates from the resource pool, with the option to incorporate individual preferences. When their resting or maintenance shifts are complete, resources are released back into the pool. Further details can be found in Algorithm 4.

Algorithm 4: Assigning Scheduling Patterns to Resources

Input: a list of tuples representing combined shifts, a threshold γ, a pool of available workers
Output: a list of tuples representing assigned shifts

$Assigned \leftarrow \emptyset$;
for $shift\ in\ Combined$ **do**
    if $Value(shift) \geq \gamma$ **then**
        Assign an available worker in the pool to $shift$ according to preference if possible;
        $Assigned \leftarrow Assigned \cup \{shift\}$;
    end
end
return $Assigned$;

2.3 Rolling horizon approach

To address the uncertainty present in demand prediction, a rolling horizon approach is employed. This involves iteratively assigning cheap and efficient shifts to workers by advancing the planning horizon with updated demand predictions at each iteration. The selection of shifts within each planning horizon is crucial, as fixing shifts too early may result in overstaffing in the presence of significant demand prediction intervals, while selecting shifts too late may lead to high emergency penalties and leave insufficient time for crew planning. Therefore, we evaluate shifts using the value function outlined below:

$$Value = \alpha \times \frac{\text{Duration threshold } \tau \text{ to fix a shift}}{\text{Shift start time} - \text{Current time } t} + \beta \times \frac{\text{Working time}}{\text{Maximum working time } \rho} + \gamma \times \frac{\text{Working time}}{\text{Resting time}}$$
$$\alpha + \beta + \gamma = 1$$

The rolling horizon approach is employed to iteratively assign efficient and cost-effective shifts to workers using updated demand predictions. To evaluate shifts, a value function is utilized, and a continuous shift or combination of shifts with a value greater than a threshold δ ($0 \leq \delta \leq$

1) is fixed and assigned to an available worker. The parameters α, β, γ, δ and τ can be adjusted to minimize costs under different prediction scenarios. After a resource's assigned shifts are finished, they are released back to the workforce pool and become available for their next day shifts. Additionally, as workload predictions are updated and shifts are assigned, the corresponding workload is subtracted from the new predictions to be used in the next planning horizon.

3. Experimental results

To assess the benefits of our proposed heuristic model for shared resource allocation in the hyperconnected logistic networks, we also conduct experiments using logistics networks from the logistics company in China, leveraging an urban logistics simulator to dynamically collect parcels' arrivals at hyperconnected hubs. In our experiments, 52 local hubs and gateway hubs from the company's logistics networks in Shenzhen, China are included. We set the planning horizon to be 24 hours and there exist 1,173,253 parcel arrivals at hubs during a day. We assume the maximum dwell time $\zeta = 1$ hour and the working efficiency $\mu = 150$ parcels/hour, and our models to be run every $\epsilon = 60$ minutes utilizing updated predictive results. It takes about a minute to run the methodology for a whole day with the rolling horizons.

We consider various types of resources that can be utilized in hyperconnected logistics networks, including human workforce and picking robots. The key distinguishing factor among them is the maximum allowable working duration during a day. Specifically, contracted employees are restricted to working for a maximum of 8 hours, whereas robots can operate continuously until their batteries are depleted. Hence, we categorize resources into three types in the experiment, each with a distinct daily working hour limit of 8, 15, and 22 hours, respectively.

Since the prediction of parcels' arrival time at hubs can be dynamically improved as they approach to the hubs, in the experiment we assume that the prediction of number of arrivals p of time t_1 conducted at time t_0 can be written as

$$p = C * e^{r*(t_1 - t_0)}$$

where $r \sim normal[\mu, \sigma^2]$ and C is the actual number of arrivals at time t_1. μ and σ is set to be 0 and 0.01 in the simulation to generate prediction scenarios. The parameters to fix combined shifts during the rolling horizon are tuned like $\alpha = 0.4$, $\beta = 0.3$, $\gamma = 0.3$, $\delta = 0.9$ and $\tau = 4$. As these influence performance, different settings may be further tested.

3.1 Scheduling and allocation costs

In the proposed dynamic resource deployment and scheduling assignment system, the costs we consider include hiring cost, working cost, waiting cost and transportation cost if resources move from one hub to another hub. We also take lateness penalty into consideration if parcels could not be processed before their departure deadline. As mentioned in section 2.3.1, we utilize parcels' maximum dwell time to smooth demand peaks and reduce resource allocation costs. We also proposed two methods for resource allocation within hubs, including one Integer Programming model and heuristic algorithms 1&2. Figure 3 shows the allocation cost comparisons for resources with the 8-hour maximum daily working hour limit using optimization and heuristic methods. As shown in Figure 3(a), the heuristic algorithms can achieve near-optimal solution but takes less time for allocations given arrivals of one selected large gateway hub from the logistic company.

Also, given the scheduling and allocation results utilizing updated predictive parcel arrivals of the logistic networks, we could reduce total allocation costs, especially hiring cost, by allowing shared resources moving among the 52 local hubs and gateway hubs, as shown in Figure 3(b).
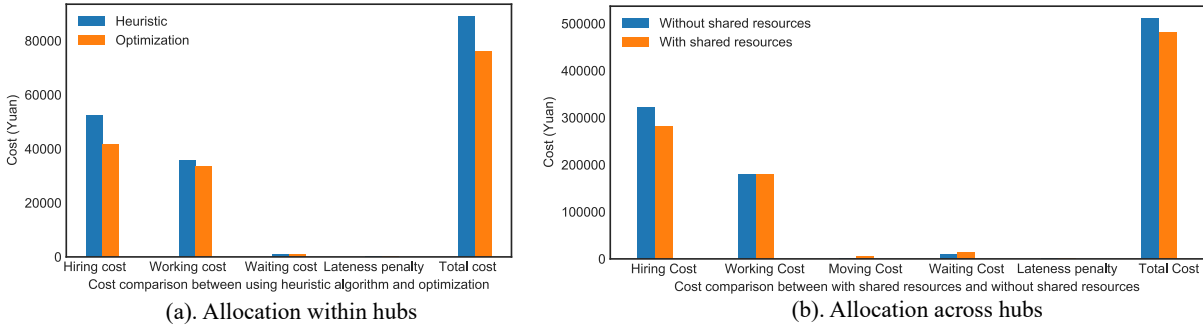

(a). Allocation within hubs

(b). Allocation across hubs

Figure 3: Cost comparisons

3.2 Parcel arrivals and resources assigned at hubs

To illustrate the dynamic assignment of shifts and resource allocations based on workload prediction, figures displaying the evolution of parcel arrivals, and the number of working and resting resources at one gateway hub and one local hub throughout a day are provided. As depicted in Figure 4, the actual number of parcels arrived at the hubs is represented by black lines, while the total number of resources at hubs is depicted in green lines, with blue and orange dashed lines indicating working and resting resources, respectively. Also, we compare two types of resources with 8-hour working limit (workforces) and 15-hour working limit (robots), shown in Figure 4(a) and 4(b) respectively. We can see that the number of resources at hubs follows a similar pattern to that of parcel arrivals, but the arrival peaks are flattened. Also, resources tend to take rest during arrival valleys. Moreover, the working hour limit does not have large influence on the number of resources assigned at hubs, but resources with larger working limit tend to have more resting time at hubs.
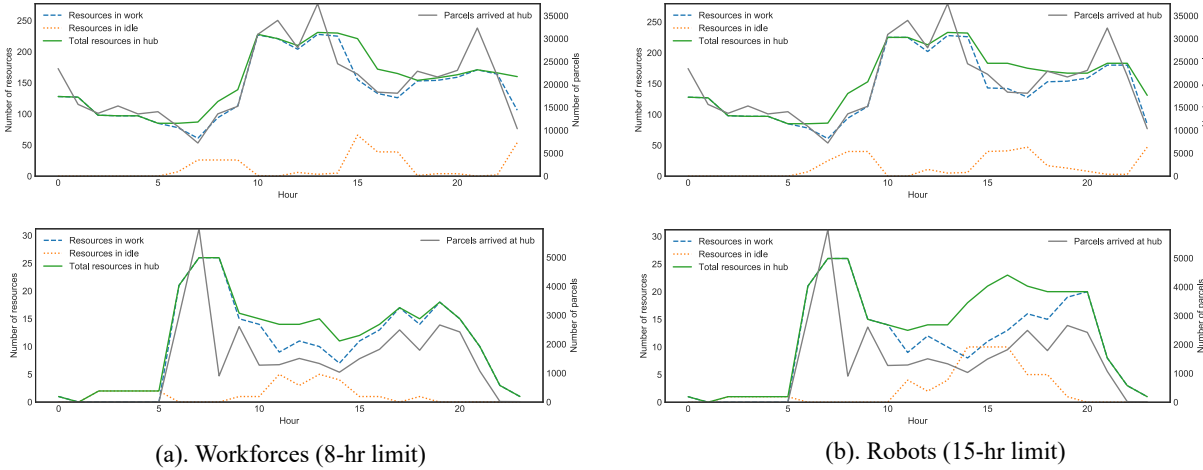

(a). Workforces (8-hr limit)

(b). Robots (15-hr limit)

Figure 4: Parcels arrived and resources assigned at one larger gateway hubs (above) and one smaller local hubs (bottom)

3.3 Complexity of assigned shifts

In this section, we show the complexity of assigned shifts to workforce and robots with 8 working hours and 15 working hours limit. By allowing movements across hubs, we assign 9.9% of total shifts for workers and 18.5% of total shifts for robots moving across nearby hubs, as shown in Figure 5. In addition, even though most of the shifts assigned within hubs have maximum allowed duration, allowing movements across hubs improve the average working

duration by combining short shifts into a long shift. The comparison of the number of hours in daily of shifts between with and without movements across hubs is also shown in Figure 5.
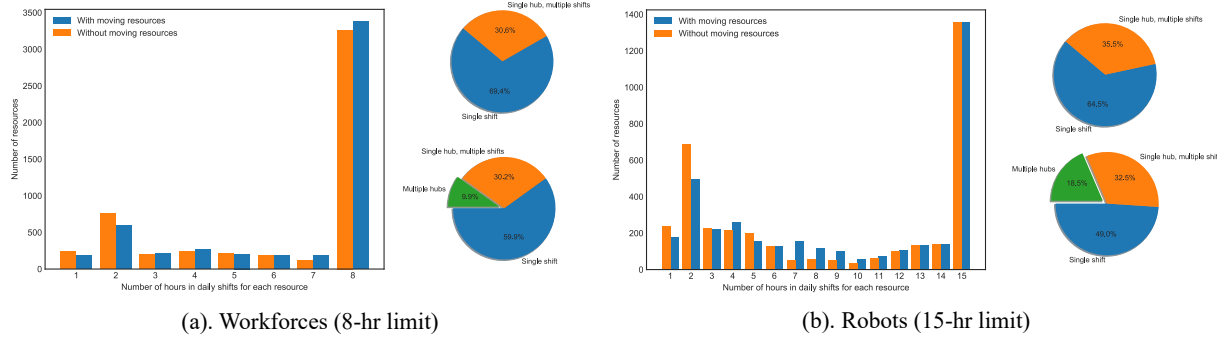

(a). Workforces (8-hr limit)   (b). Robots (15-hr limit)

Figure 5: Complexity of assigned shifts

3.4   Resources in hub and flow across hubs

We also plot the locations of hubs as well as how workers appear and move across hubs during a day. As shown in Figure 6, the size of the circles indicates the number of shifts assigned in each hub while the width of lines signifies the number of workers transported from one hub to another hub every 12 hours with 8, 15 and 22 working hour limit. The three large circles in each picture mean that many shifts are assigned to the three gateway hubs to cover comparatively large quantities of arrivals, many resources move between gateway hubs and local hubs from 12 AM to 12 PM because of their different parcel arrival patterns during this time span. Also, more resources tend to move from one hub to another hub with larger working hour limit.

We have also visualized the hub locations and resource movements throughout a day with 8, 15, and 22 working hour limits. Figure 4 illustrates the number of shifts assigned in each hub with circle size and the number of workers transported from one hub to another every 12 hours using the line width. The three larger circles in each image correspond to the three gateway hubs, where more shifts are assigned to cover larger quantities of arrivals. The workers are observed to move between gateway hubs and local hubs from 12 AM to 12 PM due to the different parcel arrival patterns during this time frame. Additionally, there is a higher frequency of worker movement between hubs with larger working hour limits.
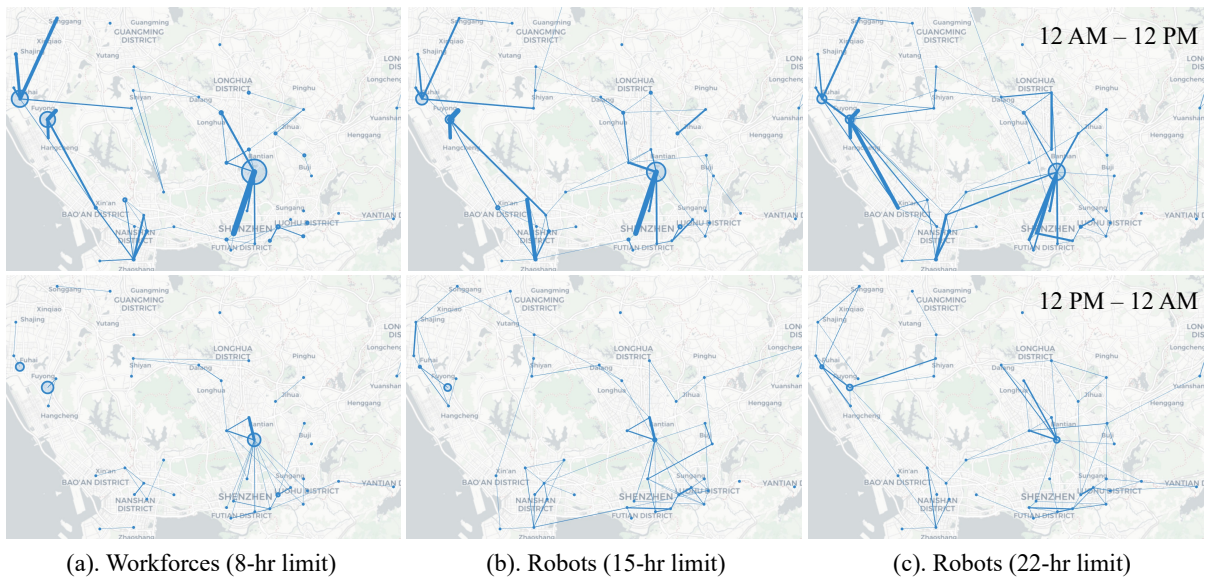

(a). Workforces (8-hr limit)   (b). Robots (15-hr limit)   (c). Robots (22-hr limit)

Figure 6: Resources in hubs and flow across hubs

4.   Conclusion and Future Research

In this paper, we propose a novel reactive scheduling and allocation model with rolling horizons for efficient and reliable resource management in the hyperconnected logistic hubs. First, the paper demonstrates the feasibility and cost-effectiveness of incorporating mobile resources among nearby hubs, particularly for logistics networks operating in urban regions. Second, the paper highlights the impact of shared mobile resources with different daily working limit. Lastly, the paper highlights the usefulness of the proposed rolling horizon method, which utilizes updated predictions to manage workload uncertainty.

In addition to the resources allocated for in-hub activities, the scheduling and allocation system could also incorporate resources for transporting goods across hubs, such as trucks, trailers and containers. Moreover, to enhance the overall performance and swiftly respond to dynamic situations, future research may involve exploring diverse predictive scenarios for dynamic decision-making and employing stochastic optimization models for robust scheduling that combines long-term planning with short-term adjustments. The paper also suggests investigating sequential decision-making to enable dependable and informed decision-making under stochastic conditions.

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PI Containers: Assessment of Functions and Development from an Engineering Design Related Perspective

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Abstract:

The idea of containerizing goods is a central component of the Physical Internet philosophy, as this containerization serves to abstract and standardize goods and shipments. This approach promises to simplify the handling of shipments on the one hand and deliver shipments more efficiently throughout the transport network.

In the present work, scientific publications were evaluated according to the terms Physical Internet, PI Container and containerization. Out of almost 300 examined scientific publications, more than 25 could be identified that had a strong focus on the topics of PI Containers and containerization. These identified articles were methodically compared by categorizing them according to aspects highlighting the technical view on the current state of development of PI containers.

Our research shows that over the past 12 years, just a few cases were documented where specific engineering design solutions of a PI container were presented and tested in real-life applications. Thus, we conclude that further research into the technical design of PI Containers is needed to identify use cases where the deployment of PI Containers has a significant positive impact, is accepted by users, and is accessible under economic, ecological, and technical aspects.

Keywords: *Containerization, Physical Internet, Physical Internet Container, Transportation, modularization*

Conference Topic(s): *interconnected freight transport; material handling; Modularization; PI fundamentals and constituents; PI impacts; PI implementation; vehicles and transshipment technologies.*

Physical Internet Roadmap (Link): Select the most relevant area for your paper: ☐ *PI Nodes,* ☒ *PI Networks,* ☒ *System of Logistics Networks,* ☒ *Access and Adoption,* ☐ *Governance.*

1 Introduction

The idea of containerizing goods is a central component of the Physical Internet philosophy, as this containerization serves as a tool to standardize goods and shipments. This approach promises to simplify the handling of freight on the one hand and to deliver shipments more efficiently throughout the transport network on the other. (Montreuil, 2011)

Therefore, it is unavoidable that, in future scenarios, special PI Containers need to be developed and used within the PI network. In the past, PI Containers appeared in many publications and had many shapes and forms in different scientific works. However, most of these studies had one thing in common: they generally assume that the boxes already exist in real life. The actual scientific investigations, however, are mostly virtual, that is, simulation-based. In these publications, the PI Containers served as a model for simulation or even exist just as a mathematical model or in visualization. Except for fewer exceptions, such as the MODULUSHCA project, where a PI Container was designed, built and tested in real-life scenarios. Most of the research on PI container behaviour has been conducted virtually, using mathematical models on a simulation basis since the introduction of the Physical Internet Idea in 2011.

The MODULUSHCA project seems to be one of few works and scientific publications that let the PI Container leave the virtual world. (Landschützer et al., 2015) Designing, building and testing a real-life PI Container bring new challenges that must be considered. Physical properties, such as mass and the volume of the PI Container, the strength of the material, as well as costs, ecological benefits and operational factors, e.g. the complex functions and the usability, may not be crucial aspects for simulation studies according to routing or packing problems. Still, for real-life PI Containers, going through transport networks, they are and will be decisive for whether PI Containers can sustain in real-life scenarios and transport networks..

As containerization is one of the crucial pillars of the Physical Internet, this paper will address the evolution of PI Containers from the very beginning of the Physical Internet Philosophy in 2011 to the present, from an engineering design-related perspective, including the analysis of how the design of PI Containers has evolved. The other aspect of this paper will be to show the number of projects and papers dealing with the practical application and introduction of PI Containers (or separate functions) to the logistics network.

Therefore over 300 PI-related publications, papers or projects were analyzed and evaluated following a Systematic Literature Review. The research questions discussed within this paper will be elaborated on and explained in the methodical part (see section 3.1). However, this work will focus on the overarching question:

- According to an Engineering Design Related Perspective, how physical is the Physical Internet Container?

2 Methodology

A Systematic Literature Review (SLR) applied in that paper allows the summary and process of information and the literature on a specific topic, in this case, PI Container. Therefore in the first step, all relevant information and literature need to be collected and reviewed. The aim is to screen the applicable literature for relevance according to the research questions. Therefore, the literature review focused on Papers and Publications which address the topic of Physical Internet Containers. Further, to gain information on the evolution of the Physical Internet

Containers, the most relevant publications were analyzed and categorized considering different aspects. According to the schema and the workflow of this method of Systematic Literature Review, the following steps were processed (Xiao et al., 2017):

- Problem Statement/problem Formulation
  Objective: Clarification of the Research Question
- Development of the review protocol
  Objective: Setup of explicit inclusion/exclusion criteria
- Data acquisition
  Objective: Search of relevant Literature → Review title
- Data screening
  Objective: Screen for inclusion → Review Abstract
- Data quality
  Objective: Assess Quality → Review Full-text
- Data Extraction
  Objective: Validate and categorize data
- Analysis and Syntheses
  Objective: Findings of the Literature Review, Answer the Research Question

Chapter 3 shows the application of those steps SLR steps on the current research topic.

3   Systematic Literature Review – Method application

In chapter 2 the method of the Systematic Literature Review was described. This chapter will show the application of this method, including all process steps of the method on the present research question. All process steps, beginning with the setting of the research question, will be applied and described separately in the following section 3.1 to 3.6

3.1   Problem Statement

The aim of this paper is to show *the development of PI Containers over the last years as well as the technology readiness of specific solutions*. Therefore this literature review focuses on PI-related work which directly or indirectly addresses the topic of PI Container to answer the following research questions:

- RQ 1: How many works addressed the PI Container as a primary topic (including development over the last years)
- RQ 2: What's the degree of abstraction of the PI Container treated in the different works
- RQ 3: To what extent are physical aspects included in the design of the PI Container

3.2   Development of the review protocol

The International Physical Internet Conference (IPIC) proceedings were defined as the primary source for publications. Therefore all proceedings from IPIC 2014 to IPIC 2021[1] were described as a source of relevant literature.
As a second source of potential literature, all works which cited the MODULUSHCA project publications were also included in the pool of potentially relevant publications.
In addition, further popular search engines for scientific work (Google Scholar, ResearchGate and Scopus) were used to find other publications dealing with the Physical Internet, specifically

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[1] In year 2022 IPIC 2022 was not held due to the global COVID19 pandemic situation

with the sub-topic of Physical Internet Containers. Therefore, the following keywords were defined:

"Physical Internet" or "PI" or "π"

and

"Container" or "Containerization/Containerization"

Further, it was defined that the process steps of *data acquisition (Review title)* and *data screening (Review Abstract)* will be applied simultaneously.

3.3 Data acquisition

As a first step, all potentially relevant papers and publications are listed. According to the review protocol, the major part of this accumulation was formed by contributions of IPIC (International Physical Internet Conference) as well as from publications which cited the MODULUSHCA project publications, in sum: 265. In addition, a minor number of publications and papers were collected via standard search engines for scientific works, in sum 32 (as described in section 3.2).

This list of publications and papers includes *almost 300 positions*. These publications were validated roughly by reviewing the works' titles and abstracts as a next step. This review aimed to sort out all publications which probably do not address the topic of PI Containers in a significant matter. Therefore, papers addressing the issue of Physical internet Containers or containerization of goods within the title or the abstract will be considered further. This adjusted list includes *25 potential publications* and serves as a base for further investigations in process step *data quality* (see section 3.4)

3.4 Data quality

The first rough review of the potential publications (see section 3.3) showed that *25 publications* potentially significantly address the topic of PI Container. In the next step, the publications were reviewed in detail to determine in which depth they focus on PI Container. To reduce the number of relevant papers again, all papers whose content does not show the relation to PI Container or interpret the PI Container differently than the PI Philosophy mentions get struck from the list of relevant publications. Therefore it has been defined that the mentions of the Physical Internet Container within the Container must exceed the references of the Physical Internet fundamental research publications (Montreuil, 2011) to take this publication under further consideration. This process step is shown in Table 1.

Table 1: List of relevant publications after data acquisition

Source	PI Container as significant content	Comment
Montreuil et al. (2014)	✓	Introduction and development of the concept of Pi Container
Pach et al. (2014)	✓	PI Container as a Hexader for packaging simulations
Walha et al. (2014)	✓	PI Container with different dimensions, mathematical model
Tran-Dang et al (2015)	✓	PI Container with different dimensions for packaging simulations
Tretola et al. (2015)	✗	Definition of Data Sets based on MODULUSHCA
Landschützer et al. (2015)	✓	Specific design and prototype of PI Container for field testing

Chakrouun et al. (2016)	×	General description of PI Container
Kapplmüller at al (2016)	✓	Specific design of a PI Container incl. specific dimensions and functions
Hao et al. (2016)	✓	General description of PI Container, function of PI Container in PI Hub
Salley et al. (2016)	×	General description of PI Container, focus on information exchange
Faugere et al. (2017)	✓	Description of dimensions and functions
Di Febbraro et al (2017)	✓	Mathematical Modell of PI Container incl, different dimensions
Krommenacker et al (2017)	×	General description of PI Container
Tran-Dang (2017)	✓	Description of functions of PI Containers, several simulations
Chargui et al. (2018)	✓	General description of PI Container, function of PI Container in PI Hub
Buckley et al. (2018)	✓	PI Container with different dimensions, mathematical model
CLUSTERS 2.0 (2018)	✓	Detailed description of requirements for New Modular Load Units
Marino et al. (2019)	×	General description of PI Container
Bennekrouf (2019)	✓	PI Container with different dimensions for packaging simulations
Sternberg et al. (2020)	✓	General description of PI Container, packaging simulations
García-Arca et al. (2020)	×	Redesign of cardboard boxes, low relevance for PI
Tran-Dang et al. (2021)	×	General description of PI Container
Hayek et al. (2022)	✓	Development of PI Container for wood transports

Within this process step, the list of relevant publications could be reduced again and led to a final list of *16* publications which will be used for a more in-depth analysis of the contents in the next step (see section 3.5).

3.5   Data Extraction

As a next step, all relevant publications were reviewed and analyzed according to their applicability to the research questions to answer the two questions defined below (see chapter 1)

- RQ2: What's the degree of abstraction of the PI Container treated in the different works
- RQ3: To what extent are physical aspects included in the design of the PI Container

All relevant publications were categorized within the following chart, shown in

Figure *1*. Therefore two different aspects were introduced to be able to validate the various publications and place them in the chart

- The Technology Readiness Level (TRL) indicates how advanced the solutions mentioned in the publications can be seen according to their stage of development (Mankins, 1995). Therefore the scale reaches from TRL 1 (Basic Technology Research) over TRL 3 (Experimental proof of concept) and TRL 5 (Technology validated in relevant environment) to TRL 9 (Prototype in field tests)
- The scale of the relevance of physical aspects and functionality shows how the physical parameters (weight and volume of the Container, strengths of the material[2]) and functionalities were considered for the specific solutions. In order to be able to categorize the state of design of the PI Container within the publications from a design-

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[2] This paper focusses on the investagtion of the physical and mechanical properties of Physical Internet Containers (such as mentioned above) therefor the relevant parameters are weight, volume and strength of the material are taken under consideration for further research. Ecological as well as economical parameters will not included in the research within this paper.

related perspective, the method of *Planning and Design Process* is used to classify the mentioned PI Containers into the following stages within that *Planning and Design Process* (Pahl, Beitz, 1996):

- o Planning and clarify
- o Conceptual design
- o Embodiment design
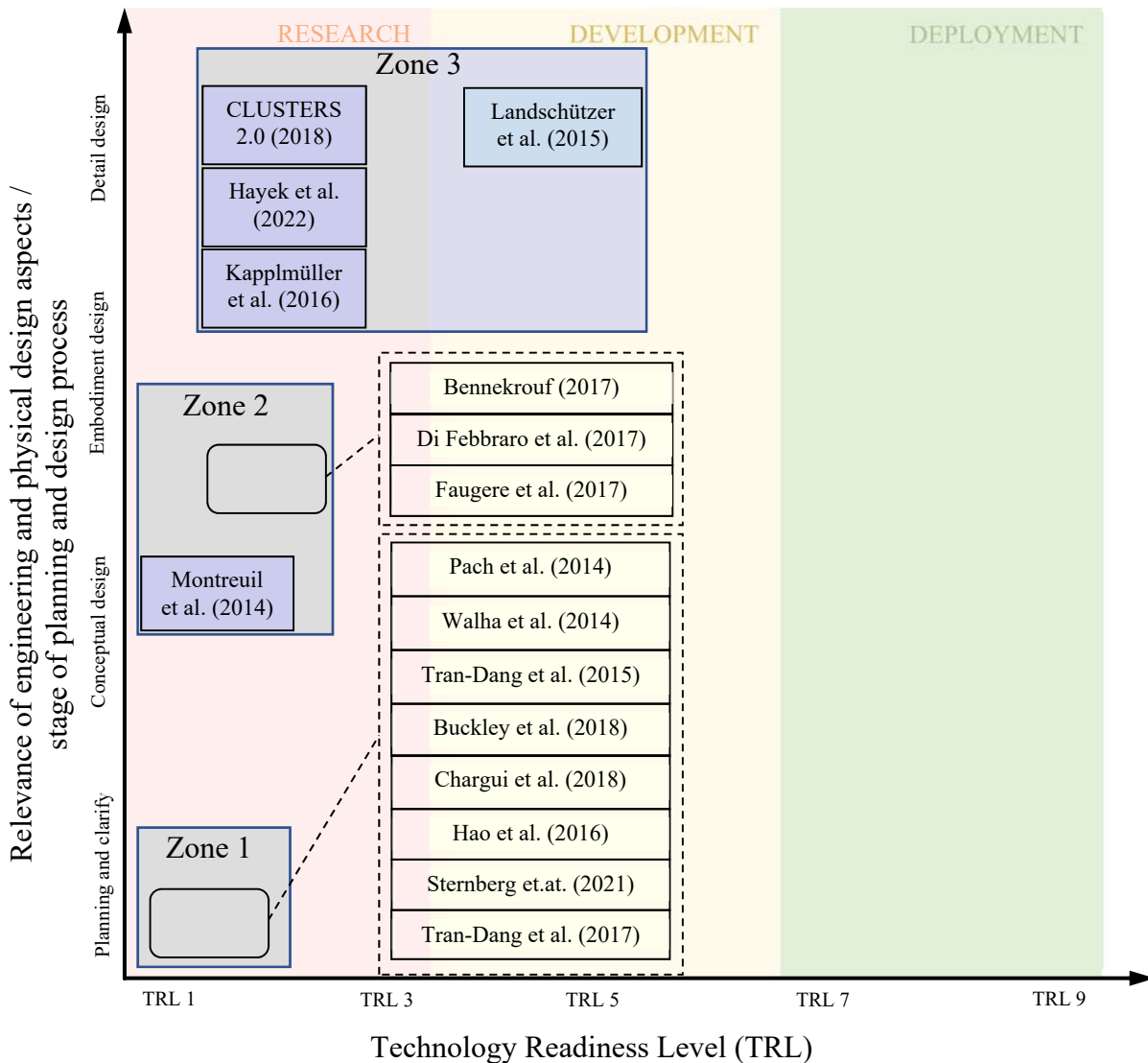- o Detail design

Figure 1: Classification of relevant publications

Further, the relevant papers can also be categorized and sorted according to their year of publication, which allows answering the research question, defined in chapter 1

- RQ1: How many works addressed the PI Container as a primary topic in the past (including development over the last years)

Table 2 shows the categorization of the most relevant papers indicating the development and the degree of scientific investigation on PI Container, represented by the number of mentions of PI Containers within scientific publications over the past years. Therefore, the last row in the table represents the total amount of relevant publications published each year.

Table 2: Evaluation of the development of relevant publications from 2014 to 2022.

2014	2015	2016	2017	2018	2019	2020	2021	2022
Montreuil et al.	Landschützer et al.	Hao et al	Tran-Dang	Buckley et al		Sternberg et al.	Tran-Dang et al	Hayek et al.(2022)
Walha et al	Tran-Dang et al	Kapplmüller at al	Di Febbraro et al	Chargui et al				
Pach et al.			Faugere et al					
3	2	2	3	2	0	1	1	0

3.6 Analysis and Syntheses

The result of the processed Systematic Literature Review can be summed up within the following *quantitive takeaway*

- Out of almost *300 papers* and scientific works addressing Physical Internet and Physical Internet Containers, *25 publications* address PI Container directly or indirectly (see section 3.3)
- Out of these *25 publications* addressing PI Container direct or indirect, no specific or unique statements or new findings according to PI Container could be made within *12 papers* (see section 3.4)
- The remaining *16 publications* were analyzed according to their quality. (see section 3.5) This analysis focussed on the development the number of mentions of PI Containers within the last years on the one hand and the approaches and solutions of PI Containers within the publications on the other.

The *qualitative takeaway,* however, will be summed up and analyzed in chapter 4 - Results.

4 Results

After processing the steps of SLR, from data acquisition to data extraction, it can be seen that the investigated publications, which deal with the PI Container in a physical matter, share similar characteristics:

- The Technologie Readiness Level (TRL) reaches a maximum of TRL 4 within one investigated publication. All other solutions or approaches of PI Containers in the other publications show lower TRL, most of them TRL 1. No projects or publications address the goal of introducing Ready-to-Use solutions (up to TRL 9) to the market, as shown in Figure 1 by the missing publications in the deployment sector.
- A few investigated publications and projects address integrating physical aspects and parameters into their solution and approach to the PI Container. This is shown by classifying the publications to the stage within the *Planning and Design Process*. A few solutions exceeded the stage of developing ideas, meaning most of the investigated publications are stuck at the stage of description and formulation of the essential functions of the PI Container without including further design steps.
- The MODULUSHCA project (Landschützer et al., 2015) is the only publication which combines a thoughtful design (including physical aspects) with and higher technology readiness level (TRL 4). However, since then, no publication has considered forward pushing of projects comparable to the MODULUSHCA project. The project CLUSTERS 2.0, which can be seen as a Follow-up project of MODULUSHCA, does catch up on the relevance of the physical properties and functions of PI containers. However, the New Modular Logistics Units (NMLU) development did not exceed the design phase and did not lead to a prototype within that project. Further, one publication

shows the detailed development of a PI Container for wood transportation (Hayek et al. 2022). Still, this publication holds a low TRL level, but it mentions the importance of introducing such solutions to the transport network.

- the SLR has shown that the number of publications dealing with PI containers as physical containers have increased in recent years.
- Further, the focus on developing Physical Internet containers has decreased over the last years. This can be underlined by a combined view of Figure 1 and Table 2, which shows that nearly all solutions and approaches of PI Papers published since 2017 need to be classified as low stage within the *Planning and Design Process* as well as TRL 1.

Although the PI Container is one of the main pillars of PI philosophy, just a few scientific publications focus on matching PI Containers for real-world application by developing, designing, building and testing PI Containers in real-life scenarios.

5 Conclusion and Outlook

The structured analysis and evaluation showed that in the research landscape, the PI Container still seems to be seen as an object in the virtual world. Further, it could be seen that the philosophy of PI assumes to a certain extent that the PI Container must exist to fulfil the tasks and objectives of the Physical Internet and to be able to apply the Physical Internet to the future transport network. However, there is less effort to develop a physical Physical Internet Container. Even the step seen in the past years creating a physical PI Container decreased in quality and intensity. Since MODULUSCA prototypes of a modular PI Container were developed, designed, built and tested, the PI Container seemed to be more virtual daily from then on. This means there is a research gap after the MODULUSHCA, shown in this paper. This gap covers the need for a physical PI Container to help the PI succeed on the one hand, as well as decreasing the effort to design and introduce such PI Container.

Further, the transport network has undergone many changes and new challenges over the last years (e.g. the increasing number of Polybags, limited transport capacities, and legal restrictions for transportation and delivery). That results in a low level of acceptance for introducing PI Container to the existing transport network. That aspect underlines the need for new approaches and design suggestions to find possible cases within the transport network where the introduction of PI Container would lead to an ecological or economic benefit and design and test PI Containers for that application.

For that reason, there will be follow-up research which will catch up on the findings of this paper and try to find some new cases or scenarios where the introduction of PI Container could help to push the Physical Internet Idea. Potential objectives for such future research efforts could be

- The definition and description of specific Use Cases within the PI network, with high potential that the usage of PI Boxes can result in an increase of efficiency regarding handling, including all physical aspects of a potential physical PI Container
- Methodical design of a PI Container which can fulfil the requirements of the Use Case, defined before, including prototypical implementation
- Definition of conditions and processing of a field test of the designed PI Container

6   Acknowledgements

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Physical Internet based Hyperconnected Logistics Platform Enabling Heavy-Duty Machinery Sharing in the Composting Industry: A Simulation-Based Scenario Investigation

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Abstract:

Composting plants face significant challenges in meeting increasing quality standards and production rates due to the high costs of essential composting machinery. To address these issues, a Physical Internet based Hyperconnected Logistic Platform for Heavy-Duty Machinery (HLHD) has been proposed. The HLHD system enables composting plant operators to share expensive machinery between plants, allowing for improved efficiency, cost-effectiveness, and enhanced compost production quality.

The HLHD operates by transporting composting machinery between designated hubs and participating composting plants, where they perform their specific tasks during the composting process. To evaluate the efficacy of the proposed HLHD system, a simulation-based study of three distinct scenarios has been conducted.

The first scenario focused on small and medium-sized composting facilities, providing an accessible and cost-effective solution for smaller facilities. In the second scenario, all composting facilities participate in the HLHD to an equal extent, while the third scenario assumed that big composting plants already own the necessary equipment. However, since the utilization of machinery at these large farms is generally low, they participate in the HLHD by serving as hubs once their machinery is idle.

Overall, the HLHD system shows great potential in addressing the challenges faced by composting plants. The proposed system can lead to improved resource utilization, enhanced efficiency, and reduced costs, ultimately leading to better quality compost production.

Keywords: *Physical Internet, Hyperconnected logistic, Heavy-Duty Machinery, Simulation, Composting.*

Conference Topic(s): *autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms) business models & use cases; communication, networks; logistics and supply networks; PI impacts; PI implementation; PI modelling and simulation; vehicles and transshipment technologies.*

Physical Internet Roadmap *(Link): Select the most relevant area(s) for your paper: ☐ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☒ Access and Adoption, ☐ Governance.*

1 Introduction

The vision of the Physical Internet is to achieve a globally accessible logistics system characterized by a combination of physical, digital, and operational interconnections enabled through the utilization of encapsulation, interfaces, and protocols. The aim is to create an ever-evolving system that thrives on technological, infrastructural, and business advancements [1], [2]. One of the areas of the PI vision is the establishment of hyperconnected networks in various fields. The approach of the PI Vision is thereby universal and not limited to a specific industry [3], [4]. Since this study deals with the organic waste industry, more specifically with composting, a brief introduction to the state of the art in Central Europe is given. The organic waste recycling and processing sector is a fast-growing industry in Europe. In the past 20 years there has been a rapid increase of over 80% in this industry, with a volume of over 40 million tonnes of compost processed within the EU in 2023 [5]. As the EU introduces regulations requiring the compulsory treatment of organic waste for member states, it is expected that this trend will continue to grow in the future [6]. The ever-increasing pace of technological advancement is driving the waste management sector to explore and implement innovative approaches to cope with the challenges. In response to this demand, significant efforts are underway in the research and development of cutting-edge technologies that can address the complex issues of the sector. The aim is to develop new methods and tools that are more efficient, sustainable, and cost-effective, while also reducing the environmental impact of waste management activities. [7]–[11]

Therefore, before addressing the PI vision's adaptation for this sector, a brief overview should be given. Composting can hereby be defined as an intricate aerobic process involving the degradation of organic materials or biogenic waste from separate collection under controlled environmental conditions. This process takes place in a composting plant, an anaerobic biological treatment facility that utilizes biological waste as feedstock, and relies on a diverse range of microorganisms for its successful execution. The produced compost is the outcome of largely completed aerobic decomposition, characterized by specific quality parameters that satisfy regulatory requirements for usage and marketability. This nutrient-rich end-product can be employed in numerous ways, including as a natural fertilizer and a soil enhancer for agriculture purposes [12], [13]. The widely used industrial technique for the production of compost is the compost windrow process, also known as "open composting". This process involves placing the organic waste material in long lanes, typically measuring between 1.2 to 1.5 meters in height and 2.5 to 3 meters in width, depending on the specific composting facility. In order to facilitate the proper progression of the biological process of composting, it is necessary that the compost windrows are regularly turned, a task which is executed by specially designed machines known as compost turners. The frequency of turning is determined by several factors, including the nature of the organic waste, ambient temperature and humidity, and the desired end-product quality. However, it is generally accepted that the turning should not occur less than three times per week in order to maintain high quality standards. The utilization of open windrow composting technology has gained significant recognition and establishment throughout Central Europe, with Austria exemplifying the adoption of this method through the establishment of numerous smaller-scale, regionally-targeted composting facilities. [14]

As the basic principles and techniques of composting are understood, it becomes clear that the underlying principles and concepts of the Physical Internet can be extended and applied to this field as well. Considering the robust growth of the composting industry, there exists an urgent and pressing need to explore and leverage the advantages and opportunities offered by the Physical Internet. It is evident that there has been a lack of research in this particular area, with

only a restricted number of studies conducted thus far. It is worth highlighting the contributions made by Larsen, Hansson and Lagerkvist in this field, who have delved into the subject of farm machinery sharing within the agricultural sector of Northern Europe. Through the utilization of survey methods, it was discovered that the practice of sharing agricultural machinery among farmers resulted in a boost in operational efficiency [15], [16]. Despite the substantial amount of research conducted on existing systems, the fundamental concept of an interconnected network, as envisioned by the Physical Internet Vision, has yet to be considered or explored within these studies. In other words, previous works have solely focused on the analysis of established systems, with little to no attention directed towards the theoretical framework proposed by the Physical Internet Vision. Consequently, there is a critical gap in the current understanding of the potential implications and benefits of interconnected network models.[17]

Therefore, this paper proposes and investigates the potential of a Hyperconnected Logistic platform for Heavy-Duty machinery (HLHD) for compost production that leverages Physical Internet (PI) concepts and principles. As synthesized in Figure 1, we introduce the HLHD concept, develop specific deployment scenarios, and investigate through a simulation-based experiment their relative performance to enable the sharing of composting machines under various constraints. Through this approach, we aim to establish a comprehensive understanding of the potential of the HLHD platform and its practical implications for the composting industry.
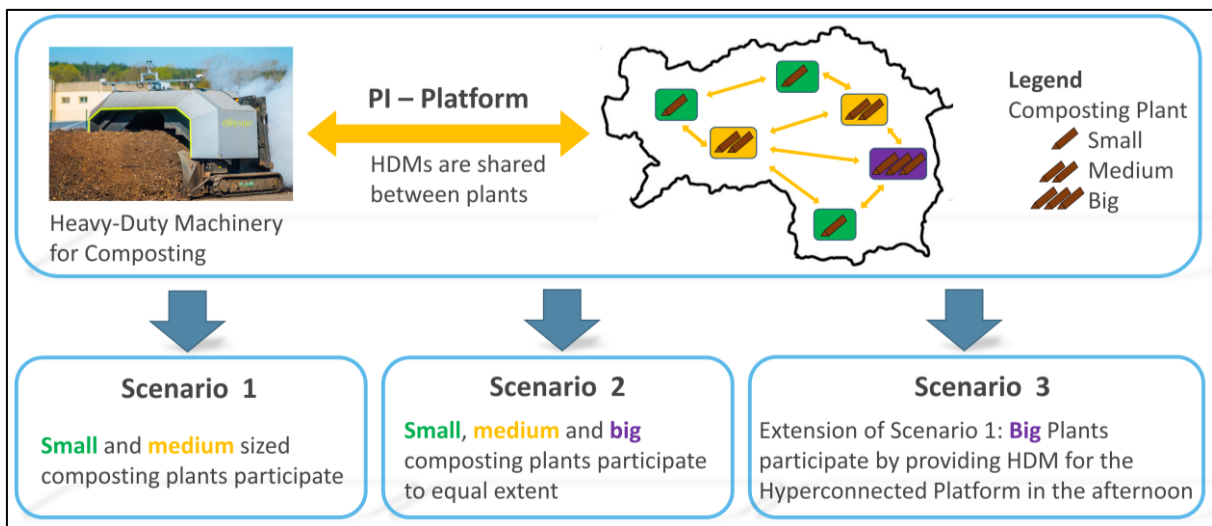

Figure 1: Proposed Physical Internet based hyperconnected logistics platform for heavy-duty machinery (HLHD)

2   Methods and Tools

As a result of the significant costs associated with the acquisition and operation of essential machinery, many composting plants are unable to procure the necessary equipment required to compete with the ever-increasing composting rate and quality standards. The objective of implementing a Physical Internet based Hyperconnected Logistic Platform (HLHD) is to mitigate this challenge by providing plant operators with the option to share the expensive composting machines among themselves. The proposed HLHD system is based on the idea that composting machines can be transported between designated hubs and participating composting plants, where they carry out their specific activities during the composting process.

This novel approach has the potential to address the resource constraints faced by composting plants, improve efficiency, and enhance the overall quality of compost production.
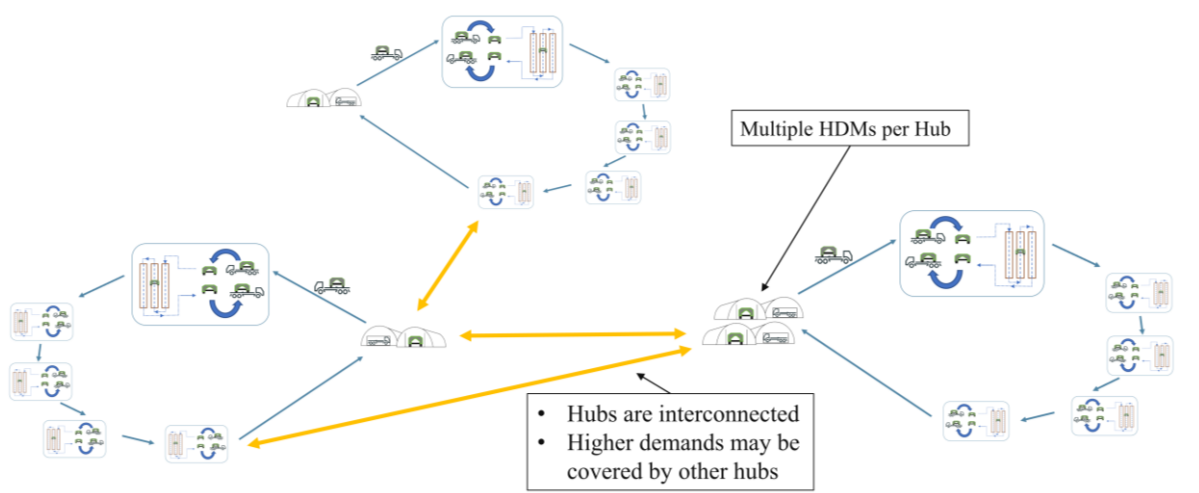

Figure 2: Overview of the Hyperconnected Logistic platform for Heavy-Duty machinery (HLHD)

Figure 2 shows the basic principle of the HLHD. This system starts at specific nodes (PI-Hubs) where the machines required for compost production are loaded onto trucks. The machines are then transported to the designated composting facilities, where they perform the required tasks. The HLHD platform operates within defined boundary conditions that are set in advance. One of the crucial requirements is the adherence to a self-defined time period for round trips. The specified time period is thereby set at one working day.

Following the Physical Internet concept, additional framework conditions must be established to augment the HLHD. One of the key considerations is the interconnectivity of individual hubs to ensure that high demand, including peak loads, can be accommodated by alternate hubs. Furthermore, the HLHD system envisages the potential for multiple machines to depart from each hub, if required. To maintain the scope of this publication, we will limit our analysis to three distinct scenarios, which will be subjected to a simulation-based study to evaluate their efficacy. Through this approach, we aim to provide a comprehensive understanding of the system's performance under varied conditions and identify potential areas for improvement.

2.1 Methods and Tools - Scenario 1: Small and medium-sized plants participate

The first scenario considers the participation of small and medium-sized composting facilities in the HLHD. This approach aims to provide an accessible and cost-effective solution for smaller composting facilities that may not have the financial means to purchase the necessary machinery to compete effectively in the market. To obtain data for the experimental investigation, surveys were conducted among composting companies in the central European region, which serves as a representative case study for the analysis. The surveys aimed to determine the duration for which composting plants utilize their composting machines on a daily basis. This information was subsequently utilized to develop profiles of typical composting plant sizes, which could then be applied to the scenario analyses. Percentiles were used to classify the composting plants according to their size and performance. The resulting profiles included a category of *small* facilities representing the 0th to 20th percentile, a category of *medium-sized* facilities covering the 20th to 80th percentile, and a category of *big* facilities covering the 80th to 100th percentile. This classification is used in the following scenarios to determine the number of composting facilities for each type. The analysis revealed that the

region under consideration has a very communal situation, with many villages in rural areas having nearby composting plants, which tend to be small and medium-sized. As expected, larger composting companies were primarily located near urban centers.

The *PI-Hubs Location Planning* step is an important part of the HLHD model, where the most suitable locations for the PI hubs are determined. To accomplish this, a capacitated facility location problem is utilized, where the capacity of each hub is set to the number of composting facilities it is expected to serve. This method enables the identification of optimal hub locations that can provide the required services effectively. For a more detailed understanding of this approach, readers are encouraged to refer to relevant literature in the field. [18, p. 53]

The *PI-based network development* of the HLHD assumes that the composting machines are transported in a round trip manner from the PI hubs to the respective composting plants, and then returning to the initial location. However, it is important to note that this condition may be subject to change in future analyses, as the HLHD is a dynamic system that can be optimized and adapted based on new data and evolving requirements. In addition to the standard vehicle routing problem, PI-based network development for the HLHD includes two additional constraints, namely "multiple depots" and "time windows". Consequently, the optimization problem becomes a multi-depot heterogeneous vehicle routing problem with time windows (MDHVRPTW). Several studies in the literature have explored the MDHVRPTW, and readers interested in a more detailed explanation of this problem may refer to these studies. [19]–[21] As previously stated, the PI-based network development is governed by a constraint that requires the roundtrips to be completed within a predetermined time frame of 10 hours, corresponding to a typical workday duration.

2.2 Methods and Tools - Scenario 2: Small, medium and big plants participate to equal extent

The second scenario assumes that all composting facilities participate in the HLHD to an equal extent. The aim of this scenario is to investigate the feasibility and performance of the HLHD model when all heavy-duty machinery required for composting is shared among composting plants of all sizes. To be more specific, this scenario examines the effect of incorporating small, medium and big composting plants in the HLHD. It is worth noting that the duration of machine usage varies across different plant sizes, with larger plants requiring the machinery for a longer period compared to smaller plants. As such, this factor is taken into consideration in the scenario to ensure that the shared machinery meets the requirements of all participating composting plants.

In Scenario 2, the methodology used to obtain results is similar to the one used in Scenario 1. The first step involves the *PI-Hubs Location Planning*, which identifies the optimal positions of the PI hubs. The process is conducted by applying a capacitated facility location problem and taking into account the number of composting facilities to be visited. After the determination of the optimal positions, the next step involves the *PI-based network development*, which calculates the round trips starting from the PI hubs. As in the previous scenario, this step is a vehicle routing problem, considering the "multiple depots" and "time windows" constraints.

2.3 Scenario 3: Big plants participate part-time

The third scenario focuses on the assumption that small and medium-sized composting companies require the use of heavy-duty machinery and, therefore, participate in the HDLH. Meanwhile, the larger plants are considered to already own the necessary equipment and, as a result, do not require their participation in the HDLH. Nevertheless, the utilization of these

large plants' machines is generally low, primarily because they are typically to be used mainly in the morning. This subsequently leaves the equipment unused in the afternoons.

As stated in the introduction, a key principle of the Physical Internet (PI) concept is to enhance the utilization of underutilized resources. As the heavy-duty machines owned by large composting companies remain idle during the afternoon, this underutilized resource can be made use of in accordance with the PI vision. In Scenario 3, it is assumed that these large companies will function as PI hubs during this particular time period.

The methodological approach for scenario 3 is similar to the previous scenarios. However, the key difference lies within the *PI-Hubs Location Planning*, since the precise location of the hubs is predetermined, as these are precisely the coordinates of the large composting plants. However, this assumption might require an extension, since the situation may arise that the number of the predetermined hubs is insufficient. This specific issue will be analyzed in greater depth in the corresponding results section.
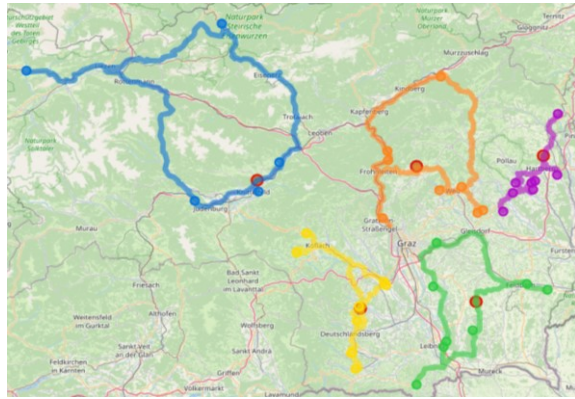
The *PI-based network development* for scenario 3 is similar to the previous scenarios. However, the time constraint of one working day has been adapted, and the routes must be completed within a shorter period of one afternoon, which is equivalent to 5 hours.

## 3 Results of the Simulation-Based Scenario Investigation

This section presents the findings of the simulation-based scenario analysis, which is organized in a similar structure to the preceding sections. Scenario 1 involves small and medium-sized facilities, Scenario 2 comprises all composting facilities, and Scenario 3 investigates the participation of small and medium-sized plants, with large composting plants functioning as hubs during the afternoon hours.

3.1 Scenario 1: Small and medium-sized plants participate

The results from the first scenario are shown in Figure 3. As can be seen, a number of 5 hubs was determined in the PI-Hubs Location Planning step. Based on these findings, 5 round trips were determined in the PI-based network development step, whereby the optimization condition was selected in such a way that the duration of all round trips is minimized. The calculated round trips are shown in Figure 3a, and the corresponding statistical evaluation is shown in Figure 3b. It is noteworthy that both the roundtrips and statistical analysis consider the time windows, which refer to the duration required by the heavy-duty machines at the composting site. The time windows are determined based on the profiles previously defined for composting plants.
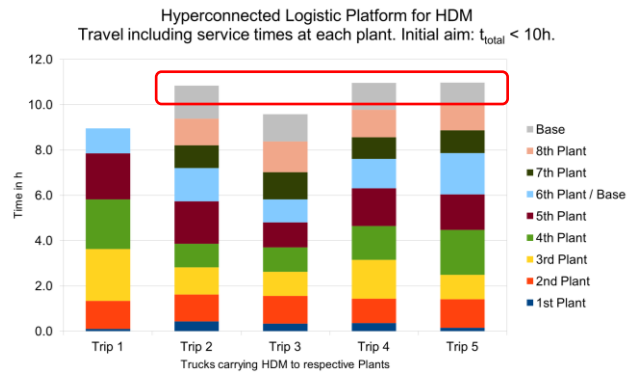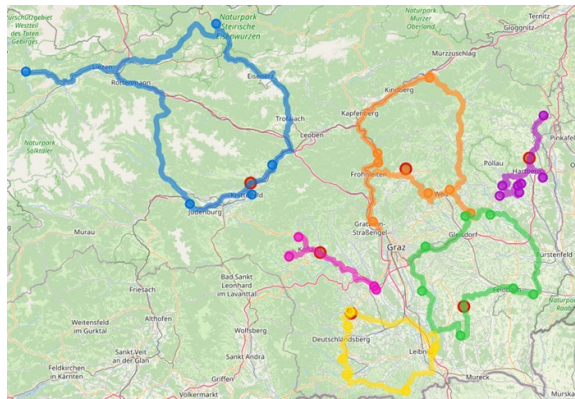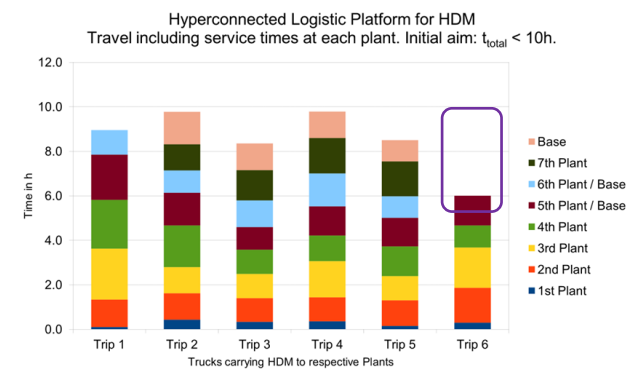
(a): PI-based network development - Routes   *(b): PI-based network development - Details*

Figure 3: Scenario - Initial results.

The results depicted in Figure 3b indicate that the initial requirement for the HLHD to cover all composting plants within a working day was not met, as roundtrips 2, 4, and 5 surpassed the given timeframe. To overcome this, an iterative approach was employed by repeating the PI-Hubs Location Planning and PI-based network development steps. In this process, a new constraint was introduced, whereby a maximum of 7 plants could be visited per hub.

(a): PI-based network development - Routes   *(b): PI-based network development - Details*

Figure 4: Scenario 1 - Refined results

The enhanced outcome is illustrated in Figure 4, depicting that 6 hubs were identified in the PI-Hubs Location Planning process. This outcome was then used to regenerate the roundtrips in the PI-based network development process, as shown in Figure 4a. It is evident from the statistical analysis presented in Figure 4b that by introducing an additional hub, the load on the other hubs was mitigated. Consequently, the initially set condition that the HLHD would serve all composting facilities within 10 hours was achieved. However, the suboptimal usage of hub 6 is the only trade-off. This particular aspect will be further addressed in the discussion section.

3.2   Scenario 2: Small, medium and big plants participate to equal extent

Scenario 2 is an extension of the former, and now also considers large composting plants. After incorporating the profiles for large plants that were defined previously, the mean duration of heavy-duty machinery usage on composting plants also increased accordingly. Subsequently, the optimal placement of the hubs was determined through PI-Hubs Location Planning, and the resulting roundtrips were computed using PI-based network development, as illustrated in Figure 5a. The evaluation of the individual roundtrips is depicted in the bar chart in Figure 5b.

Due to the inclusion of large composting plants, the number of hubs required increased to eight. In addition, a constraint is imposed that only a maximum of six composting plants per hub can be visited during a single roundtrip. The compliance with this constraint can be observed in Figure 5b, which indicates that the initial objective of completing the task in less than 10 hours is met for six out of the seven roundtrips.
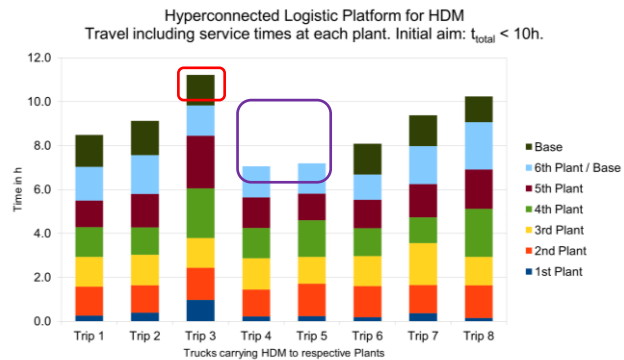
(a): PI-based network development - Routes   *(b): PI-based network development - Details*
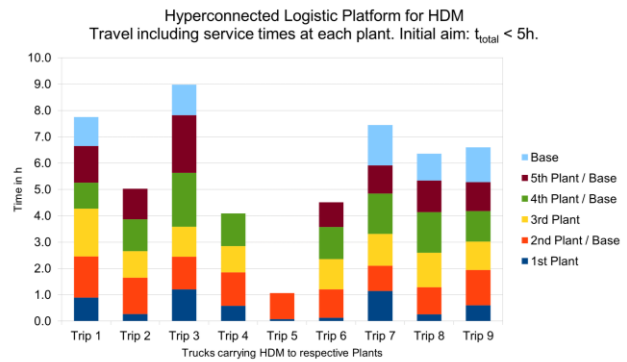
Figure 5: Scenario 2 - Results

However, it is also evident that Trip 3 clearly exceeds this threshold. Despite this overshoot, it does not seem wise to increase the number of hubs. This becomes clear when we look at trips 4 and 5, as it is clear that these two trips have a low utilization rate. An increase in the number of hubs would bring Trip 3 within the limits, but would also reduce the overall utilization. It therefore appears reasonable to introduce local constraints to limit the duration of the individual round trips. Since the introduction of a local constraint inevitably leads to a reduction of the global optimum, this issue will be addressed in more detail in the discussion section.

3.3 Scenario 3: Big plants participate part-time

The third and last scenario assumes that the large composting plants participate in the HLHD by serving as hubs in the afternoon. The PI hub location planning step, which was performed in previous scenarios, was not necessary in this scenario because the locations of the hubs were predetermined by the locations of the large composting plants. The results of this scenario are presented in Figure 6, where the optimal number of hubs was determined to be 9 based on the predefined profiles for composting plants. The corresponding roundtrips generated by the PI-based network development are illustrated in Figure 6a. In this scenario, the constraint was set that only a maximum of 5 composting plants should be visited within one single round-trip, as depicted in the bar chart in Figure 6b. In contrast to the previous scenarios, the constrained applies that the HLHD must be carried out when the machinery is idle at the big plants, that is, in the afternoon. Therefore, the HLHD must be carried out within 5 hours. Despite having an increased number of 9 hubs compared to the previous scenarios, the time limit of 5 hours could not be achieved, as shown in Figure 6b. The reasons for this non-compliance with the given assumption are explained in the following.

(a): PI-based network development - Routes *(b): PI-based network development - Details*

Figure 6: Scenario 3 - Results

On the one hand, it is clear that the positions of the hubs were predefined and therefore could not be optimally positioned by PI-Hub Location Planning. Secondly, it could be argued that the maximum number of composting plants to be visited per round trip was too high. On closer examination, however, it is immediately apparent that a reduction to 4 instead of 5 facilities per round trip inevitably leads to a situation where not all composting facilities can be visited. Since the exclusion of individual facilities from the HLDH contradicts the fundamental concept of the HLHD, this path is not pursued any further. Thus, it appears that the exclusive consideration of large composting plants as hubs is not sufficient and a further assessment is necessary. This will be addressed in more detail in the discussion chapter.

4 Discussion

In this study, several scenarios were explored to analyze use cases of the HLHD in the composting sector. Concerning Scenario 1, it was discovered that the initial results yielded a low utilization time, therefore further investigation was carried out. From a mathematical point of view, it is obvious that the introduction of local constraints leads in most cases to a reduction of the global optimal solution. In the context of the present use case, this implies that although the overall trip duration is increased, individual trips were able to comply with the specified time limit of 10 hours. Further, our findings suggest that an extension of Scenario 3 would be beneficial. Specifically, a PI-hub location planning with both fixed positions (existing composting plants) and variable positions would be necessary. The optimization algorithm should take the fixed locations in any case and calculate which variable locations must be constructed as hubs so that the HLHD works within one working day.

5 Conclusion and Outlook

In conclusion, the implementation of a Physical Internet based Hyperconnected Logistic platform for Heavy-duty Machinery (HLHD) has the potential to improve the composting industry's efficiency and overall quality. The proposed system aims to address the resource constraints faced by composting plants, which are often unable to acquire and operate essential machinery to compete with the ever-increasing composting rate and quality standards. The HLHD model is designed to transport composting machines between designated hubs and participating composting plants, where they carry out their specific activities during the composting process. The HLHD operates within defined boundary conditions, with adherence to a self-defined time period for round trips being a crucial requirement. This novel approach is a dynamic system that can be optimized and adapted based on new data and evolving

requirements. Future research topics include, in addition to addressing the aforementioned limitations of the scenarios, an even more detailed view of the overall system. On the one hand, this includes an even deeper technical consideration of the optimization models, which also take dynamic conditions such as weather into account. In particular, severe weather events such as snow storms, which often occur in Central Europe during the winter months, are a major challenge for the logistics industry. Taking these factors into account in the HLHD would be essential. On the other hand, there was demand from the industry to make the HLHD even more adapted to customer needs. This includes a more dynamic customization of the routes based on customer requirements, including options for weekly scheduling of trips. The aforementioned topics are currently the subject of intensive research and will be published in due course.

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Physical Internet Enabled Hyperconnected Circular Supply Chains

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Abstract: Physical Internet (PI) and Circular Supply Chains (CSC) are both promising supply chain paradigms aiming toward the significant improvement of sustainability. PI potentially provides a set of solutions for implementing CSC as both emphasize interconnectivity. This paper presents the Hyperconnected Circular Supply Chain (HCSC) framework, which aims to combine the strengths of both CSC and PI to create a comprehensive set of guidelines for supply chain stakeholders. The proposed HCSC framework encompasses nine core characteristics, addressing aspects such as product design for circularity, on-demand materialization in PI open production fabs, local material and energy recovery, hyperconnected logistics systems for materials and products, sharing economy enablement with PI, circular functionalities exploitation for existing facilities, open and hyperconnected sustainability performance monitoring, and technological and business model innovation.

Keywords: Circular Supply Chain Management, Physical Internet, Hyperconnected Circular Supply Chain, Circular Economy, Sustainability, Conceptual Framework

Conference Topic(s): logistics and supply networks; PI fundamentals and constituents; PI impacts; PI implementation.

Physical Internet Roadmap (Link): Select the most relevant area for your paper: ☒ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☒ Access and Adoption, ☐ Governance.

1 Introduction

According to the Footprint Data Foundation, humanity's consumption level has exceeded the planet's ability to sustain it by 1.8 times (Global Footprint Network, 2022). The Circular Economy (CE) offers a potential solution to address unsustainability challenges by transitioning from the traditional linear "take-make-dispose" model to a restorative and regenerative framework, with a zero-waste vision (Ellen MacArthur Foundation, 2013; Geissdoerfer et al., 2017). End-of-life objects are not perceived as simply disposable items, but as valuable inputs that can be reintroduced into production processes or repurposed for alternative uses. Within a CE, material and energy loops are decelerated, constricted, and sealed, accomplished through durable design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling (Geissdoerfer et al., 2017).

Supply Chain Management has historically focused on adding value, maximizing profitability through operational efficiencies, and ensuring customer satisfaction (Stock & Boyer, 2009). However, the growing importance of sustainability-related concerns has prompted the development of new frameworks, such as Circular Supply Chain Management (CSCM), which integrates circular thinking into the traditional supply chain paradigm (Batista et al., 2018; Farooque et al., 2019; Montag, 2022).

While conventional supply chains aim to maximize the supply chain's added value, Circular Supply Chains (CSC) seek to reconcile sustainability and circularity goals (Chopra & Meindl, 2016; Vegter et al., 2020; Montag & Pettau, 2022). CSCM serves as a vital mechanism for implementing CE principles within supply chain processes and practices. CSC research is currently in its nascent phase, offering numerous research opportunities for the practical adoption of its principles (Montag, 2022).

Interconnectivity among various stakeholders is an inherent requirement for CSC. To effectively and efficiently valorize secondary materials and resources, it is essential to facilitate the seamless material, information, and financial exchange among independent companies (Saavedra et al., 2018). The Physical Internet (PI), an alternative supply chain paradigm, is distinguished by its hyperconnectivity (Montreuil, 2011; Montreuil et al., 2012). This feature implies a high degree of interconnection among components and actors across multiple layers, facilitating real-time interactions at any time and place (Montreuil, 2020).

Physical Internet (PI) potentially provides a set of solutions for implementing CSC principles, through hyperconnectivity, horizontal collaboration, and optimal use of supply chain assets (Ballot et al., 2021). Despite its potential, no existing study has explored the possible synergy between PI and CSC to the best of our knowledge. The research question of this paper is thus: How can PI inspire and contribute to the implementation of CSC? In response, we introduce a conceptual framework for Hyperconnected Circular Supply Chains (HCSC) to contribute toward bridging the gap.

The remainder of this paper is structured as follows: Section 2 provides an overview and key elements of CSC and PI. In Section 3, we introduce the concept of Hyperconnected Circular Supply Chains (HCSC) and elaborate on its major characteristics. Section 4 concludes and suggests future research directions.

2 Circular Supply Chains and Physical Internet

As the aim of this paper is to investigate the potential synergy between CSC and PI, it is necessary to provide a concise introduction to these two concepts and their key characteristics. Therefore, the first part of this section is dedicated to outlining the definition of CSC and its archetypal characteristics, as described by Montag (2022); the second part describes the major characteristics of PI.

2.1 Circular Supply Chains

Considering the early stage of CSC and CSCM conceptualization, there is currently no consensus on their definitions. Batista et al. (2018) characterize CSC as the coordination of forward and reverse supply chains, while Geissdoerfer et al. (2018) defined CSCM as the configuration and coordination of various organizational functions to achieve CE objectives. Jia et al. (2020) regard CSCM as a notion that complements Closed-Loop Supply Chains.

Among the various definitions of CSCM, the one proposed by Farooque et al. (2019) is considered to provide a comprehensive and integrated perspective on the subject (Montag, 2022). Their definition is as follows: "Circular supply chain management is the integration of circular thinking into the management of the supply chain and its surrounding industrial and natural ecosystems. It systematically restores technical materials and regenerates biological materials toward a zero-waste vision through system-wide innovation in business models and supply chain functions from product/service design to end-of-life and waste management, involving all stakeholders in a product/service lifecycle including parts/product manufacturers, service providers, consumers, and users".

Montag (2022) has synthesized six archetypal characteristics of CSCM, which include: R-imperatives, restorative and regenerative cycles, sustainability framework, value focus, holistic system thinking, and paradigm shift. R-imperatives encompass a variety of product recovery strategies, such as repair, remanufacturing, refurbishing, and recycling (MahmoumGonbadi et al., 2021). These strategies involve reintegrating end-of-life products into new or alternative usage cycles, retaining their original form, or transforming them to serve different purposes, ultimately extending their life span and reducing waste. Restorative and regenerative cycles entail the circulation of both technological and biological nutrient-based products and materials throughout the economic system (Ellen MacArthur Foundation, 2013). Sustainability framework necessitates the holistic integration of the Triple Bottom Line into CSCM. This implies the simultaneous consideration of environmental, social, and economic aspects.

Value focus emphasizes the importance of leveraging various strategies to maximize resource efficiency. These strategies encompass the power of inner cycles, in which tighter loops yield greater benefits by replacing virgin materials; the power of cycling longer, where products' useful lives are prolonged by undergoing numerous consecutive cycles and remaining within each cycle for an extended period; the power of cascaded use and inbound material/product substitution, which advocates for circulating materials across a variety of product categories; and the power of purer input, necessitating a certain degree of material purity and product/component quality to maximize the value generated through the circular supply chain processes (Ellen MacArthur Foundation, 2013). Holistic system thinking highlights the significance of addressing each stage of the supply chain and comprehending the intricate interconnections among organizations. The paradigm shift entails a considerable transformation in both supply and demand sides to fully embrace CE principles.

2.2   Physical Internet

PI, as described by Montreuil (2020), is a "hyperconnected global logistics system enabling seamless open asset sharing and flow consolidation through standardized encapsulation, modularization, protocols and interfaces, to improve the capability, efficiency and sustainability of serving humanity's demand for physical objects". This vision, proposed to tackle the challenges of unsustainable global logistics, is conceptualized through a set of thirteen characteristics, which cover a wide range of logistics and supply chain issues, from product design and realization to transportation services (Montreuil, 2011). The following paragraphs in this section present these thirteen characteristics of PI, along with related recent research updates.

Encapsulate merchandises in world-standard smart green modular containers. One of the key pillars of PI is to use standard and modular PI-containers instead of current heterogeneous good packages, cardboard cases, and pallets (Landschützer et al., 2015). PI-containers shall be designed with several generic characteristics such as easy to handle, store and transport, connected, and environmentally responsible (Montreuil et al., 2015).

Aiming toward universal interconnectivity. The primary goal is to significantly reduce the time and cost associated with load breaking by fostering seamless connections across the supply chain. Achieving this level of interconnectivity necessitates the standardization of loading units, processes, and services, as well as digital interoperability among diverse stakeholders (Ballot et al., 2020; Pan et al., 2021).

Evolve from material to PI-container handling and storage systems. Logistics nodes in PI embrace automated standardization and interconnected processes (Ballot et al., 2020). In particular, Chargui et al. (2022) explore the PI's impact on cross-docking platforms, emphasizing their open, automated nature compared to traditional setups.

Exploit smart networked containers embedding smart objects. PI-containers need unique identification, tracing, tracking, and monitoring capabilities, while adhering to data compatibility, interoperability, and confidentiality standards. As active products, they should conduct scheduled reporting, event initiation, goal adjustment and communication, peer interaction, negotiation with equipment, and learning from experiences (Sallez et al., 2016).

Evolve from point-to-point hub-and-spoke transport to distributed multi-segment intermodal transport. With this feature, PI contributes to reduce driving distances and durations, greenhouse gas emissions and social impact of truck driving (Fazili et al., 2017).

Embrace a unified multi-tier conceptual framework. In urban environments, this characteristic can be manifested as appropriate urban pixelization and an interconnected multi-layer logistics web linking meshed networks (Montreuil et al., 2018).

Activate and exploit an open global supply web. Supply network nodes should be accessible to most actors, enabling on-demand service capacity usage and effective handling of stochastic client demand (Ballot et al., 2020). Nodes can be classified into four categories: production fabs, deployment centers, logistics hubs and customer interfaces (Montreuil, 2020). Production fabs, conceived under the hyperconnected mobile production framework, incorporate distributed, outsourced, on-demand, modular, additive, mobile, containerized, and hyperconnected production strategies (Fergani et al., 2020). Deployment centers facilitate the prepositioning of objects to efficiently fulfill demand, while logistics hubs streamline processes such as consolidation, cross-docking, sorting, swapping, and transshipping. Customer interfaces encompass smart lockers, retail stores, and other points of customer interaction.

Design products fitting containers with minimal space waste. Product design should consider logistics, ensuring compatibility with specific container sizes and easy completion near the point of use. This entails creating modular products for quick assembly, disassembly, and adaptation to local conditions. This idea can be considered as an integration of design tools, including design for assembly, disassembly, and logistics (Chiu & Okudan, 2010).

Minimize physical moves and storages by digitally transmitting knowledge and materializing objects as locally as possible. This can be achieved by standardized dematerialization specifications, readily accessible hyperconnected mobile production facilities, and robust legal safeguards to protect intellectual property and ensure product authenticity. 3D printing is a promising technology for the implementation of this feature (Ryan et al., 2017).

Deploy open performance monitoring and capability certifications. PI emphasizes the need for live, globally accessible performance tracking, which promotes informed decision-making and continuous improvement. Transparency is essential for building trust and collaboration among logistics stakeholders. Encouraging improvement through benchmarking based on publicly available performance records fosters continuous innovation within the industry.

Prioritize webbed reliability and resilience of networks. In PI, the network utilization adapts to reduce adverse effects by effectively combining transport and storage resources, altering modes and routes as needed. This ensures consistently high network performance and a guaranteed service level (Ballot et al., 2020; Kulkarni et al., 2022).

Stimulate business model innovation. PI requires a paradigm shift in the logistics industry, prompting stakeholders to adapt and seize opportunities. By promoting diverse business models and collaboration among manufacturers, distributors, and retailers, PI fosters innovation, efficiency, and sustainability in the logistics ecosystem.

Enable open infrastructural innovation. PI encourages the enhancement of infrastructure capacity by leveraging standardizations, rationalizations and automations (Montreuil, 2011). Such advancements are expected in vehicles, carriers, facilities and their interconnections.

3   Hyperconnected Circular Supply Chains

In this section, we present the Hyperconnected Circular Supply Chain (HCSC) framework, depicted in Figure 1. The framework is composed of nine key characteristics that contribute to the improvement of product design, manufacturing, logistics operations, ultimately promoting circularity and interconnectivity within supply chains. These characteristics are derived from merging CSC and PI features discussed in Section 2. The connections between HCSC and PI features, as well as HCSC and CSC features, are visually illustrated in Figure 2 through a qualitative Sankey diagram. HCSC features are displayed in the center, and the flows connecting CSC and PI features represent their relative contributions to the development of HCSC features. The nine characteristics of HCSC will be elaborated upon in the subsequent parts of this section.
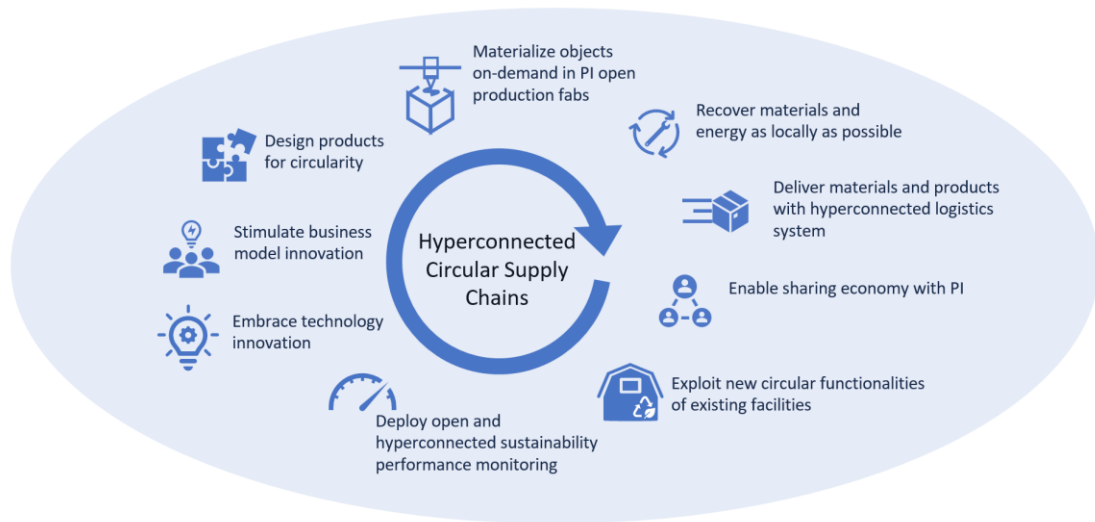

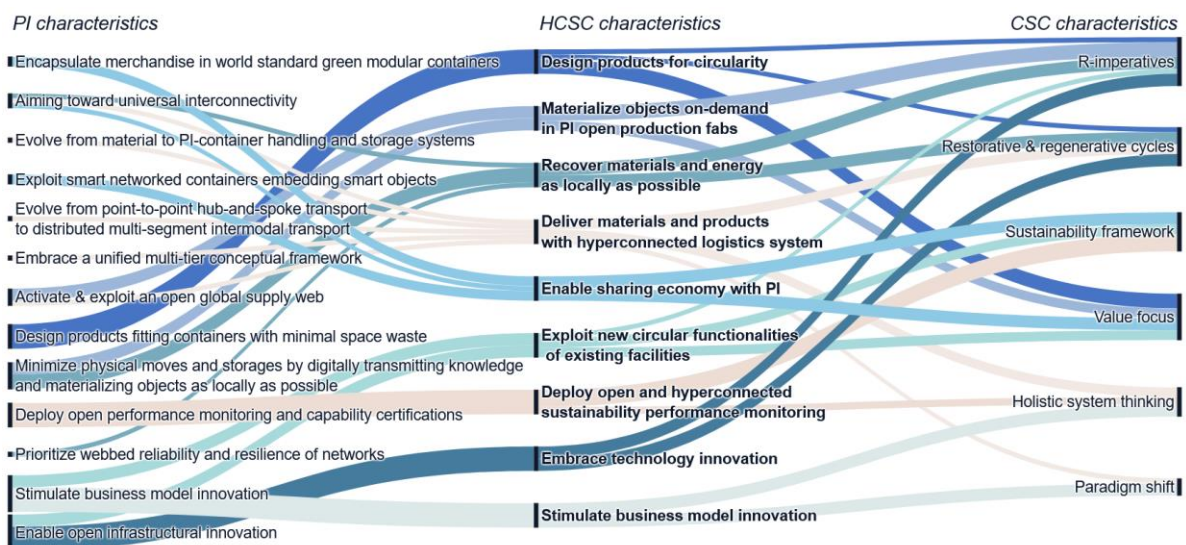*Figure 1: Core characteristics of Hyperconnected Circular Supply Chains*

Figure 2: Interrelationships between HCSC, PI, and CSC features

3.1 Design products for circularity

In the HCSC framework, products are specifically designed to ensure they can be easily disassembled, repaired, ungraded and recycled. Emphasis is placed on modular design, where products are composed of self-contained units or modules (Nowak et al., 2018). Product subassemblies and modules should be tailored to specific PI-container sizes to fully capitalize on the efficient logistics operations enabled by PI.

Repairing and upgrading of products are significantly simplified for end-users due to the ease of exchanging modules with new, refurbished, or upgraded ones. The rapid delivery of these modules, facilitated by the efficient logistics operations of PI, further contributes to the accessibility of repairing and upgrading processes, thus retain values. Moreover, the cost of repairing or upgrading an existing product is expected to be considerably lower than purchasing a new one, making it a more sustainable and economically viable option for consumers. Additionally, recovery processes for products are smoother as a result of their easy disassembly. This allows for the seamless reintegration of modules and units into another usage cycle following appropriate treatment.

3.2 Materialize objects on-demand in PI open production fabs

Products are occasionally discarded due to the unavailability of spare parts or the prohibitive cost of sourcing or producing the necessary components. PI open production fabs can address this issue by manufacturing spare parts on demand and close to the point of use. By digitally transmitting drawings and production specifications for required spare parts to PI open production fabs, localized production can be achieved, enabling rapid delivery to users. Additive manufacturing is one of the key technologies that empowers localized on-demand manufacturing (Foshammer et al., 2022).

Materializing objects on demand can also help address the complexity arising from product differentiation strategies employed by manufacturers. These strategies are intended to attract customers but can create significant additional workload for product recovery processes. Customized refurbishment or upgrading solutions often need to be developed for each model within a product category. The HCSC framework offers a potential solution by proposing a single standard core for refurbishment or upgrading, with model compatibility addressed by the customized production capabilities of open production fabs, operating on demand.

This HCSC feature helps extend product lifetimes and preserve value by simplifying repairs, refurbishments, and upgrades. It is enabled by the PI's open global supply web and guided by the principle of minimizing physical moves and storages.

3.3 Recover materials and energy as locally as possible

The zero-waste vision of CSC highlights the potential for outputs from one actor to serve as inputs for others. "Waste" can be converted into valuable resources through recycling (materials recovery) and thermal processing (energy recovery) (Themelis & Bourtsalas, 2019). Building recycling centers and waste-to-energy power plants within or near urban areas can contribute to localized resource utilization and minimizing transportation needs.

This feature exemplifies the PI principle of minimizing physical moves and storages while simultaneously leveraging and promoting universal interconnectivity and network resilience. As actors interconnect through resources and energy, their dependence on remote suppliers diminishes, leading to a more efficient supply chain with increased resilience. Moreover, it supports the implementation of R-imperatives and fosters restorative and regenerative cycles.

3.4   Deliver materials and products with hyperconnected logistics system

The enhanced logistics efficiency provided by PI can significantly transform the way that objects are realized, used, and recovered. In HCSC, multiple options are provided for users to return end-of-life products, such as home pick-up, retail store, recycling bins, or smart lockers (Bukhari et al., 2018). The hyperconnected logistics system ensures a smooth circulation of materials and products.

This feature is empowered by several characteristics of PI, including universal interconnectivity, PI-container handling and storage systems, distributed multi-segment intermodal transport, a unified multi-tier conceptual framework and an open global supply web. It can facilitate the cycling of materials and potentially drive a paradigm shift.

3.5   Enable sharing economy with PI

The sharing economy is characterized by consumers providing temporary access to their under-utilized physical assets ("idle capacity") to one another, often in exchange for financial compensation (Böcker & Meelen, 2017). This concept can also be found in the Service Web of PI, which aims to enhance the accessibility and usage of assets and goods through interconnected open pooling (Darvish et al., 2014). For instance, it is conceivable that infrequently used tools, such as hand tools, gardening tools, or power tools, can be easily transported via hyperconnected logistics network. Customers can access these tools without incurring high ownership costs, using them as needed. The production of fewer tools overall leads to reduced energy and resource consumption.

This feature aligns with the value focus and sustainability aspects of CSC. By using objects more efficiently, value is retained. Economic, environmental and social benefits are expected, as both providers and users can receive monetary rewards, efficient use of goods can conserve resources otherwise needed for production, and beneficial human interactions can be fostered.

3.6   Exploit new circular functionalities of existing facilities

Both CSC and PI recognize the presence of untapped value in existing assets, and exploring alternative uses for these assets can contribute to enhanced efficiency and sustainability. CSC emphasizes the importance of R-imperatives, wherein repurposing materials or components is a common practice. PI seeks to optimize production, logistics and transportation assets utilization. For example, public transportation vehicles and infrastructure are employed for parcel delivery (Crainic & Montreuil, 2016), thereby reducing the need for additional trucks in urban areas.

In HCSC framework, the potential of existing customer interfaces and other infrastructure will be maximally exploited to smoothly interconnect circular processes and make CE practices more accessible to end users. For instance, retail stores can integrate repair, refurbishment, and recycling functions for certain products.

This feature necessitates innovation in both business models and infrastructure to unlock additional value for existing facilities. By generating revenue, reducing environmental impact through the avoidance of new constructions, and creating job opportunities, it contributes to the triple bottom line of sustainability.

3.7   Deploy open and hyperconnected sustainability performance monitoring

In the HCSC framework, the implementation of performance assessment and capability certification systems necessitates the inclusion of sustainability and CE metrics, in addition to traditional measures such as speed, service level, and reliability. These new metrics can be

categorized into four dimensions: circularity, economy, environment, and society (Vegter et al., 2020; Montag & Pettau, 2022). By employing an open and hyperconnected performance tracking system and incorporating holistic system thinking, continuous improvement and innovation are encouraged across all stakeholders within a supply chain ecosystem.

3.8   Embrace technology innovation

Transitioning to a CSC requires an innovation-rich process that includes restructuring and adjustment, with both technical and non-technical aspects needing consideration. Technological innovation can enhance the eco-design of products, services, and promote sustainable consumption (Kasmi et al., 2022).

This feature capitalizes on the PI's ability to facilitate open infrastructural innovation, contributing to a greater variety of material and energy recovery options and improving the circulation of materials and energy.

3.9   Stimulate business model innovation

Similar to PI, HCSC fosters the evolution of business models. As CSC hinges on cooperative efforts among multiple actors and system-wide integration, innovative organizational and commercial approaches are needed to enable stakeholder cooperation and potentially trigger a paradigm shift. The ReSOLVE framework, featuring regenerate, share, optimize, loop, virtualize, and exchange as key business actions, was introduced by the Ellen MacArthur Foundation (2015) as a tool to generate circular initiatives.

4   Conclusion and Perspectives

The Hyperconnected Circular Supply Chain (HCSC) framework proposed in this paper aims to offer a comprehensive set of guidelines for implementing Circular Supply Chains (CSC) by harnessing the synergy between CSC and Physical Internet (PI). This framework comprises nine core characteristics that encompass product design, manufacturing, waste management, logistics, performance monitoring, and innovation. It is designed to be serving as a blueprint for various supply chain stakeholders to follow in order to optimize resource utilization, reduce waste, and minimize the environmental impact of their operations while maintaining high levels of customer satisfaction. Transitioning towards HCSC necessitates embracing change, proactively adapting products and processes, fostering collaboration, and promoting open communication on best practices.

Future research avenues include further refining and expanding of the HCSC framework to incorporate additional characteristics; exploring the framework's full potential through case studies across various industries; investigating its implementation potentiality at different scales through simulations, digital twins, field pilots, and living labs; quantifying, analyzing and learning from a multi-criteria and holistic perspective.

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Resilience Assessment of Hyperconnected Parcel Logistic Networks Under Worst-Case Disruptions

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Abstract: *Logistics networks that shape the Physical Internet's logistics web are prone to potentially adversarial disruptions that impact their performance severely. In this article, we study a network interdiction problem on a multi-commodity flow network in which an adversary totally disrupts a set of network arcs with an intention to maximize the operational costs of delivering parcels. We formulate it as a two-stage mixed-integer linear program. To solve such complex large-scale program, we use linear programming duality and provide an algorithm based on the structure of the program that computes the set of network arcs that can be interdicted in order to reduce its size. Finally, we use the model and solution framework to evaluate the resilience capabilities of topology optimized hyperconnected networks and compare it with lean networks. We find that our developed solution methodology reduces the size of network interdiction program substantially and showcases superior computational performance against off-the-shelf optimization solvers. Furthermore, the resilience comparison between hyperconnected networks and lean networks depicts enhanced capabilities of the topology optimized hyperconnected networks to sustain worst-case disruptive events as opposed to that of lean logistics networks.*

Keywords: *Hyperconnected networks, Resilience, Worst-case disruptions, Stackelberg game, Physical Internet*

Conference Topic(s): *Logistics and supply networks.*

Physical Internet Roadmap *(Link):* ☐ *PI Nodes,* ☒ *PI Networks,* ☐ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

1 Introduction

Due to increased internet accessibility to a wider population worldwide, there has been an upsurge in world-trade and e-commerce industry. This has ultimately led to a steep growth of the parcel delivery industry across the globe (Jin, 2018). This parcel delivery industry is inherently characterized by its reliance on numerous assets, such as hub facilities and vehicles, to deliver parcels to customers. These customers are spread out across a wide geographical region with an ever-increasing expectation of swift parcel delivery in a reliable manner. Such complex operations require meticulous planning and proper execution. Hub network design forms one of the major components of the planning phase (Cordeau et al., 2006). These hub facilities serve as parcel sortation and consolidation centers which are used to generate shipments and send them towards their respective destinations. Routing parcels through these hub facilities help consolidate them together thus yielding savings in transportation costs and

greenhouse emissions and increasing the ability to provide better service between locations due to frequent transport connections.

Hub network design has been widely studied in the literature for the past thirty-five years (Campbell & O'Kelly, 2013) and hub-and-spoke networks have been recommended for parcel delivery industry. These hub-and-spoke networks are hierarchical networks which force parcel(s) to go through central hub(s) in order to consolidate them together and then deliver them to destination locations. This induces unnecessary travel for parcels and gives rise to parcel congestion at hub(s) at peak delivery times (Montreuil et al., 2018; Tu & Montreuil, 2019). In order to mitigate these issues, hyperconnected networks are proposed in the realm of Physical Internet (Montreuil, 2011). These hyperconnected networks are multi-plane open access interconnected hub meshed webs that link hubs at multiple planes. These densely connected meshed networks provide better degrees of freedom for parcel movement while retaining the benefits of cost savings achieved through parcel consolidation.

All hub networks, including hyperconnected networks, face various types of disruptions on a daily basis. These disruptions include but are not limited to traffic congestion on roads, power failure at hub facilities, hub throughput reduction due to pandemic, and total breakdown of network components in a region due to a natural disaster. These disruptive events lead to increased operational costs, late parcel deliveries, decreases in customer satisfaction, and ultimately lesser profit margins. Hence, it is essential to prepare against such disruptions. On a broader level, these disruptions can be classified as either total or partial disruptions (Mohammadi et al., 2016). A total disruption of a network component refers to the component being totally dysfunctional whereas a partial disruption of a component would render it functional but at a reduced capacity. All in all, due to the regular occurrence of such disruptive events across the hyperconnected networks, it is indeed paramount to develop a toolkit to assess the resilience of such networks.

There has been a growing interest among researchers regarding network resilience and its evaluations. For supply chain and logistics networks, one of the definitions of network resilience is the ability of a network to provide acceptable service level in presence of disruptions (Smith et al., 2011). One of the widely researched directions for resilience evaluation is through simulating disruptive events on the logistics networks to understand their performance under such events. Such experiments are usually termed as disruption experiments and they serve as a medium to understand the resilience properties of such network in depth (R. Li et al., 2017; Osei-Asamoah & Lownes, 2014). These experiments can simulate different types of disruptive events in which the network components fail either in a random manner or in a localized manner (Kulkarni et al., 2021). However, due to limitations in computing infrastructure, simulating all possible disruption events is pragmatically infeasible. To tackle such situations, analytical methods are developed to estimate the resilience of the pertinent network. These analytical methods study the network's structural properties, which estimate the vulnerability of the network and approximate its susceptibility to disruptions. These topological measures include but are not limited to node/edge degree, reachability, closeness centrality, betweenness centrality, short path lengths, and number of edge-disjoint paths (Bai et al., 2020; Ip & Wang, 2009, 2011; Kim et al., 2017; Kulkarni et al., 2021, 2022). Indeed, these simulation experiments or the topological measures provide a resilience assessment toolkit for stochastic disruptive events only.

Although useful, the above-mentioned disruption experiments require data about disruptive events in order to simulate them and evaluate resilience of the networks. However, availability of such data about the disruptive events is often limited which makes the results of the disruption experiments less accurate. One such instance is disruptions due to natural disasters.

As they occur very infrequently, having good quality data about them to prepare response actions is difficult. Nonetheless, as such disruptions cause significant harm to the networks, it is of paramount importance to be prepared for such events. Such disruptions are termed as worst-case disruptions and logistics networks are prone to them. As a result, there is a need to also develop a tool to assess resilience of the networks under such worst-case disruptive events. In such worst-case disruptions, a fictitious malicious attacker disrupts network components in such a way that causes maximum harm to the network operations. Such situations are modelled through game-theoretic approaches using optimization framework (Lim & Smith, 2007). In particular, such games known as Stackelberg games involve two-person decision making usually with conflicting objectives to attain and the problem is widely known as a network interdiction problem (Wood, 1993; Washburn & Wood, 1995). In this problem, the first player, a leader, is an adversary who fully or partially disrupts network components in order to block the follower's commodity flow. Such settings are modelled through two-stage optimization formulations and techniques from robust optimization are employed to solve them. Multiple variants of this problem are studied in the literature differentiated by the leader's objective. These include but are not limited to shortest path interdiction where leader aims to maximize the total shortest path length(s) that follower can use (Israeli & Wood, 2002); maximum flow interdiction where the leader aims to minimize the total commodity flow the follower can send in the network (Wollmer, 1964); minimum cost interdiction where the leader maximizes the cost that the follower face in order to fulfill the commodity demand in the network (Lim & Smith, 2007).

The contributions of the article are three-fold. First, we study the network interdiction problem through a Stackelberg (leader-follower) game where the leader (or interdictor) maximizes the parcel delivery costs and the followers objective is to minimize the costs after disruption. We formulate the said problem as a two-stage mixed-integer program where the outer problem belongs to the adversary where they maximize the cost of parcel delivery through interdicting transportation edges under a given interdiction budget. The inner decision problem belongs to the logistics company where they minimize the cost of parcel delivery operations, modelled as minimum-cost multi-commodity network flow problem after the edge interdictions. Our problem generalizes the shortest path interdiction problem proposed by (Israeli & Wood, 2002) to account for multiple commodities. Second, we analyze the structure of the problem and provide a two-phase methodology to solve the problem exactly. In the first phase we smartly deduce the network components that can be disrupted in the worst-case, which helps us reduce the size of the optimization formulation drastically. In the second phase we solve this new smaller optimization problem directly to obtain an optimal solution of the original problem. Third, we perform experiments to understand the computational performance of our solution approach, and then we compare the resilience capabilities of topology optimized hyperconnected networks generated through various methods (as proposed in the literature) with that of lean hyperconnected networks. The computational experiments depict the ability of developed solution methodology to efficiently evaluate the resilience of hyperconnected networks in worst-case disruptions as opposed to using optimization solvers. Next, these results indicate that the increase in operational costs during worst-case disruptions in topology optimized hyperconnected networks is lesser than that of lean hyperconnected networks. Moreover, the topology optimized hyperconnected networks are better able to maintain connectivity between the O-D pairs to allow parcel flow than the connectivity maintained by lean hyperconnected networks.

The rest of the paper is organized as follows: Section 2 describes the problem setting and formulates it through a two-stage mixed-integer linear program. Section 3 discusses the nature

of the formulated problem and describes the solution methodology to solve the problem exactly. Next, we provide in Section 4 an in-depth computational study where we analyze the computational performance of the developed solution methodology against that of an optimization solver and compare the resilience of the hyperconnected networks with that of lean networks under adversarial disruptions. Finally, Section 5 lays out the concluding remarks and presents avenues of future research.

2 Problem Description

We consider a logistics company or group of such companies that delivers parcels across a given geographical region through its network. The company is interested in assessing the performance of its logistics network during a worst-case disruptive event, i.e., in a worst-case disruption scenario.

Formally, we consider a set of locations $\mathcal{S}$ where the parcel demand originates and a set of locations $\mathcal{T}$ where the parcels must be delivered. Let $\mathcal{P} \subseteq \mathcal{S} \times \mathcal{T}$ be the set of origin-destination (O-D) pairs of interest with each pair $p \in \mathcal{P}$ having a demand of d_p parcels. The company has opened a set of logistics hubs $\mathcal{H}$ at discrete locations to serve the O-D pairs. We consider the directed graph $\mathcal{G} = (\mathcal{S} \cup \mathcal{H} \cup \mathcal{T}, \mathcal{A})$ where commodities are transported from origins $\mathcal{S}$ through logistics hubs $\mathcal{H}$ to finally be delivered at destinations $\mathcal{T}$ through available transportations arcs $\mathcal{A} \subseteq (\mathcal{S} \cup \mathcal{H} \cup \mathcal{T})^2$. These logistics hubs serve as locations where the parcels are sorted and shipped towards their respective destinations. As these parcels are not stored for a longer duration at these hubs, the hub capacities are not restrictive. So, we assume that the hub has sufficient capacities to sustain the logistics operations and satisfy the demand. Moreover, due to the huge volume of parcel flows that the network faces, the parcel flow costs can be approximated through a linear flow function. Hence, for a parcel to traverse a transportation arc $(i, j) \in \mathcal{A}$, it faces a cost of $c_{i,j}$ per unit of parcel.

In order to evaluate the performance of the network under the worst-case disruption, we consider a fictitious adversary (leader) who intends to interdict network arcs to maximize the total parcel delivery cost. We assume that the adversary has a budget of totally interdicting β arcs in the network. We model this decision through a binary variable $x_{i,j} \in \{0,1\}$ that assumes a value 1 if the arc $(i, j) \in \mathcal{A}$ is interdicted or 0 otherwise. Next the logistics company (follower) responds to the disruption through routing the parcel flow in the network for each O-D accordingly to incur minimum possible cost. To this end, we define continuous parcel flow variables $f_{i,j}^p \geq 0$ for each transportation arc $(i, j) \in \mathcal{A}$ and between each O-D pair $p \in \mathcal{P}$. Now, the problem can be formulated as the following two-stage mixed-integer linear program:

$$E(\mathcal{P}, \mathcal{A}) = \max_x \min_f \sum_{p \in \mathcal{P}} \sum_{(i,j) \in \mathcal{A}} (c_{i,j} + M \cdot x_{i,j}) f_{i,j}^p \tag{1}$$

subject to:

$$\sum_{j \in \mathcal{T} \cup \mathcal{H}|(s,j) \in \mathcal{A}} f_{s,j}^p = d_p, \qquad \forall p = (s,t) \in \mathcal{P} \tag{2}$$

$$\sum_{i \in \mathcal{S} \cup \mathcal{H}|(i,t) \in \mathcal{A}} f_{i,t}^p = d_p, \qquad \forall p = (s,t) \in \mathcal{P} \tag{3}$$

$$\sum_{j \in \mathcal{T} \cup \mathcal{H}|(i,j) \in \mathcal{A}} f_{i,j}^p = \sum_{j \in \mathcal{S} \cup \mathcal{H}|(j,i) \in \mathcal{A}} f_{j,i}^p, \qquad \forall p = (s,t) \in \mathcal{P}, \forall i \in \mathcal{H} \tag{4}$$

$$\sum_{(i,j)\in\mathcal{A}} x_{i,j} \leq \beta \tag{5}$$

$$f_{i,j}^p \geq 0, \qquad\qquad\qquad \forall p = (s,t) \in \mathcal{P}, \forall (i,j) \in \mathcal{A}$$

$$x_{i,j} \in \{0,1\}, \qquad\qquad\qquad \forall (i,j) \in \mathcal{A}.$$

The outer problem represents the decision problem of the adversary who maximizes the total transportation cost of the parcels by interdicting network arcs. Constraint (5) restricts the number of interdicted arcs based on the available arc interdiction budget. The inner problem represents the response by the logistics company and is a multi-commodity minimum-cost-network-flow problem. It minimizes the total transportation costs of parcels after the arc interdictions. We allow parcels to flow through interdicted arcs but with a very high penalty of M units in addition to the regular transportation costs. It indeed incentivizes the parcels to travel along uninterdicted arcs unless no other alternative is present. Constraints $(2) - (4)$ enforce the commodity flow balance conditions at each node. Finally, the remaining constraints define the domain of the involved decision variables.

By solving this two-stage optimization problem, we can estimate the performance of logistics networks under worst-case disruptions. However, this program cannot be directly fed to optimization solvers due to its bilevel nature and is challenging to solve even for small sparse network instances. In the next section, we propose a solution methodology to optimally solve this problem for large-scale densely connected networks such as hyperconnected networks.

3 Solution Methodology

In order to develop a solution framework to solve the optimization problem described by equations $(1) - (5)$, we study the structure of the problem. A closer inspection of the problem indicates that the decision problem of the logistics company i.e., the inner decision problem is indeed a linear program due to the presence of continuous f variables only. As a consequence, we can leverage tools from linear programming duality theory to study the problem. Let π_i^p be the corresponding dual variables of constraints $(2) - (4)$, for every $p \in \mathcal{P}$ and every $i \in (\mathcal{S} \cup \mathcal{H} \cup \mathcal{T})$. Therefore, taking the dual gives us:

$$E(\mathcal{P}, \mathcal{A}) = \max_{x,\pi} \sum_{p=(s,t)\in\mathcal{P}} d_p(\pi_s^p - \pi_t^p) \tag{6}$$

$subject\ to$:

$$\pi_i^p - \pi_j^p \leq c_{i,j} + M \cdot x_{i,j}, \qquad\qquad \forall p \in \mathcal{P}, \forall (i,j) \in \mathcal{A} \quad (7)$$

$$\sum_{(i,j)\in\mathcal{A}} x_{i,j} \leq \beta \tag{8}$$

$$x_{i,j} \in \{0,1\}, \qquad\qquad\qquad \forall (i,j) \in \mathcal{A}.$$

From this dualization procedure, the two-stage program is reduced to a lesser complex single-stage mixed-integer linear program. However, this newly obtained mixed-integer linear program $(6) - (8)$ comprises $(|\mathcal{P}| \times |\mathcal{A}| + 1)$ constraints, which still are substantially high. One potential option to reduce the size of the problem through analyzing the adversary's behavior is via figuring out the set of network arcs $\mathcal{A}' \subseteq \mathcal{A}$ that can be interdicted in the worst-case disruption. To this end, we perform an analysis of the decision problem of the logistics company. As we know, it is a multi-commodity minimum-cost-network-flow problem. Due to

absence of capacity restriction at logistics hubs, the minimum-cost route to deliver parcels for each O-D pair $p = (s, t) \in \mathcal{P}$ can be computed independently and will resemble the shortest path between the corresponding origin s and the destination t. Hence, given the interdicted arcs, the problem of the logistics company can be decomposed into $|\mathcal{P}|$ independent sub-problems with each sub-problem solved through finding the shortest O-D path on the available network after arc interdictions.

Now, let us understand which arcs will be interdicted in worst-case disruptions based on the interdiction budget. When $\beta = 0$, i.e., no arcs are interdicted, the logistics company will use the shortest path on the original graph $\mathcal{G}$ to transport parcels between each O-D pair. Let $\mathcal{A}_1$ be the set of such arcs. When $\beta = 1$, the adversary will interdict one of the network arcs from set $\mathcal{A}_1$ that will cause highest transportation cost increase. Now, when $\beta = 2$, the adversary will interdict at least one arc from $\mathcal{A}_1$ and the other (if budget allows) from the set of arcs $\mathcal{A}_2$ that comprises arcs of the second shortest paths between each O-D pair when one of the arcs from $\mathcal{A}_1$ is interdicted.

Indeed, this showcases that the network arcs that will be interdicted depends upon the available interdiction budget. It can be obtained by decomposing the problem for O-D pair p and using a search tree. The search tree iteratively obtains all permutations of arcs that can be interdicted and then subsequently computes the next shortest path for transportation of parcels. Algorithm 1 outlines the procedure to compute such arc set $\mathcal{A}'$. Once $\mathcal{A}'$ is obtained, we formulate this reduced problem $E(\mathcal{P}, \mathcal{A}')$ and feed directly to the optimization solver. In order to achieve even more speedups, we set $\pi_t^p = 0$ for every $(s, t) \in \mathcal{P}$ in $E(\mathcal{P}, \mathcal{A}')$ as π is invariant to translation.

Algorithm 1: Search strategy to find $\mathcal{A}'$

> **Input**   : Original Graph $\mathcal{G} = (\mathcal{S} \cup \mathcal{H} \cup \mathcal{T}, \mathcal{A})$, Interdiction budget β
> **Output**   : Subset of Arcs $\mathcal{A}' \subseteq \mathcal{A}$ that can be interdicted

1 Initialize: Set of arcs $\mathcal{A}' \leftarrow \emptyset$;
2 **for** every $(s, t) = p \in \mathcal{P}$ **do**
3   Initialize: Set of search tree nodes $\mathcal{N} \leftarrow \emptyset$, Interdicted Arcs at each node $(\mathcal{I})_{n \in \mathcal{N}} \leftarrow \emptyset$, Tree depth at each node $(\mathcal{D})_{n \in \mathcal{N}} \leftarrow 0$, Children of each node $(\mathcal{C})_{n \in \mathcal{N}} \leftarrow \emptyset$, Shortest path at each node $(\mathcal{SP})_{n \in \mathcal{N}} \leftarrow \emptyset$, Copy of Graph at each node $(\mathcal{X})_{n \in \mathcal{N}} \leftarrow$ Copy of $\mathcal{G}$, nodes counter $m \leftarrow 0$;
4   Append root node r: $\mathcal{N} \leftarrow \mathcal{N} \cup \{r\}$;
5   **while** $\mathcal{N} \neq \emptyset$ **do**
6   Select a node $n \in \mathcal{N}$ and remove the arcs $\mathcal{A}_n \leftarrow \mathcal{A}_n \setminus \mathcal{I}_n$ in the graph $\mathcal{X}_n$;
7       $\mathcal{SP}_n \leftarrow$ Shortest path for between s and t in the graph $\mathcal{X}_n$;
8   **if** $\mathcal{D}_n \leq \beta$ **then**
9   **for** every $(i, j) \in \mathcal{SP}_n$ **do**
10             $m \leftarrow m + 1, \mathcal{I}_m \leftarrow \mathcal{I}_n \cup \{(i, j)\}, \mathcal{C}_n \leftarrow \mathcal{C}_n \cup \{m\}, \mathcal{D}_m \leftarrow \mathcal{D}_n + 1, \mathcal{N} \leftarrow \mathcal{N} \cup \{m\}$, $\mathcal{A}' \leftarrow \mathcal{A}' \cup \{(i, j)\}$;
11       $\mathcal{N} \leftarrow \mathcal{N} \setminus \{n\}$;
12 **return** $\mathcal{A}'$

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4 Computational Study

In this section, we apply the developed resilience performance evaluation framework on various types of logistics networks. To this end, first we design multiple large-scale hyperconnected intercity parcel logistics hub networks to be the backbone infrastructure of China for ground transportation and consolidation of parcels. The networks are able to serve regions that house

93.58% of the Chinese population, are spread across 95.09% of the Chinese inhabitable land, and generate 94.42% of total Chinese GDP (Li et al., 2018). We design these networks through minimizing k-shortest paths (Kulkarni et al., 2021) and k-shortest edge-disjoint paths between each O-D pair (Kulkarni et al., 2022). We generate networks with number of paths, $k \in \{2,4\}$ and the hub cardinality, $N \in \{60,70,80,90\}$.

First, we show the value of the developed solution methodology in assessing the resilience performance of k-shortest edge-disjoint path networks. Table 1 depicts the computational performance of our methodology against that of the off-the-shelf optimization solver Gurobi when we assess the k-shortest edge-disjoint path networks of various cardinalities with an interdiction budget of 2. Due to the presence of large number of variables and constraints, Gurobi struggles to solve the problem and after 12 hours of execution as well is not able to obtain an optimal solution. In particular, the last retrieved optimality gaps in such cases are at least 500%, which showcases the best-known solution at the end of 12 hours is potentially far-off from the true optimal solution. On the other hand, we observe that the set of arcs that can be interdicted $\mathcal{A}'$ computed via Algorithm 1 is around half of the total arc set $\mathcal{A}$. As a consequence, this helps us reduce the size of the problem drastically. Specifically, the number of variables and constraints are reduced by at least 82% and 97% respectively. This reduced-size problem when next fed to Gurobi is solved in under a minute with total time required being under two minutes. Indeed, these results depict the efficacy of the developed solution methodology through which we can solve large-scale problems optimally and quickly. In turn, this methodology can be leveraged by any logistics company for resilience evaluation of their networks in the worst-case disruptions.

Table 1: Computational performance of developed solution methodology for k-shortest edge-disjoint path networks ($k = 2$) and interdiction budget $\beta = 2$.

Method	N	$|\mathcal{A}|$	$|\mathcal{A}'|$	# Variables	# Constraints	Total time (sec)	Optimality gap (%)
Algorithm 1 + Gurobi	60	1005	586	3137	4288	54	0
	70	1074	656	3227	4571	59	0
	80	1344	767	3312	4836	62	0
	90	1429	817	3403	5912	82	0
Gurobi	60	1005	-	18207	150,976	43200	504.5
	70	1074	-	18641	163,420	43200	831.4
	80	1344	-	21290	212,830	43200	1392.5
	90	1429	-	23388	261,777	43200	1965.2

Next, we compare the performance of these topology optimized hyperconnected networks with that of lean hyperconnected networks which are designed through efficiency considerations only. These lean networks are obtained through minimizing the (first) shortest path for each O-D pair with same hub cardinality as that of hyperconnected networks. Table 2 shows the comparison results of performance of these networks under various worst-case disruptions characterized by $\beta \in \{1,2,3,4,5\}$. We can observe that in all the networks, these worst-case disruptions fully disconnect multiple O-D pairs, which prevents the parcels from reaching the corresponding destinations. With an increase in the strength of the disruption event, we observe the number of O-D pairs that are disconnected increases. However, this effect is more nuanced. The topology optimized hyperconnected networks outperform the lean hyperconnected networks as they guarantee the flow of parcels for larger proportion of O-D pairs during a disruption event. In majority of cases, the disconnected O-D pairs for the k-shortest path or k-

shortest edge-disjoint path networks are half of their lean counterpart. This can be attributed to the presence of multiple paths that connect each O-D pair in the proposed hyperconnected networks. Moreover, the proposed hyperconnected networks guarantee this better O-D pair connectivity with overall lesser additional cost incurred during the worst-case disruptions for the connected O-D pairs. In particular, the percentage increase in costs for lean hyperconnected networks is at least two times more than that of topology optimized hyperconnected networks. Because these hyperconnected networks are designed through minimizing either multiple short paths or multiple edge-disjoint short paths, these hyperconnected networks have paths of comparable lengths which can be traversed during such disruption. The additional travel incurred in such cases is minimal, which is reflected through lower percentage increase in operational costs in hyperconnected networks. Importantly, in terms of both degradation metrics, the topology optimized hyperconnected networks worsen at comparatively slower rate than lean hyperconnected networks that worsen in a rapid manner. Overall, topology optimized hyperconnected networks outperform the lean hyperconnected networks substantially in terms of both maintaining better connectivity between the O-D pairs as well as lesser additional cost incurred under such adversarial disruptive event due to the presence of multiple short paths of comparable lengths.

Table 2: Performance of networks with size $N = 60$ in worst-case disruptions

Degradation Metric	Interdiction Budget (β)	Lean networks	k-shortest path networks		k-shortest edge disjoint path networks	
			$k = 2$	$k = 4$	$k = 2$	$k = 4$
# O-D pairs disconnected during the disruption	1	0	0	0	0	0
	2	3	3	0	1	0
	3	7	7	2	3	0
	4	16	13	11	10	6
	5	23	20	14	15	12
% Increase in costs for connected O-D pairs during the disruption	1	0.1096	0.06870	0.0027	0.19157	0.0265
	2	1.5051	0.48908	0.0584	1.63959	0.0763
	3	4.2091	2.06826	0.3765	1.03674	0.5112
	4	7.3841	2.20335	2.2176	0.00000	0.0000
	5	0.0000	2.33931	0.5587	0.00958	0.0042

Among k-shortest path networks or k-shortest edge-disjoint path networks, the latter in all disruptive events are able to maintain better connectivity between the O-D pairs; this is attributed to the presence of overall higher number of edge-disjoint paths that help maintain the connectivity. On the other hand, the additional costs incurred during the disruptions depict an interesting behavior. For lower disruption strength, specifically when $\beta \in \{1,2\}$, the k-shortest path networks depict lower additional costs increase whereas for higher strength of disruption, the k-shortest edge-disjoint path networks showcase better performance. As k-shortest path networks comprise of multiple paths of comparable lengths, it leads to lower increase in costs for lower strengths of disruptions. Moreover, because such paths have overlapping edges, and when such edges are disrupted in events with higher values of β, the additional cost incurred is considerably higher which doesn't occur in k-shortest edge-disjoint path networks.

Finally, we analyze the performance of hyperconnected designed with different values of k. Among these networks, we notice that with increase in value of k, the resilience capabilities of the networks also increase. As we decrease the value of k, higher number of O-D pairs are

being disconnected and the increase is costs are higher as well. All in all, these worst-case disruption experiments corroborate the network performance predictions proposed by (Kulkarni et al., 2022) and demonstrate the value of considering network structure while designing hyperconnected networks to generate resilient logistics networks.

5   Conclusion

In this article, we motivate the need of assessing hyperconnected networks under adversarial attacks in the realm of Physical Internet. To the best of our knowledge, this paper serves as one of the initial investigations that provides a framework to assess the resilience of the hyperconnected networks in such worst-case disruptive events. We take inspiration from Stackelberg games and formulate a two-stage mixed-integer linear program that provides performance (in terms of costs) of a logistics network in the worst-case disruption. In order to solve the optimization problem optimally, we leverage tools from linear-programming duality theory to reduce the problem to a single-stage mixed-integer program. Furthermore, to reduce the size of the single-stage program, we study the arc(s) interdiction behavior and propose a search strategy that obtains the network arcs that can be interdicted. Finally, we solve the reduced single-stage program for the subset of arcs that can be interdicted through an off-the-shelf optimization solver to obtain the total operational costs faced by the network in the worst-case disruption.

In the computational study, we first design hyperconnected networks generated through either minimizing k-shortest paths or minimizing k-shortest edge-disjoint paths between each O-D pair as proposed in the literature. Next, we compare the computational performance of our developed solution methodology with that of off-the-shelf optimization solver through assessing the worst-case performance of these generated hyperconnected networks. We observe that off-the-shelf optimization is unable to obtain an optimal solution and terminates with huge optimality gaps due to the problem size. On the contrary, Algorithm 1 helps reduce the size of the original problem both in terms of number of variables and constraints substantially. In turn, it provides solution time speedups and is able to provide optimal solutions for even densely connected hyperconnected networks within few seconds. Indeed, this showcases the superior performance of the developed methodology which can be leveraged by logistics companies to evaluate the resilience of their networks under worst-case disruptive events.

Finally, we compare the worst-case performance of k-shortest path and k-shortest edge-disjoint path hyperconnected networks with that of lean hyperconnected networks. We find that topology optimized hyperconnected networks are able to maintain better connectivity between the O-D pairs and incur less additional operational costs during the worst-case disruption as compared to lean hyperconnected networks. Finally, we assess the resilience capabilities of hyperconnected networks and find with increase in value of the parameter k, the resilience of the networks increases. We notice that k-shortest edge-disjoint path networks are able to maintain better connectivity between the O-D pairs compared to that of k-shortest path networks. In terms of additional costs incurred for the connected O-D pairs, we observe that the k-shortest path networks showcase superior performance under worst-case disruption of lower intensity whereas with k-shortest edge-disjoint path networks depict better capabilities to sustain worst-case disruptions of higher degree.

The current work opens multiple avenues for future research. First, the hub capacity restrictions and parcel consolidation route generation can be embedded in the proposed modelling framework to capture the problem situation in a more realistic manner. Consequently, it motivates the need to develop tailored solution techniques that leverage the structure of the problem and concepts from the bilevel programming literature to solve such an optimization

problem. Second, such worst-case disruptive events should be considered while designing hyperconnected networks in order to design networks with better resilience capabilities.

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Modular Containerization of Parcel Logistics Networks: Simulation-Based Impact Assessment

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Abstract: The parcel industry has undergone significant changes in recent years, primarily driven by the surge of e-commerce and new technologies. The Physical Internet (PI) provides initiatives to optimize parcel flow and jointly address economic, operational, social, and environmental sustainability issues in the industry. Encapsulating parcels in modular PI containers is a promising method to enhance efficiency by consolidating parcel flows which can increase vehicle capacity utilization, leading to significant cost and transit time reductions. In this paper, we investigate the potential benefits of containerization in the parcel industry using simulation-based scenario designs and assessments. The results are evaluated across several performance facets, such as transport efficiency, handling operations, induced costs, and greenhouse gas emissions. The simulation results focusing on the East Coast region of the USA demonstrated that containerization and tiered mesh networks lead to cost savings and efficient space utilization, with multiple container sizes and a mesh network approach being more effective. This approach also reduces driving time per leg, improving efficiency and driver well-being. In conclusion, the study offers conclusive remarks and suggests further research avenues in this domain.

Keywords: Hyperconnected Logistics Infrastructure, Containerization, Modularization, Mesh Networks, Physical Internet, Routing Protocols, Network Architecture, Multi-tier Networks, Hyperconnected Service Network

Conference Topic(s): Modularization; PI fundamentals and constituents; PI impacts; PI implementation; PI modelling and simulation

Physical Internet Roadmap: ☐ *PI Nodes,* ☒ *PI Networks,* ☒ *System of Logistics Networks,* ☒ *Access and Adoption,* ☐ *Governance.*

1 Introduction

In recent years, there has been a notable transformation in the postal and parcel industries, which can be attributed to the advent of e-commerce and pervasive technologies. This development has had a significant impact on logistics and freight transportation, resulting in an increase in business-to-consumer deliveries in certain areas and a rise in demand for swift and cost-effective deliveries. In response to these challenges, the Physical Internet framework has provided a range of avenues for optimizing parcel flow and address the economic, operational, social, and environmental sustainability concerns of the parcel industry supply chain.

In the literature on parcel logistics, economies of scale and flow consolidation have been identified as key techniques for cost reduction, improving service levels, minimizing transit

time, enhancing sustainability, and ensuring timely delivery (Baumung et al., 2015). The parcel industry is characterized by a high volume of individual parcels that originate from various sources and are destined for multiple destinations, which favors PI-centric logistic network topologies for efficient consolidation and economies of scale (Gakis & Pardalos, 2017). However, one of the primary obstacles toward achieving efficient parcel flow is the sorting and handling of individual packages, which often have varying attributes such as volume, weight, shape, as well as conditioning and handling requirements.

Montreuil et al. (2018) proposed leveraging the concepts of hyperconnectivity and modularity to address the global challenges facing the parcel logistics industry, such as the need for faster and more sustainable delivery across urban areas, especially in megacities. The authors emphasized the need for disruptive transformations in package logistics hubs and networks, including multi-tier world pixelization through space clustering, multi-plane parcel logistics web, smart dynamic parcel routing, hub-based consolidation, and modular parcel containerization. In the study by Sarraj et al. (2014), the authors evaluate the efficiency of interconnected logistics networks and protocols through simulation-based assessments. They concluded that the integration of various logistics networks could lead to higher efficiency and sustainability, especially when combined with protocols that regulate the use of resources. Ballot et al. (2014), Meller et al. (2014), Montreuil et al. (2014), and Montreuil et al. (2021) propose functional designs for Physical Internet logistic hubs, each focused on a given application. Their studies highlight the importance of efficient and flexible transportation and handling processes to maximize the benefits of the Physical Internet. Venkatadri et al. (2016) address the impact of consolidation on transportation and inventory costs within the Physical Internet framework. Their results demonstrate that consolidation can lead to significant cost savings, especially for companies located far from their markets. Overall, these studies suggest that Physical Internet can bring about significant improvements in the efficiency and sustainability of logistics networks (Sallez et al., 2015), but careful design and implementation are essential for realizing its full potential.

The present study explores the feasibility of enhancing operations through the utilization of standard modular containers. These containers are envisioned to facilitate efficient handling and increase vehicle capacity utilization, which are fundamental components of the Physical Internet [Montreuil et al., 2011; Montreuil et al., 2016]. Specifically, we investigate the potential benefits of consolidating parcels into smartly designed containers that follow the same route. This approach aims to avoid the sorting process at congested hubs and achieve significant reductions in transit time and costs. Container consolidation involves combining individual parcel flows into larger-volume shipments that are destined for locations in the same general direction. This consolidation process is expected to streamline handling and sorting procedures, minimize the likelihood of packages getting damaged or misrouted during transportation, and result in time and effort savings. Notably, containerization can also relieve the sorting capacity burden at critical hubs as containers can be transshipped, bypassing the sorting process, and simplifying handling, loading, and unloading at the intermediary hubs.

Drawing upon our collaborative research with a major parcel logistics service provider, this research paper examines the potential of containerized ground network operations in the East Coast Region of the USA. To this end, simulation-based scenario designs and assessments were conducted, with the aim of analyzing the effectiveness of containerization in enhancing logistics network operations. The remainder of this article is structured as follows. Section 2 presents the conceptual model of the logistics network, specifying the scope and operations of the network. In Section 3, we describe the agent-based simulation model and dynamics,

highlighting the various containerization scenarios that were developed. Section 4 presents the results of the simulations, comparing and discussing the findings from the different scenarios. Finally, in Section 5, we draw conclusions and propose avenues for future research and scalability. The study contributes to the ongoing discourse on the use of containerization in the parcel logistics industry and provides insights into its potential benefits and challenges.

2   Methodology

The parcel delivery process involves several key steps to ensure efficient and timely delivery. In this paper, we focus on in-network delivery operations, from first hub to the last hub, and exclude first and last mile operations. It begins with parcel origination, where parcels are collected, labeled, and sorted. Next, path assignment occurs, determining the route based on the origin, destination, and service level of the parcel (ODS) and network connections. A suitable truck is then assigned, considering capacity, availability, and estimated arrival time. Lastly, parcels may dwell in facilities for consolidation or sorting before continuing their journey to the destination.

In the current parcel delivery method, companies collect parcels and classify them according to size and service level requirements. At each facility, parcels can be consolidated into bags or moved as single units. Parcels are sorted and loaded into trailers for transport to the next facility. Trailers arriving from other facilities can be loaded or unloaded before onward shipment, or sent without being opened. Parcels and bags are scanned during the loading process to ensure proper handling and tracking.

The containerized parcel delivery method replaces all bags and trailers with modular containers. Parcels are loaded into at least one container when being transported and can be consolidated into larger containers as needed. This approach aims to improve efficiency, reduce handling time, and minimize potential damage to parcels during the transportation process.

By incorporating a mesh network with a fully containerized method, we can optimize parcel delivery by categorizing facilities into tiers and revising network edges and routing protocols. We classify facilities based on function, capacity, and location to ensure better resource management and workload distribution. We revise network edges to create a robust, adaptable and hyperconnected network that supports efficient routing. We update parcel and truck routing protocols using advanced algorithms and decision-making tools, which accommodate service level requirements, facility capacities, and network congestion.

The subsequent sections outline the methodology employed in parcel generation, network creation, and operational protocols to ensure efficient, timely, and transparent parcel delivery.

2.1   Demand Generation

To forecast parcel demand in the East Coast region of the USA, we obtain population data from each 5-digit zip code in the region, which serves as the basis for predicting parcel demand in each zip code. In addition, we enhance the accuracy of our parcel demand forecast by leveraging partner data on origin to destination flow proportions and trends. The data set encompasses 23 states, including New York, Pennsylvania, Florida, Georgia, Michigan, North Carolina, Ohio, Virginia, Tennessee, Indiana, South Carolina, Kentucky, Alabama, Maryland, Massachusetts, New Jersey, Mississippi, Connecticut, West Virginia, Delaware, Maine, Rhode Island, and Vermont. We use statistical distributions, specifically normal distributions based on the average weight and volume of packages shipped in the region, to assign weight, volume, and service level to each parcel. Finally, we generate a demand forecast for each zip code and assign weight, volume, and service level to each parcel accordingly.

Parcels are classified into small, regular, and irregular categories based on size and weight. Small parcels, like letters, can present handling challenges and are often transported in bags for efficiency. Regular parcels fit standard conveyor belts in sorting facilities, while irregular parcels have excessive volume, weight, or unusual shapes. Differentiating small parcels from regular ones is essential, as the aggregated size of small parcels impacts space and weight constraints within the logistics network.

Table 1: Parcel Types and their Weight-Volume Relationships

Parcel Type	Weight(lb)	Volume (cubic inches)
Small	< 10	< 450
Regular	≤ 75	< 10,000
Irregular	> 75	-
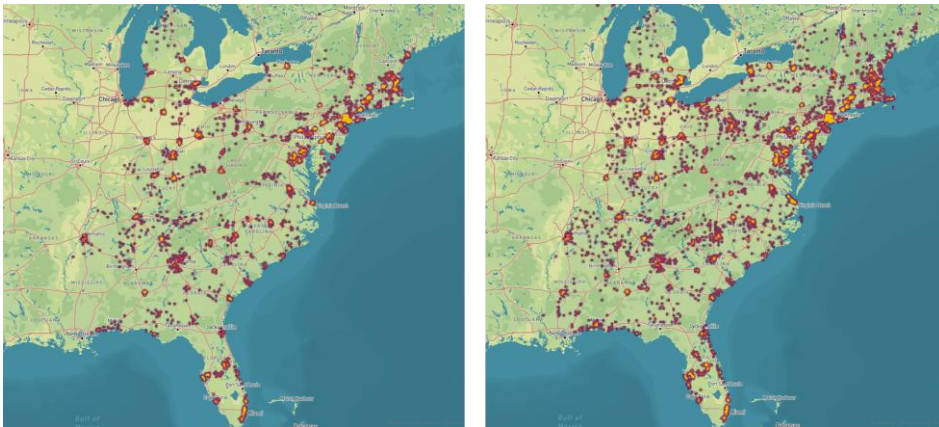
Figure 1: Geospatial heatmap representation of parcels generated over 10 days period (Left: Origins, Right: Destinations)

2.2   Hyperconnected Networks Creation

To create the hub networks for parcel logistics in East Coast USA to be contrasted through the simulation experiment, we analyzed demographic data to determine the population density of various regions and identify areas with high concentrations of potential customers. We also considered the location of major cities and major highway intersections, as they are typically associated with high levels of economic activity and generate significant parcel traffic. To further inform our decision-making, we analyzed historical flow and origin-destination pair trends from partner data to identify patterns in parcel delivery.

Based on our analysis, we identified potential hub locations, taking into account the surrounding regions that could be efficiently served by the hub. This allowed us to first create a base network of strategically placed hubs that could efficiently serve the surrounding regions while meeting the demands of customers for reliable parcel delivery services. The set of hubs in the base network includes all hubs displayed in the upper maps of Figure 2. The base network has allowed flow links between every pair of hubs, as it is based on direct point-to-point dispatch movement of freight, where a load is picked up at an origin and dropped at the destination.

Utilizing the same set of hub locations as the base network, we devised a system of hyperconnected tiered mesh networks for the physical internet. These networks comprise horizontal and vertical networks, each tier hosting its own horizontal network while vertical networks connect neighboring tiers. The tiered structure enables horizontal networks to function within a single tier, and vertical networks to link hubs in adjacent tiers. Mesh networks form within each tier, with direct links between nearby hubs. Hyperconnectivity is attained by incorporating 'hyperlinks' in vertical networks, interconnecting horizontal networks. Finally, networks are classified as open or dedicated, based on usage and accessibility.

The multi-tier, interconnected logistics network proposed by Montreuil et al. (2018) consists of six spatial cluster planes and corresponding hub resource tiers. Customer locations (plane 0) are clustered into unit zones (plane 1), which are then combined into local cells (plane 2), areas (plane 3), regions (plane 4), blocks (plane 5), and finally into our planetary world (plane 6). Corresponding hub tiers include access hubs (tier-1) networked in plane 1, local hubs (tier-2), gateway hubs (tier-3), inter-regional hubs (tier-4), global hubs (tier-5), and earth-planetary hubs (tier-6). These hubs are interconnected with nearby hubs within the same tier, as well as the tiers directly above and below.

Local hubs (tier-2) are situated within urban areas to facilitate parcel delivery within city limits, serving as secondary transfer points for parcels. Gateway hubs (tier-3), typically near major transportation hubs, serve as primary transfer points for parcels moving between areas, utilizing advanced sorting and tracking systems. Regional hubs (tier-4) handle the most consolidated load, equipped with infrastructure and technology to manage high parcel volumes. This multi-tier, multi-plane logistics network enables efficient and seamless parcel movement between various spatial clusters and hub resource tiers.
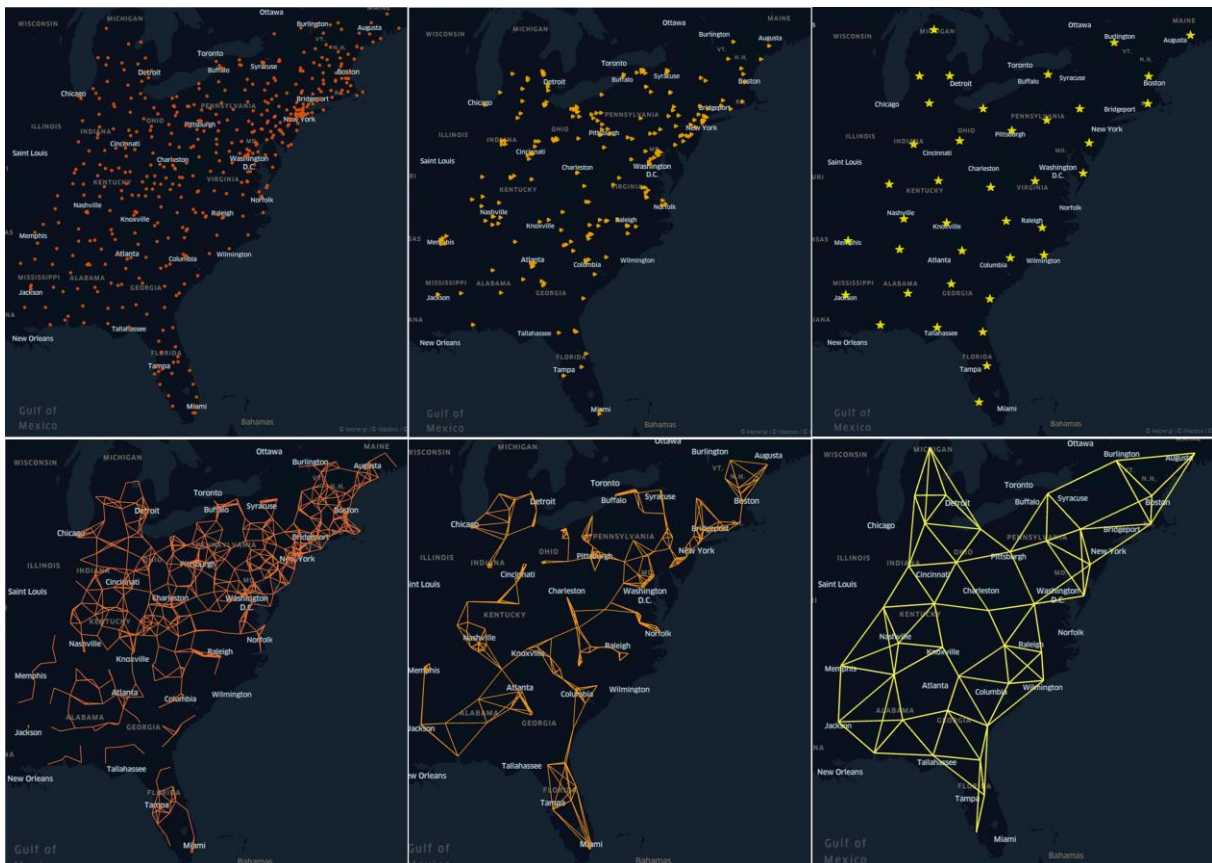

Figure 2: Showcasing the spatial distribution (top) and typical horizontal inter-hub flows (bottom) of local hubs (left), gateway hubs (center), and regional hubs (right)

2.3   Design Elements of Operational Protocols

This section examines key operational protocols in parcel management, including the parcel routing algorithm, bagging and containerization logic, and parcel sorting and trailer loading methodologies, all of which contribute to optimizing efficiency and ensuring timely, accurate deliveries.

2.3.1 Parcel Routing Strategies

When a package enters the system, three elements are already known: origin (O), destination (D), and service level (S). The parcel route determines the sequence of facilities that are visited by the parcel before it arrives at its destination. For the base network, we use the shortest path algorithm from origin to destination hubs to determine the parcel path while respecting the promised service level.

The base network parcel routing algorithm (Algorithm 1) identifies nearest hubs to origin and destination, calculates adjusted service level, generates feasible paths, and selects paths that maximize consolidation. Direct shipments are used when service level requirements cannot be met through planned routes.

Algorithm 1

1: **procedure** PARCELROUTE(O, D, S) ▷ Origin, Destination, Service Level
2: $H_O \leftarrow$ nearest hub to O, $H_D \leftarrow$ nearest hub to D, $S' \leftarrow (S -$ time to hubs$)$
3: **for** each $O'D'S'$ combination **do**
4:   Generate k feasible paths considering S' constraints
5:   Select a path that maximizes consolidation
6: **end for**
7: **if** package cannot be delivered within S following the selected path **then**
8:   send parcel directly to D
9: **else**
10:   send parcel via determined route, traversing hubs until it reaches H_D and finally D
11: **end if**
12: **end procedure**

Algorithm 1: Parcel Routing in the Base Network

The parcel routing algorithm for mesh networks (Algorithm 2) effectively sends parcels between origins and destinations using a tiered hub system: local hubs (Tier 2), gateway hubs (Tier 3), and regional hubs (Tier 4). The algorithm checks for direct paths and identifies the nearest hubs of each type. It evaluates whether to escalate the parcel to a higher tier based on the optimal route. By strategically routing the parcel through the most suitable combination of hubs, the algorithm ensures efficient parcel delivery to the destination, while meeting the specific service requirements for each package (Shaikh et al., 2021).

Algorithm 2

1: **procedure** OPTIMALPARCELROUTE(O, D) ▷ Origin, Destination
2: **if** direct path between O and D **then** ▷ Direct path
3:   send parcel directly to D
4: **end if**
5: $LH_O, LH_D \leftarrow$ nearest local hub to O and D ▷ Local Hubs
6: **if** direct path between LH_O and D **then**
7:   send parcel via LH_O to D
8: **else if** direct path between LH_O and LH_D **then**
9:   send parcel via LH_O, LH_D, and then to D
10: **end if**
11: $GH_O, GH_D \leftarrow$ nearest gateway hub to LH_O and LH_D ▷ Gateway Hubs
12: **if** direct path between GH_O and LH_D **then**
13:   send parcel via LH_O, GH_O, LH_D, and then to D
14: **else if** direct path between GH_O and GH_D **then**
15:   send parcel via LH_O, GH_O, GH_D, LH_D, and then to D
16: **end if**
17: $RH_O, RH_D \leftarrow$ nearest regional hub to GH_O and GH_D ▷ Regional Hubs
18: **if** direct path between RH_O and GH_D **then**
19:   send parcel via LH_O, GH_O, RH_O, GH_D, LH_D, and then to D
20: **end if**
21: find shortest path from RH_O to RH_D using feasible regional hub connections
22: send parcel via determined route, passing through regional hubs until it reaches RH_D, then send it to GH_D, LH_D, and finally to D
23: **end procedure**

Algorithm 2: Parcel Routing in the Hyperconnected Tiered Mesh Networks

2.3.2 Parcel Consolidation with Bags and Containers

Bags and containers use different consolidation rules due to their inherent handling requirement difference. Bagging consolidation is carried out in two stages. In the first stage, small packages with the same origin, destination, and service level are combined into a single bag at their point of origin. If this bag reaches at least a 50% fill rate, it remains sealed throughout its journey and is only opened upon arrival at its destination. However, if the bag's fill rate is below 50%, it undergoes further consolidation at the initial hub. Here, it is merged with other bags sharing the same first and last hubs, as well as the same hub service level. This newly consolidated bag is then opened at the final hub, where individual bags are created based on their respective destinations for the final leg of the journey.

In the mesh network, parcels enter the Tier-1 network and advance to higher tiers for long-distance transport. Upon arriving at a Tier-1 hub, a parcel's next destination is determined using the routing protocol. Consolidation within the mesh network employs π-containers in various sizes. In our case study, we opted for five modular container sizes: 1x1x2ft, 2x2x2ft, 2x2x4ft, 4x4x4ft, and 4x4x8ft. Container consolidation occurs on two levels. First, packages are elevated from the Tier-1 hub to the designated Tier-2 hub, if their paths involve higher tiers. At their Tier-2 origin (T2O), packages are consolidated into containers along with others sharing the same destination and service level (ODS). Some packages may not need to enter the Tier-3 hub network, depending on their service level and destination, and can travel within the Tier-2 network.

Packages with Tier-3 nodes in their paths are then elevated to assigned Tier-3 hubs, where they are further consolidated with other packages heading in the same direction. As each container incurs a handling cost upon de-consolidation at a hub, a fill rate threshold is assigned. If a container is at least 80% full, it remains sealed throughout the entire route and is only opened at the final Tier-3 destination. If a container is below the threshold at its initial hub, it is consolidated with other packages moving in the same direction and with the same service level at subsequent hubs. Once the containers reach their final Tier-3 destination, they are lowered to Tier-2 and then to Tier-1 for de-consolidation and ultimate delivery to the customer.

2.3.3 On-Demand Trucking

We leverage the on-demand trucking feature from the HyPTLI framework (Shaikh et al., 2021). On-demand trucks are utilized for transportation, with each vehicle being used for a single leg of the journey. These trucks share the same design and features, and it is assumed that they can accommodate up to three trailers each. Trucks are loaded with urgent parcels first, ensuring timely delivery as per the service promise. Once these high-priority parcels are loaded, other non-urgent parcels are added as fillers. This approach enables faster parcel movement through the system, optimizes truck and trailer utilization, and promotes effective consolidation.

3   Simulation Design

This section describes the structure of a discrete-event agent-based simulation developed in AnyLogic®. Figure 3 describes the simulation design, showing the interactions between active agents, passive agents, and objects in uncontainerized and containerized settings.

Active agents represent real-world entities and make decisions based on predefined rules or algorithms. In the simulation, six agents with specific roles collaborate for efficient parcel transportation and logistics, including the parcel router, loader/unloader, sorter/consolidator, bagging manager, containerizer, and equipment manager/router. Passive agents perform operations based on instructions without making decisions. Two passive agents, the demand

generator and demand manager, collaborate in the system. They create and predict demand using statistical distributions or historical data.

Objects, non-autonomous entities, require agents' assistance for transportation. The simulation includes five object types: packages, vehicles, trailers, bags/containers and hubs. Each type possesses unique attributes and is managed by agents. The discrete-event agent-based simulation model enables the study and optimization of various system aspects, such as package scheduling and equipment utilization.
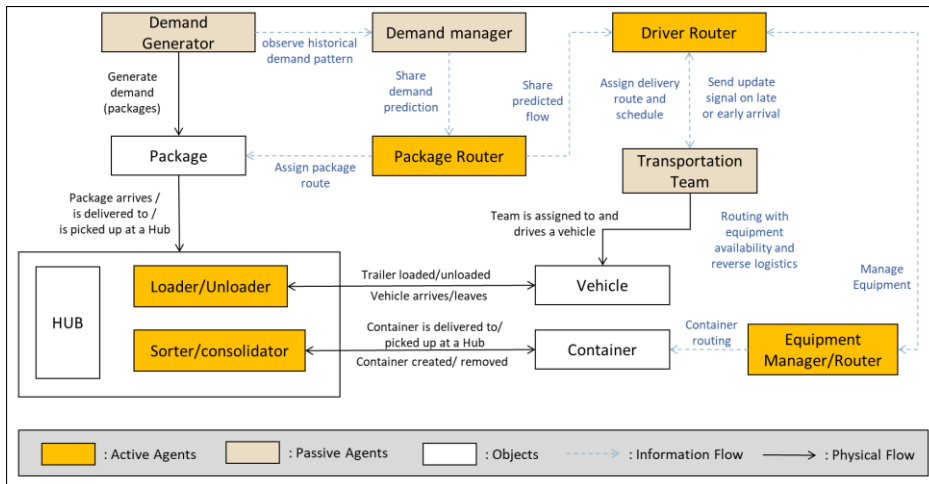
Figure 3: Simulation Model of Containerized Parcel Logistic Network

4. Experimentation

In our experimentation, we generated over 19 million parcels spanning ten days for the East Coast USA region. The base network consists of 713 hubs. As part of the transition to the mesh network, we implement a hub structure consisting of 457 local hubs, 217 gateway hubs, and 39 regional hubs organized into three tiers. To evaluate performance, we design and implement four different scenarios. The first scenario involves a base network without containerization, while the second scenario incorporates a single large container size (4x4x4) into the base network. In the third scenario, we utilize the base network with multiple container sizes, including small containers (1x1x2, 2x2x2, and 2x2x4) and large containers (4x4x4 and 4x4x8). Lastly, the fourth scenario involves a mesh network that utilizes multiple container sizes.

Table 2: Performance Evaluation Scenarios for Base and Mesh Networks with Containerization

Network/ Transportation	Containerization		
	No containers (NC)	Single Large Container (SLC)	Various Size Containers (VC)
Base Network	Scenario 1 (BN-NC)	Scenario 2 (BN-SLC)	Scenario 3 (BN-VC)
Tiered Mesh Network			Scenario 4 (MN-VC)

The cost structure used in the study was based on previous research conducted for an international parcel delivery company. Transportation costs were calculated as $2.5 per traveled mile. The handling costs were determined based on a cost-per-unit structure, with different costs for unloading, emptying, sorting, filling, crossdocking, and loading, depending on the parcel type. For example, the handling cost for an irregular parcel was $0.55 per unit, while the handling cost for a regular, small parcel was $0.15 per unit. Large containers had a higher handling cost of $1.61 per unit due to their size, while small containers had a lower handling

cost of $0.27 per unit. These cost structures provided a standardized framework for the analysis of the cost savings associated with different parcel transportation strategies.

The cost table (Figure 4) indicates that scenario 2 (BN-SLC), which introduced a single large container size, resulted in an increase in total operations cost to $235 million compared to scenario 1 (BN-NC) without containerization. This suggests that the use of a single large container size led to an inefficient use of trailer space. Scenario 3 (BN-VC), which utilized multiple container sizes, resulted in a cost reduction to $161 million compared to scenario 2. This suggests that the use of a variety of container sizes allowed for a more efficient use of container and trailer space, contributing to the cost savings observed. Finally, scenario 4 (MN-VC), which implemented a mesh network with multiple container sizes, resulted in the most significant reduction in total operations cost to from $190M to $74M, resulting in savings of $116M. The savings are primarily from the reduction in sorting operations and loading/unloading operations. The component-wise handling cost is depicted in Figure 5.
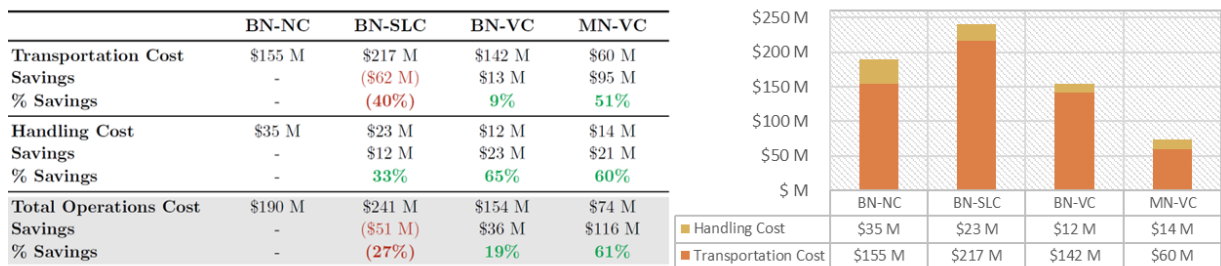
	BN-NC	BN-SLC	BN-VC	MN-VC
Transportation Cost	$155 M	$217 M	$142 M	$60 M
Savings	-	($62 M)	$13 M	$95 M
% Savings	-	(40%)	9%	51%
Handling Cost	$35 M	$23 M	$12 M	$14 M
Savings	-	$12 M	$23 M	$21 M
% Savings	-	33%	65%	60%
Total Operations Cost	$190 M	$241 M	$154 M	$74 M
Savings	-	($51 M)	$36 M	$116 M
% Savings	-	(27%)	19%	61%

	BN-NC	BN-SLC	BN-VC	MN-VC
Handling Cost	$35 M	$23 M	$12 M	$14 M
Transportation Cost	$155 M	$217 M	$142 M	$60 M

Figure 4: Cost comparison with Varying Degrees of Containerization and Mesh Network Implementation

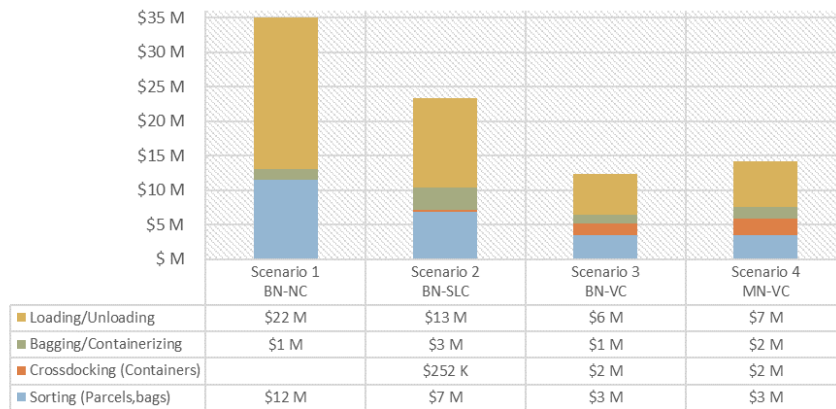|	Scenario 1 BN-NC	Scenario 2 BN-SLC	Scenario 3 BN-VC	Scenario 4 MN-VC
Loading/Unloading	$22 M	$13 M	$6 M	$7 M
Bagging/Containerizing	$1 M	$3 M	$1 M	$2 M
Crossdocking (Containers)		$252 K	$2 M	$2 M
Sorting (Parcels,bags)	$12 M	$7 M	$3 M	$3 M

Figure 5: Component-wise handling cost for each scenario

The results show a significant reduction in transportation costs with the implementation of containerization and mesh network strategies. In scenario BN-NC, transportation costs amounted to $155 million, while in scenario MN-VC, transportation costs decreased to $60 million. This reduction is a direct result of reduction in the number of trips required to transport parcels. In scenario 4 (MN-VC), the total number of trips required was 174,618 which is on average 19% lower than the number of trips required in scenarios 1-3. This decline in the number of trips can be ascribed to the mesh network's more efficient use of container space. Additionally, there was almost a twenty-fold increase in the number of trucks that utilized three trailers in the mesh network compared to the base network. Furthermore, the environmental impact was also significantly reduced, with carbon emissions (CO_2 in kg) decreasing from 10.5 million kg to nearly 4 million kg, showing a reduction of 62%.

The study examined trailer fill rates in various scenarios, using two metrics: effective fill rate and trailer-container fill rate. The first metric, the effective fill rate, is calculated by dividing the parcel volume by the trailer volume. The second metric, the trailer-container fill rate, is determined by dividing the container volume by the trailer volume. Results showed that the effective fill rate was generally lower than the trailer-container fill rate, indicating underutilized container space. However, as scenarios progressed, more efficient space utilization was observed. Fill rate improvements were noted for all trailers.In scenario 1, average effective fill rate was 35% for trailer 1, while in scenario 4, the average effective fill rate for trailer 1 reached 57%. Similar improvements were noted for trailers 2 and 3. The trailer-container fill rate averaged at 58% in scenario BN-VC while at 80% in scenario MN-VC.

Two main transportation teams exist: regular feeder (single-driver) and sleeper (two-driver) teams. Sleeper teams are used for long-haul routes, but are more expensive and less desirable for drivers. As shown in Fig. 5, in the mesh network we are able to reduce average driving time per leg, that can almost eliminate sleeper team operations and enable return-to-home daily schedules for majority of drivers.
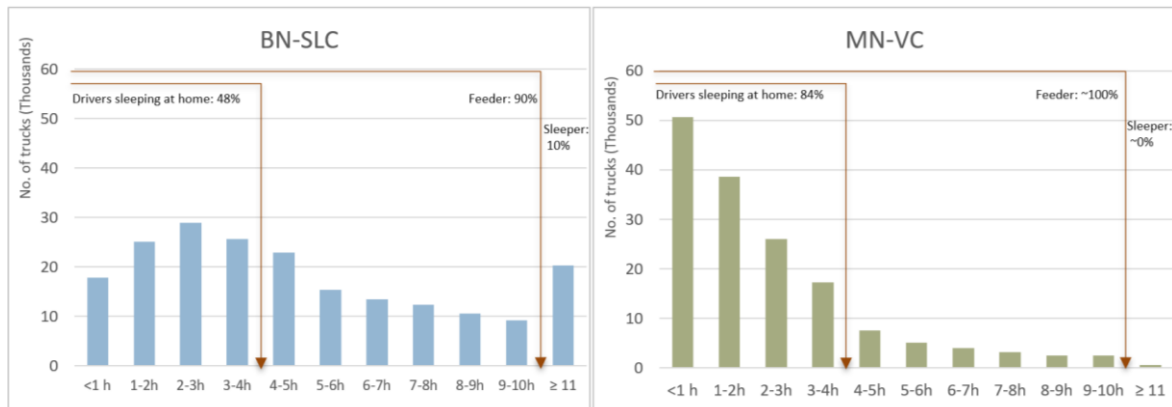

Figure 6: Comparison of Truck Leg Travel Time Distribution between BN-NC (left) and MN-VC (right) scenarios

4 Conclusion and Further Research

In conclusion, this study explores the effects of containerization and mesh network strategies on transportation costs, space utilization, and environmental impact. Findings reveal that using diverse container sizes and a mesh network approach significantly reduces operational expenses, improves space utilization, and fosters a greener transport system. The mesh network strategy also enhances driver well-being and overall efficiency. This research highlights the advantages of these strategies, emphasizing the importance of considering driver well-being and minimizing driving distances in transportation operations.

The current investigation into containerization and mesh network strategies in transportation operations reveals several promising directions for future research. One potential avenue is to examine the influence of other factors on transportation costs and efficiency, such as the nature of the cargo, the size and capacity of trucks, and the geographical location of transportation hubs. Investigating these factors will provide further insights into the efficacy of containerization and mesh network strategies. Additionally, future research could explore the application of advanced technologies, including automation and artificial intelligence, in transportation operations to optimize efficiency further. By delving into these future research directions, we can develop a more comprehensive understanding of transportation operations and provide practical solutions for enhancing efficiency, decreasing costs, promoting sustainability, and prioritizing driver well-being.

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Upgrading the Export Logistics Network with Cyber-Physical Internet

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Abstract: *Given the complexity of the environment around export logistics, we look to apply physical internet to this case in order to increase effectiveness and save costs. In order to realize the interaction between diverse digital information at the cyber level and various physical entities in the logistics network, this article proposes the concept of the Cyber-Physical Internet(CPI), which focuses on installing routers in nodes for forwarding and routing. This research will examine how CPI establishes a multi-layer system to achieve vertical and horizontal interconnection of logistics network, using the digital Internet as an analogy, and attempt to determine the functional reality of each layer and the dependency between layers. Similar data packets and cargo units will be packaged or dismantled during this procedure, which will also be described in detail in paper.*

Keywords: *Export logistics, Cyber-Physical Internet, Logistics network, Digital Internet; Multi-layer system*

Conference Topic(s): *PI fundamentals and constituents*

Physical Internet Roadmap: *Select the most relevant area for your paper:☐ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.*

1 Introduction

In the context of economic globalization and global trade, today's international logistics and supply chain network has developed more giant, complex, and demanding, but now they are faced with more uncertainties than ever, such as international trade friction, geopolitics, global epidemics and other challenges of uncertainty, transnational logistics and supply chain management are facing higher challenges. Chinese Guangdong-Hong Kong-Macao Greater Bay Area, one of the world's busiest regions for international trade since last century, is an important starting point for international logistics.

Since the nineties of the last century, China's pearl river delta region as China vigorously promoted reform and opening up, with its adjacent to Hong Kong and Macao location advantages, special shipping conditions and the tradition of opening to the outside world became the bridgehead of China's foreign trade, the Pearl River Delta region has since played an essential role in manufacturing and exports.

With the planning and proposal of the Guangdong-Hong Kong-Macao Greater Bay Area, relying on the three world-class ports of Shenzhen Port, Guangzhou Port and Hong Kong Port, Three major airports: Shenzhen Bao 'an International Airport, Guangzhou Baiyun International Airport, Hong Kong International Airport and as an important starting point of

the China-Europe Express, the Greater Bay Area will continue to play an important role in the export trade between China and the world, and how to utilize the unique advantages of the Guangdong-Hong Kong-Macao Greater Bay Area to build an export logistics network with the Greater Bay Area as the centre will be a challenge for logistics and supply chain managers.

In Guangdong-Hong Kong-Macao Greater Bay, the construction of the logistics system still needs to face the problems of system differences among Guangdong, Hong Kong and Macao and the low degree of collaboration among regional logistics enterprises. To achieve an export logistics network with the Greater Bay Area as the centre today's managers must consider how to make export logistics starting from the Greater Bay Area run more efficiently, effectively, resilient and sustainably, which asks every participant in the process to cooperate and connect from physical operation to digital interconnection.

Physical Internet(PI) is a contemporary proposal for a ground-breaking invention that aims to significantly increase the sustainability and efficiency of the movement, deployment, realization, and supply of physical items in order to reduce the previously mentioned societal, environmental, and economic sustainability. (Montreuil 2011)

As many technologies have been designed and the possibilities of PI applications in relevant industries and sectors have been explored, we believe that logistics and transport networks in export scenarios can also be enabled with PI.

We aim to deliver a well-defined and detailed example of how PI is used in a realistic export logistics and transportation cases. The plan of the paper is as follows. Section 1 briefly reviews the busy exports in China's Pearl River Delta region, which is why we want to apply PI to this scenario. Section 2 describes the export procedure and generally uses the concept of PI nodes to replace the traditional nodes in the logistics and transportation network. The following section abstracts the PI-enabled export logistics network, attached with PI routers, and the generated routing table, which works in the network layer is the main reason we call it cyber physical Internet(CPI); routing information can guide transportation macro. In section 4, we focus on the detail of how the cargo moves in the network and do the encapsulation and de-encapsulation like digital data.

2   Export logistics

2.1   Logistics and transportation in the export environment

The international movement of goods requires the cooperation and shared responsibility of a large number of stakeholders, which in the most straightforward two-party relationship appear to be providers of logistics transport and users of logistics transport, with providers actually including carriers, third-party logistics service providers, infrastructure owners, users including shippers, retailers, manufacturers and businesses, or to call them exporters, who initiates the export process as it involves the production and shipping of the goods they wish to sell. They prepare the shipping documentation and ensure that the products meet the destination country's requirements. Plus, third-party legislators include governments, international logistics and transport organisations.

2.2   Components of an export logistics and transport network

The starting point of the graph is always to be the exporter's factory or warehouse, and the end of this export journey is its target place of sale or the location of its clients. To connect the origin and destination, there are various of transportation lines needed, whose type and construction are determined by different carriers. In domestic logistics, trucks and railways are usually the priority carrier. The components of road transportation include factories or warehouses with truck landing platforms, all levels of the highway, and railway transportation includes freight railway stations (sometimes there is a special rail line connecting the factory

or warehouse to the station) and freight-grade rail lines. To do cross-border transportation, railway, ship, and aircraft can be chosen, ship transportation is the most common choice and aircraft transportation can be used to transport high-value freights. From one port to the next port, shipping lines and aircraft lines usually already exist and are set by the administration, but they also exhibit a network structure, finding an optimal routing is our task.

All the terminals in PI we call PI nodes, including factories, warehouses, railway stations, ports and airports(Montreuil et al., 2014, Ballot, Montreuil, and ThiviergeC, 2014). In CPI, a PI router will be set in each PI node. Routing is the process of finding the optimal transport route, a collection of mode selection and route optimisation, usually in an export environment with fixed route options, but with the launch of PI, there will be more options in a more open international logistics and transport environment in the future, PI router's job is to do routing.

Figure 1 and Figure 2 illustrate the real export optional routing with PI routers.

Figure 1: Optional Routes of Domestic Logistics

The router symbol is similar to what is used in digital Internet, combined with different shapes to represent routers set in various types of nodes, which is distinguished by shipping mode here. The router symbol with a square means the truck or railway station router, the router symbol with a triangle means the harbour router, and the router symbol with a rhomb means the airport router. Different type of transportation also has different representation, solid line means this shipment section is carried by truck; in Figure 1, the company's two factories locate at Huizhou and Shenzhen separately, after the manufacturing in factories, starting from here the products will be packed into a truck and shipped to the cross-border ports through the solid line. There're 3 harbours: Shenzhen Port, Guangzhou Port and Hong Kong Port, which are set triangle routers and 2 airports: Shenzhen Bao 'an International Airport, and Hong Kong International Airport, which are set rhomb routers in Figure 1.

Meanwhile, Figure 2 illustrates the optional routes of cross border logitics. The products are carried to cross-border ports, and the routers set here will begin working to figure out the optimal routes for transporting these freights. Dash line means products to be carried by ship through this line, dot line means by aircraft, and dot-dash line represents by railway.

PI nodes, routers and routings help us construct an export logistics network graph; some more components need to be considered because this network needs to implement the transmission(transportation) function.

Containers, which are used to pack goods, and standard freight container is common in today's transportation. In PI, Montreuil *et al.*(2015) introduced PI container, we must choose an appropriate container to package goods which can be considered as the most minor units of the physical entities that are transported in this network.
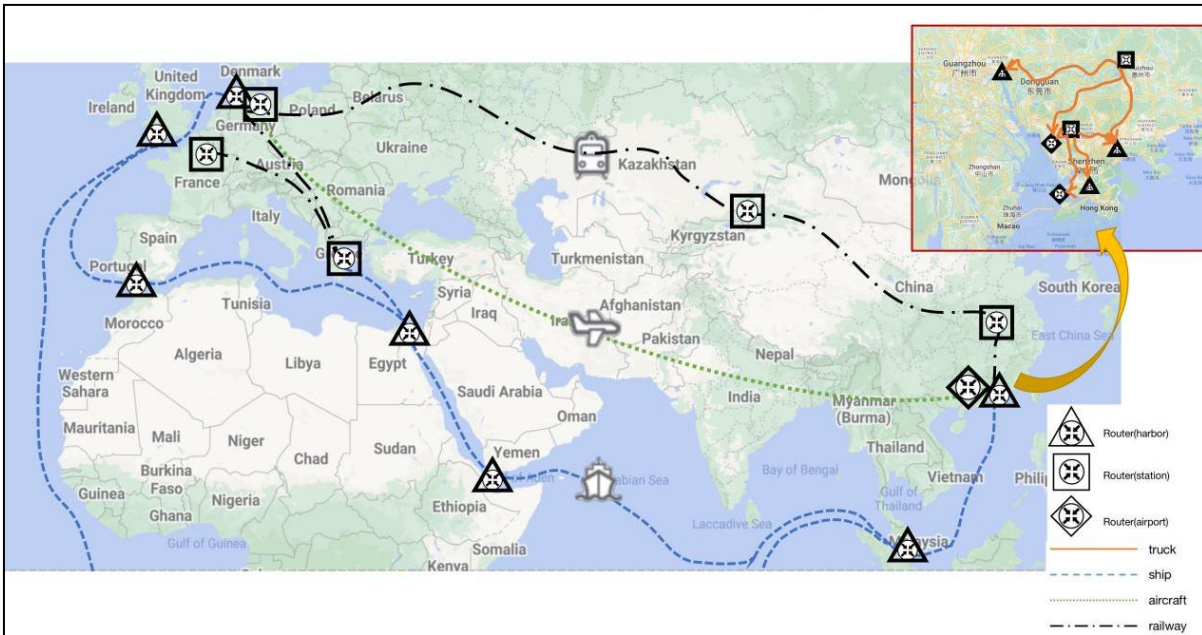

Figure 2: Optional Routes of Cross-border Logistics

Carriers mode of transportation usually to be considered together with routing. To be specific, there are 4 types of transportation, truck and train through road, ship through waterway and aircraft through airway. After determining the mode of transportation, the specific carriers will be assigned at stop nodes whether needs to be loaded, unloaded, split or filled and, most importantly, where they will ship to in the next phase. There're even more detailed things to be considered alongside carriers, like when it arrives at the node, when to leave, which platform to stop, and so on.

In addition to the physical components, operators and regulators must also be considered for a mature system.

3 Cyber-physical Internet

The parallel between the "digital" Internet and the "physical" Internet is the technical blueprint's foundation. Montreuil et al. (2012) propose an Open Logistics Interconnection (OLI) model for the physical Internet, which is similar to the Open Systems Interconnection (OSI) model for the digital Internet. The OLI model maps the digital Internet to the physical Internet by defining three interaction layers of the PI. Sarraj, Ballot, Pan and Montreuil (2014) then delved into this analogy and focused on implementing network routing.

The connection of the cyber level and physical level will be achieved through the establishment of a routing function, and to be displayed on the routing table.

In the last section, PI routers are set at each node in an export logistics network. We can ignore each node's specific physical properties but use a digital abstraction with several parameters to represent the physical node. The router will then use this digital information to do routing, which means that instead of traditional origin-destination trip transportation, the PI routers dynamically find the most appropriate modes, carriers loading and routes for the received freights to direct their next transportation stage between multiple open PI nodes.

Figure 3 illustrates the abstraction of typical export logistics with CPI, the far left is the starting point, the company's factory or warehouse, and the far right is the destination, usually is the wrarehouses of retailers or clients at the target country or region. In CPI, we won't use one direct trip to transport freight from origin to destination. Otherwise, the route in the figure will show as a single line compared to multiple segments shown in Figure 3. Router 1 is the router set in origin, and the next stage of the origin node is the cross-border nodes; therefore, router 1's task is to find possible shipping patterns and routes for Container-packed goods from the origin to the cross-border node (the next hop of origin), rather than directly determining a fixed path to the destination.

Router 1 connects routers set on cross-border nodes, obtains information about routers to the next hops, and generates routing tables based on goods destinations and transport requirements.

Router	Destination (32bit)	Mask (32bit)	Protcol (8bit)	Pre (8bit)	Cost (16bit)	Next hop (32bit)	Interface (8bit)	Metric (16bit)	Transportation (8bit)
R1	R10	255.255.255.0	OSPF(time)	10	100	R3	Ethernet0/0	453	Truck
R1	R10	255.255.255.0	OSPF(time)	10	60	R3	Ethernet0/0	129	Train
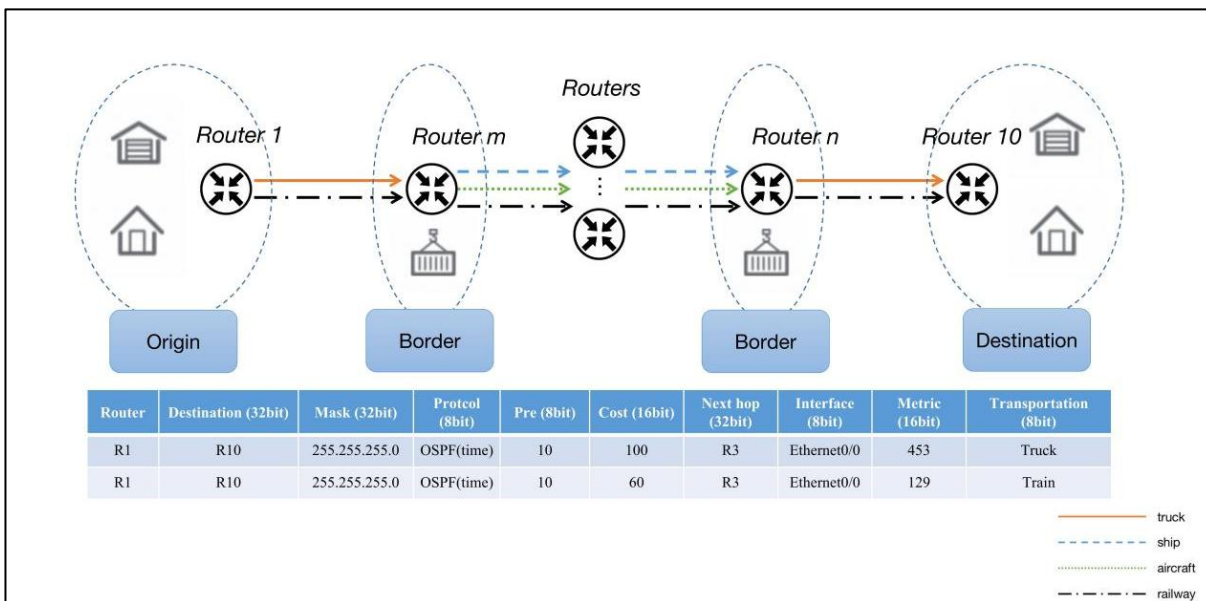
Figure 3: Routing Procedure of Export Logistics

Figure 3 provides part of the routing table of router 1, which shows the shipment from the origin node where router 1 is to the destination where router 10 is. Two transport modes (truck and railway) are available to transport the shipment to the next hop node where router 3 is set. The information in the routing table also includes route generation method (protocol), priority (pre), cost through the node(cost), and metric for using the path(metric), etc.

The router calculates routes at the network layer of CPI, generates routing tables to store the surrounding path information, and becomes a database to record the path information and provide services for the physical nodes that need the information. Based on the information in this database, finding the optimal transport route between the two nodes will be easy.

4   The flow of cargo in CPI

In the previous discussion, we solved the routing problem at the network layer of the physical Internet by setting up routers on nodes that can generate routing tables using digital data and route any goods they receive.

This will break down the traditional way of deciding how to get goods from start to finish into a phased search for the proper mode and route at multiple nodes. Thanks to cyber and digital technology, decisions will be based on real data that is updated in real-time and can be effectively tracked. This will improve the overall elasticity of transport.

It is important to note that goods are abstractly treated as a whole when routed, without considering that as physical entities, goods may be disassembled and reassembled, and specific vehicles need to be specified for transport; only the mode of transportation is not sufficient. These must be considered if we want to make full use of capacity. So to achieve this, we need to focus on how goods flow in the CPI, both horizontally between nodes and vertically at the level of goods disassembly and reassembly. The link layer below the network layer will give the implementation of the transfer of cargo between two nodes.
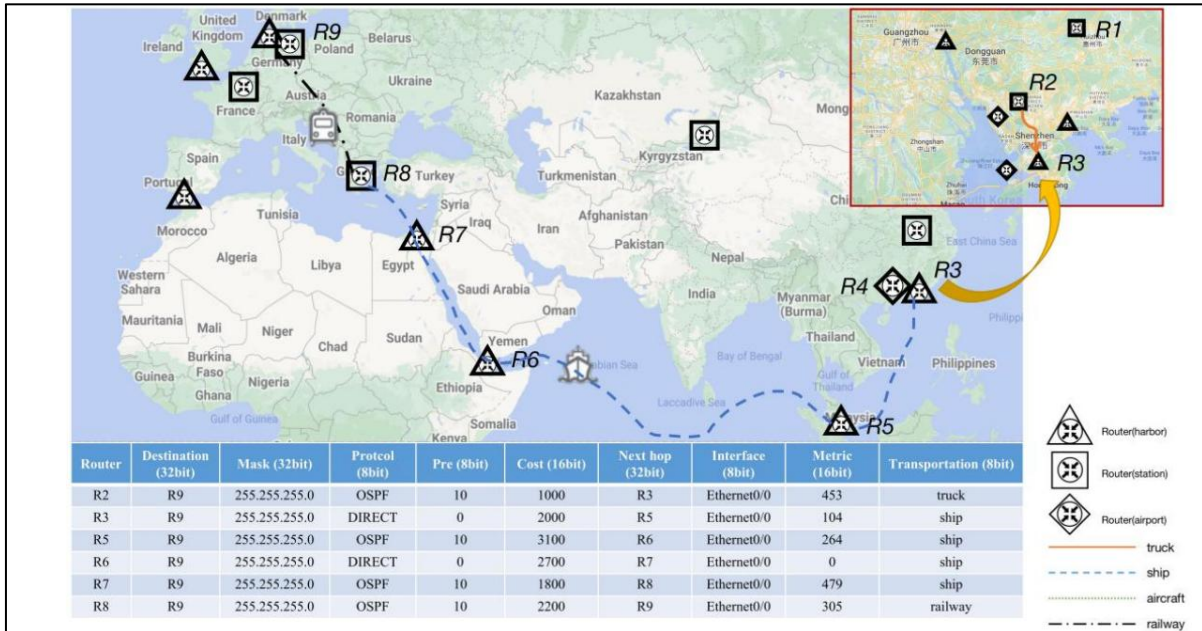
Figure 4: Optimal Route Chose by Router

Figure 4 illustrates one optimal route chosen by routers from many options we discussed before, we will use this path as an example to describe the flow process of the cargo unit.

The route information corresponding to this path is also shown in Figure 4, a process of transporting goods from router 2 to router 9. router 2 to the cross-border node. router3 selects truck. Shipping is used from router3 to router8, and when router8 enters continental Europe, it is transferred to rail to reach its destination. As we described earlier, shipping in CPI is a multi-stage process that occurs between multiple open nodes.

Before analysing the whole process of cargo flow, we first focus on how the cargo unit performs a process similar to the data unit unpacking on the digital Internet. The goods sent from the factory are packaged, we think the container used here should be a PI container. The PI container was first introduced by Montreuil et al. (2014), they proposed a three-tier modular design for PI containers: T-containers, H-containers and P-containers. Lin et al. focus on the dimensional design of PI container sets (2014), and Gazzard and Montreuil (2015) focus on the functional design of containers.

An independent PI container will be the smallest unit in the transportation of goods. It will not be unpacked during transportation. At this time, the additional information on this product unit (except the information on the loaded goods) is only the origin and destination. or to say in this layer what we know is just we need to send this container to our client, it's an end-to-end process, or to say in this layer what we do know is to package this shipment in some PI containers and send them to their destination, but don't know whom to carry it and how to transport it. This is the condition of the goods at the transport level of the Internet.

According to the design of the PI container, the PI container has standard specifications, which can be easily combined into existing standard containers. Standard containers have been proven in practical use that they can be conveniently loaded and unloaded between

different carriers, multimodal transport has been widely used in modern transportation. Therefore, before the appropriate transport mode is determined through routing and then the designated carrier is loaded to start the transport process, it is appropriate for goods to exist in standard container units instead of scattered PI containers. We believe that in this layer which we called as the network layer, goods are represented in the form of containers. Multiple PI containers can be combined in one container, which may come from different businesses or different companies. But as long as they can have the same destination, they can be combined into one standard container to make the most of the loading space and freight capacity.
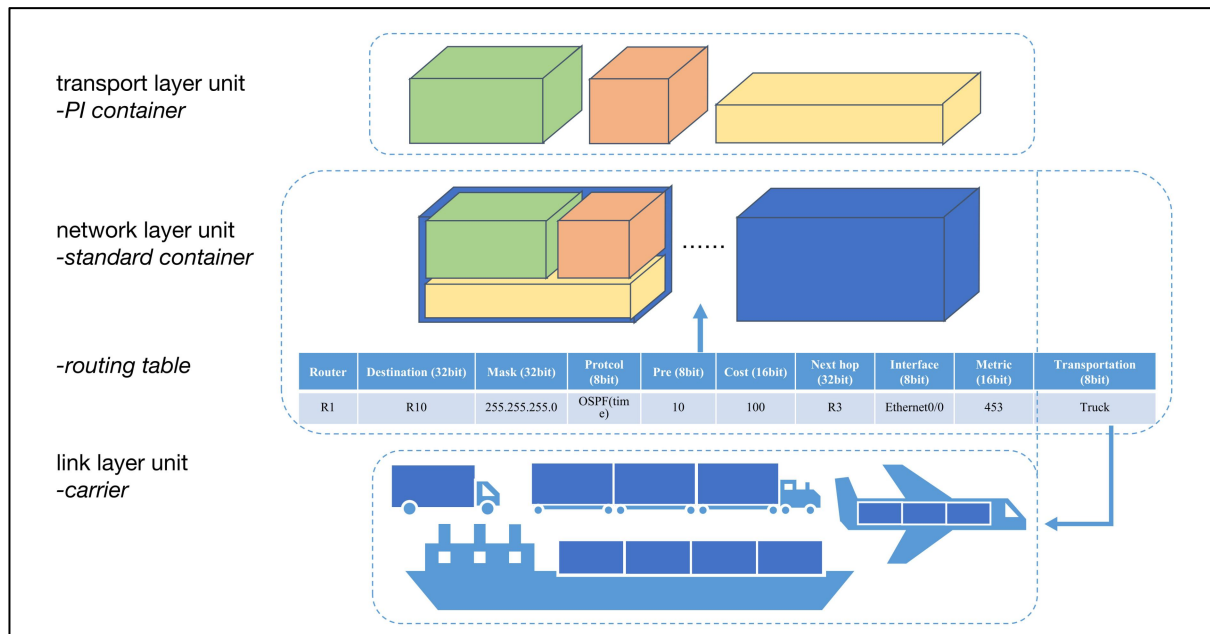
Figure 5: (De)Encapsulation of Object Unit

Remember that the routing process we discussed earlier with the generation of routing tables does exactly take place at the network layer, making goods exist in standard container units, and routing for those containers is matched to determine the appropriate transport mode and route. In this layer, related information generated on the routing table, such as the next hop and the transportation mode, will be attached to each standard container unit.

The cargo is packaged into standardised containers that can be loaded and unloaded between different transport vehicles. With routing table information, the problem of how to get the cargo from one node to the next node can be solved at the next layer: the link layer, which focuses on how to get from one node to another within a network. Containers are transported along routes using corresponding transport vehicles. At the link layer, cargo flow between nodes as a whole in the form of vehicles containing these containers. The specific vehicle information will be added to the additional information of the cargo unit.

So we can analyse the encapsulation and de-encapsulation procedure of the optimal route given in Figure 4 now, which is shown by Figure 6, only the abstract nodes and the routers of each node are retained, but showing in detail the shape transformation process in the goods transportation.

At the origin node, a complete encapsulation of cargo is carried out. The cargo are packed into PI containers and marked with the place of origin and destination. PI containers with the same destination are put into the same standard container. The origin PI router uses the routing table to determine the route for each standard container according to the routing information and affirms the information to each standard container before loading. A unit in the form of such a vehicle loaded freights will actually flow on the physical level. At the destination node, a complete de-encapsulation of goods is carried out which is the reverse of the previous process.
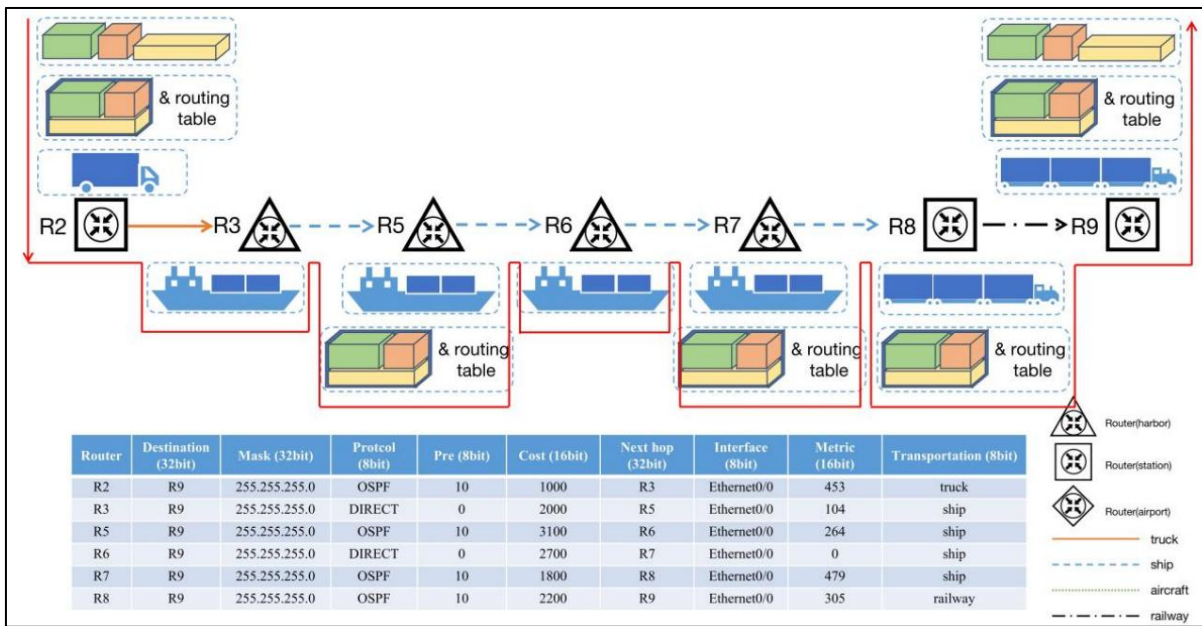
Router	Destination (32bit)	Mask (32bit)	Protcol (8bit)	Pre (8bit)	Cost (16bit)	Next hop (32bit)	Interface (8bit)	Metric (16bit)	Transportation (8bit)
R2	R9	255.255.255.0	OSPF	10	1000	R3	Ethernet0/0	453	truck
R3	R9	255.255.255.0	DIRECT	0	2000	R5	Ethernet0/0	104	ship
R5	R9	255.255.255.0	OSPF	10	3100	R6	Ethernet0/0	264	ship
R6	R9	255.255.255.0	DIRECT	0	2700	R7	Ethernet0/0	0	ship
R7	R9	255.255.255.0	OSPF	10	1800	R8	Ethernet0/0	479	ship
R8	R9	255.255.255.0	OSPF	10	2200	R9	Ethernet0/0	305	railway

Figure 6: (De)Encapsulation Procedure of an Optimal route

Next, focus on the process of the intermediate node (R3-R8). What the intermediate node needs to do is to route the received goods and decide the next hop. Obviously, this needs the work of the router, which takes place at the network layer. First of all, from the physical layer to the link layer, the physical entity form of reality is unsealed into the form of the transport vehicle loaded with goods. From the link layer to the network layer, the form of the transport vehicle loaded with goods is unsealed into the standard container. The router can route the standard container form. That is, determining which node to jump to next and which mode of transport to use. It should be noted that if the next hop node is fixed, routing on this node is not required, that is, the router is actually similar to a switch in the digital Internet, so it does not need to work at the network layer and unseal the mode of the transport vehicle loaded with goods into a standard container. The work of this node takes place directly at the link layer, and the vehicle information can be changed. The physical layer corresponds to the vehicle that transfers the container to the next hop, such as the nodes where router 3 and router 6 reside in Figure 6.

5 Conclusion

International logistics is characterized by a wide range of systems, different logistics environments and high standardization requirements. Today's global logistics network requires more mutual support and rapid and effective information transmission among all links.

So in the export logistics scenario, we are looking for a more interconnected and open logistics or supply chain system which not only enables different operators to cooperate and connect but also realizes the interaction of logistics information and transportation entities.

This article hopes to achieve such a connection goal through the establishment of Cyber-Physical Internet(CPI), which is derived from a computer network and has some similarities with the existing Physical Internet(PI) theory, but also certain differences. It hopes to deconstruct this complex system through a hierarchical structure in this system, connect each logistics terminal with the network, and carry out relevant management and decision-making in it. Export goods can be transmitted in the CPI of export logistics like network data, and finally connect the business level, physical level and information level of logistics so as to strengthen the integrity, stability, interactivity and sustainability of the logistics system.

In the sense of the adoption process of PI, ALICE (2017) has created a roadmap of how the PI

will gradually develop and finally replace the current logistics and transportation system. The roadmap is based on the notion that development will occur in accordance with predetermined. Transportation system. The roadmap has identified 5 main areas of development. This paper's design can help and give a reference to develop from Logistics Networks to Physical Internet Networks.

At the physical level, all goods flow is implemented based on pi-containers, which are the smallest units of physical activity. Efficient movement is made possible by labelling these units and reassembling the goods at nodes rather than repeatedly loading and unloading them. Open logistics nodes have been simplified in the discussion of this paper, but they must have a complete design at the physical level, reasonably deploy these nodes in geographical locations and upload their physical information to the network level. The internal design of nodes is also important, such as the update of information in and out of warehouses, storage and flow inside warehouses, multimodal transport, transfer and reorganisation of container operations. As PI is enabled, corresponding updates are required. The vehicle needs to be tracked and fed back to the network.

At the cyber level, this paper emphasizes the routing function of the PI router at the network level, reading the goods information, time information, destination information, etc., for the received goods, looking for the appropriate means of transport and selecting the appropriate transport route, and generating the routing table with this routing information. We think of this as the link between cyber and physical systems, which is used to guide the functional implementation of the connection layer and the physical layer. The specification of the routing table and routing protocol needs further design in practical application.

Overall, CPI, as an extension of PI, proposes to set routers in the nodes of the logistics and transportation network to complete the routing work so that goods can be transported as data is transmitted over the digital Internet, and this process should be accomplished through a multi-layer structure. Taking the export logistics transportation from China to Europe as an example, the design example of this paper is given. The export logistics transport system with CPI can make full use of the transport capacity and improve the system resilience.

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Enhancing Energy Efficiency and Dynamic Carbon Footprint Calculation at Container Terminals

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Abstract: *The paper presents the results of the proof of concept (PoC) developed in the scope of the iTerminals 4.0 Project, to achieve a real-time calculation of the carbon footprint generated in port container terminals. iTerminals 4.0 is an innovation project co-funded by the Connecting Europe Facility Program (CEF) of the European Commission, with the objective of deploying and implementing the necessary concepts, tools, and systems to enable digital transformation of the port container industry, thus achieving the paradigm of 'container terminal 4.0' based on the integration of Industry 4.0 principles. The iTerminals 4.0 project comprises a study with pilot deployments in real operations at European port-container terminals, focused on digitization of port operations and adoption of Industry 4.0 technologies within the container-handling sector. A wide range of transversal benefits is expected from the digital transformation of container port operations, like operational efficiency increase, safety and (cyber) security improvement, costs reduction and carbon footprint decrease, to name only a few.*

Keywords: *Port Container Terminals, Process Standardization, IoT, Big Data, Carbon Footprint, Key Performance Indicators, Energy Efficiency*

Conference Topic(s): *Communication, networks; interconnected freight transport; logistics and supply networks; material handling; ports, airports and hubs; technologies for interconnected logistics (5G, 3D printing, Artificial Intelligence, IoT, machine learning, augmented reality, blockchain, cloud computing, digital twins, collaborative decision making).*

Physical Internet Roadmap (Link): Select the most relevant area for your paper: ⊠ *PI Nodes,* ☐ *PI Networks,* ☐ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

1 Introduction

Port container terminals and their logistic infrastructures are essential to keep the European Union (EU) in the leading position of world-developed areas. The impact of this strategic sector in the quality of life of European citizens and in the EU competitiveness is crucial, as freight transport is a powerful key driver for job creation and economic growth. Promoting innovation on efficiency, sustainability and safety of the port-container industry is a fundamental issue.

The significant economic growth before the global financial crisis and the increase of cargo volumes have driven maritime ports into developing their capacities in unexpected ways. Infrastructures, services, and equipment have achieved a significant development of capabilities and complexity. This evolution has provided remarkable benefits for the performance of container handling and logistics. However, operational missing links and bottlenecks remain, resulting in significant negative effects like performance inefficiencies, labor accidents, increased energy consumption as well as pollutant and greenhouse gas emissions.

In parallel, the development of the 4th Industrial Revolution in the last decade (Industry 4.0) has progressively deployed new concepts that, with different degree of adoption, are currently adopted in strategic sectors (automotive, heavy industries, energy, health, etc.) (Madsen, 2019). The adoption of concepts like Internet of Things, Big Data, Artificial Intelligence, Cloud Computing, Robotics and Automation is transforming the industry and society. The port industry, however, is not taking advantage of the benefits and impacts derived from the digital transformation due to the low degree of implementation of such technologies and digital solutions.

Fast advances in information technologies and in particular, digitization, machine learning and Internet of Things have created new possibilities for the cargo handling industry, that could improve processes by connecting all equipment and systems in real time, thus enabling seamless data exchanges. Under these new conditions, more automated and inter-operable solutions could be achieved by the sector with less risk, at a lower cost and faster lead-time, thus allowing universal connectivity of port equipment regardless of the type of manufacturer.

iTerminals 4.0 (Application Of Industry 4.0 Technologies Towards Digital Port Container Terminals) is a project awarded in mid-2018 by the **Connecting Europe Facility Programme** of the European Union that has studied and tested the implementation of the 4th Industrial Revolution concepts in the Port Container Terminal Industry. The iTerminals 4.0 project addresses this gap and comprises the study and pilot deployment in real operations at European port-container terminals of Industry 4.0 technologies within the container-handling sector. The Pilot described in this article is a Proof of Concept (PoC) of how the data can be used to provide this added value regarding energy efficiency and carbon footprint monitoring at TEU or container granularity level and in real time.

Addressing the CO_2 emissions and carbon footprint at a container terminal is not an innovative concept. Previous research in this sense can be found in the literature. There is, for instance, the work of Van Duin and Geerlings (2011), that provide a methodology to predict CO_2 emissions on a yearly basis at container terminals, based on estimates of energy consumption patterns for each type of machine used in container handling. Vasanth et al. (2012) performed a study of CO_2 emissions by type of machinery and Scope (1, 2 or 3) for a complete year. Prayogo (2019) proposed an approach of dynamic modelling and optimization of CO_2 emissions in container handling operations for one year, based on estimates of carbon footprint per handled container for each type of machine at the terminal. More recently, Budiyanto et al. (2021) have developed a methodology to estimate CO_2 emissions at a container terminal, based on data of energy consumption and estimates of consumption per move or cycle for each type of machine. The article presented is built on the same foundations as these previous works, having as the objective in this case **the carbon footprint for each identified handled container** within the terminal, **in near real-time**, thanks to the development implemented in the context of the iTerminals project. With this information, a terminal operator can devise specific KPIs to aggregate the information and observe its evolution through time, with a granularity of seconds, if needed. The information is processed and served directly from the data being monitored from all the machines involved in container handling, therefore it is not a statistical value, nor a monthly average based on energy bills, but an actual, dynamic and real measurement.

2   The TIC 4.0 model. Definition and objectives

The iTerminals 4.0 project has developed its Proof of Concepts (PoCs) applying the common data model and semantics defined by the Terminal Industry Committee 4.0 (TIC 4.0[1]). The TIC

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[1] https://tic40.org

4.0 initiative aims to bring together representative companies from both the Terminal Operators Industry, Port Equipment Manufacturers and Digital Solution Providers to collectively work on the elaboration of port terminal standards, with the objective of defining and agreeing on a **common language** and process definitions among the agents involved in the cargo handling industry. Moreover, this initiative has facilitated the **interoperability** of different information sub-systems of a cargo handling facility in a seamless way.

Due to separate development in the first decades of containerization of terminal operation solutions in several regions around the world, there is not a single definition for processes or machine movements at the terminal. A multitude of varying descriptions can be found with different words, sentences, protocols, languages for the same unique physical element, making it unusable for virtual representation and use of new technologies. For example, the word "Move" is used in all areas of terminal operations and can refer to certain parts of the process and certain units being handled i.e. at the Berth, STS, Yard, Gate, Port or Terminal and Box, TEU, Reefer, Over height Load etc. With Port Equipment the word "Cycle" has different meanings depending on the equipment and brand i.e. for STS, ASCs, RMGs, RTGs, Straddle Carriers, Reach-stackers, Spreaders, Terminal Trucks, AGVs, etc.

This challenge has been taken up by the industry stakeholders with the foundation of the Terminal Industry Committee 4.0 (TIC 4.0) to properly define unique physical elements using a common agreed language/vocabulary for virtual transformation, as can be seen in the conceptual image depicted in Figure 1.

Figure 1. TIC 4.0 common semantics and data model approach

In the context of the iTerminals 4.0 project, the TIC 4.0 communication architecture (see Figure 2) has been implemented and tested in different port container terminals in the EU, such as Malta Freeport, Thessaloniki, Dunkirk and Montoir terminals, as well as PSA Antwerp, Sines and Genoa. In this architecture, the IoT gateways deployed at each Container Handling Equipment (CHE) gather and circulate real-time information to a central node where a Big Data platform is located, so that specific Key Performance Indicators (KPIs) can be computed in real-time and visualized in different dashboards in order to deliver to the container terminal staff useful insights regarding the cargo handling performance.
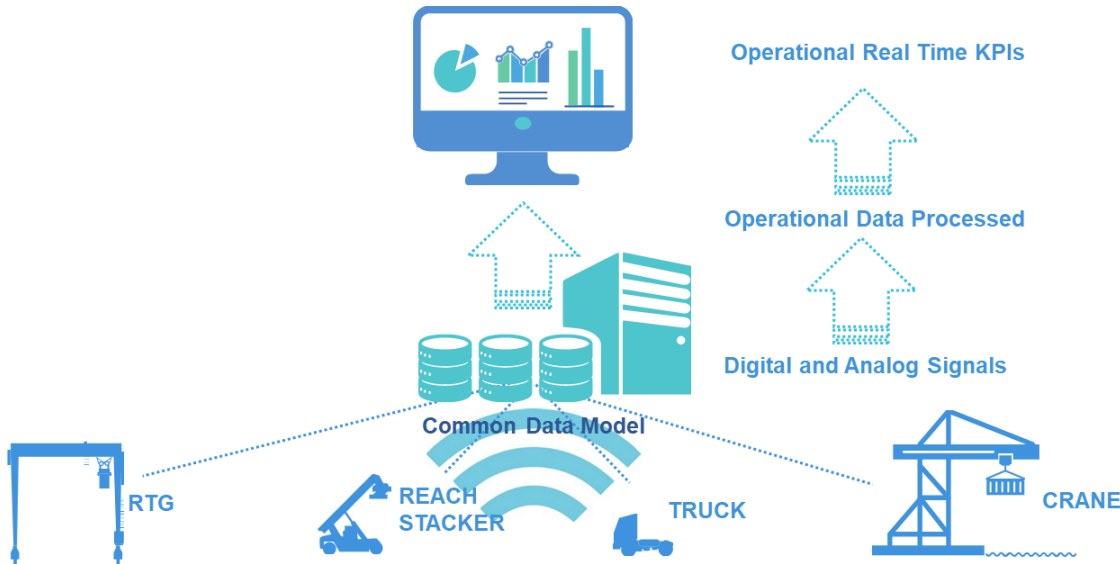
Figure 2. iTerminals 4.0 communication architecture

3   Energy Efficiency and Carbon Footprint Pilot

Besides the improvement in the operational processes, thanks to highlighting bottlenecks and idle times in the CHEs, the TIC 4.0 communication architecture in a container terminal opens a wealth of opportunities for the development of new value-added services. In the context of a transition at the EU to a zero-emission maritime transport and a carbon neutral economy by year 2050, one of the most promising ones is to estimate and compute a real-time **dynamic carbon footprint per each specific handled container**. The carbon footprint (in gCO2 per kWh), the total energy used (in kWh), and the total energy cost (in €) can be calculated in a straightforward way, assigning to each manipulated container a unique carbon footprint value generated during its handling. The data is provided by the iTerminals 4.0 communication architecture, and it is the real-time data monitored by each CHE handling the container, therefore it is the real energy used in handling each specific container. The diagram in Figure 3 illustrates this approach.

Carbon footprint signature
(logistic operative):

18 gCO2/kWh
11 kWh used
0.98 € in energy cost
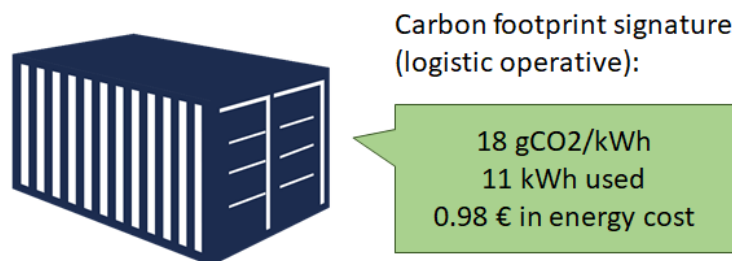
Figure 3. Example of container carbon footprint signature.

A key variable in these analyses is the value of the carbon footprint of all the energy sources used in the terminal. In most of the cases, this input is limited to two main sources of energy: diesel combustion engines, usually used by Rubber-Tyred Gantries (RTGs), Terminal Tractors (TT), Reach Stackers (RS) and other machinery used for container handling; and electricity supply from the grid, mainly for Ship-To-Shore (STS) cranes and minor consumers as offices and lighting. Identifying the carbon footprint for these sources of energy is the core of all the subsequent KPIs related to energy efficiency and carbon footprint being analysed.

Regarding diesel fuel, the carbon footprint will be a fixed, constant value, that may vary as a function of the Port, the machine, or the fuel supplier. Regarding the electricity supply coming from the grid, however, the carbon footprint may vary through the day, depending on the following factors:

1. Typically, the electricity production mix of a territory will match the variable demand through the day, switching on and off fossil-fuelled production plants considering the variability of the intermittent renewable energy plants (such as wind and solar). The carbon footprint of the electricity consumed will therefore not be constant, varying as a function of the contribution to the energy being produced from these pollutant production plants.

2. If the terminal has contracted an electricity supply with a green certificate from a retailer, it could be assumed that the carbon footprint is zero, although this may not be the case, unless the energy has a unique, direct supply coming from a renewable energy production plant nearby.

3. The port or the terminal may have a renewable energy production plant located at their premises, feeding the port's electricity grid with renewable energy. In this case, given that the electricity grid at the port is not isolated from the distribution grid, how this production plant contributes to lower the carbon footprint of the energy mix should be studied.

Given that the carbon footprint of the electricity grid varies with time, the platform should be prepared to input variables that may change their values dynamically through the day. It is therefore necessary to address whether this dynamical information regarding the carbon footprint is available or not. In some countries, such as France, the information of the carbon footprint is available in real time through an API[2] and can also be visualised by means of a web interface[3]. This value is computed for each fifteen-minutes step, having therefore 96 different values available per day. It must be noted, however, that these carbon footprint values are calculated from fuel consumption of energy sources only in French territory, therefore international interconnections are not considered.

Spain, for instance, implements another API[4] that gives carbon footprint and total emissions from each pollutant source, allowing as well to visualise the data by means of a web interface[5]. The carbon footprint value provided in this case is a daily average, computed as the quotient between the total emissions from pollutant sources in the day, by the total energy produced by energy sources (both renewable and non-renewable) in the Spanish territory. It can be noted, again, that the computation is not including international interconnections.

Regarding Malta, one of the Pilot locations, no information on the carbon footprint is available in real time. The Maltese Distribution System Operator (DSO), Enemalta, publishes an annual

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[2] https://opendata.reseaux-energies.fr/explore/dataset/eco2mix-national-tr/information/?disjunctive.nature
[3] https://www.rte-france.com/eco2mix/les-emissions-de-co2-par-kwh-produit-en-france
[4] https://www.ree.es/es/apidatos
[5] https://www.ree.es/es/datos/generacion

report with the average carbon footprint in the electricity supply, calculated for the whole year, being the last provisional value available for the year 2019[6]. Malta's electricity supply has a mix of around 68% coming from natural gas plants, 7% from renewables, mainly photovoltaic plants, and 25% imported from a high voltage interconnection with Sicily (Italy).

3.1 Proof of Concept of Dynamic Carbon Footprint and Energy Cost per Container

3.1.1 Carbon footprint per container

In order to compute the carbon footprint, the platform must be able to group all the cycles from all the machines (CHE) that have operated a given container. Each cargo (i.e. container) has a unique ID, and has been identified using the following variable from the TIC4.0 data model: **che.cycle.cargo**. Once grouped under a same cargo ID, the energy or fuel consumption from each cycle and machine that participated in moving the cargo is read, including the energy used while these machines were idle in the cycle. The energy used is available in the TIC 4.0 data model, with the following notation: **che.cycle.energy.consumed**. Different units can be found (see Figure 4).
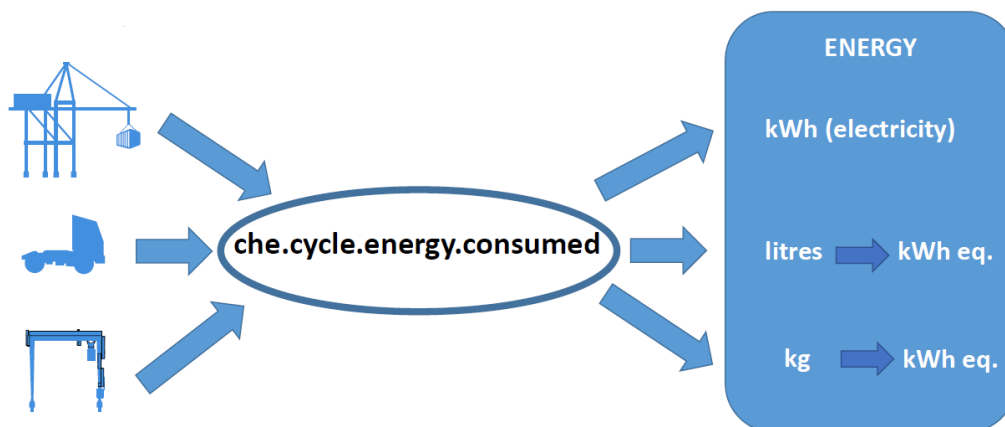
Figure 4. Measure of energy consumption using TIC 4.0 data model.

Once the energy consumption needed by each machine to move a single container is obtained, the following steps are followed:

1. A cost to each energy source (€/kWh and € per litre of gasoil) is assigned.

2. Litres of diesel used are converted to equivalent kWh.

3. Total emissions from each energy source (g CO2) are computed.

4. The following values are calculated:

   a. Total energy used (kWh)

   b. Total emissions (g CO2)

   c. Total cost (€)

   d. Carbon footprint (g CO2 / kWh)

This way, the carbon footprint for each cargo (container) is obtained. Besides, the information can be even more disaggregated if it is considered of interest. For instance, **per operative**, i.e., a carbon footprint could be calculated only for loading/unloading operation, or for

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[6] https://www.enemalta.com.mt/environment/fuel_mix_for_energy_distribution/

housekeeping operations. The different moves, in the case of cranes, are also measured using TIC 4.0 data model, therefore it is possible to apply the same steps commented to calculate the carbon footprint per container only for the targeted operation.

3.1.2 Key Performance indicators

From the individual carbon footprint signatures of all the containers, some key performance indicators and other variables have been computed. In the context of this Pilot, different indicators and variables have been grouped in three different levels: terminal, service or container. Indicators at **terminal** level indicate the overall progress of the terminal in terms of energy efficiency and carbon footprint:

1. KPI on **global carbon footprint per physical container**. Computed as a rate, obtained as the quotient between the sum of total carbon footprint signatures of all the containers, divided by the number of containers passing through the terminal.

2. KPI on **global carbon footprint per weighted Tonne**. Similar to the previous one, in this case the rate is obtained per weighted tonne, given that the weight of all the containers is being measured and the data are available.

The first KPI is obtained from the information previously calculated of the carbon footprint per container. This information should be available for the desired time interval for this KPI (e.g. the last day, the last month, the last year…). There is an additional variable needed, the number of containers, to compute the average. Therefore, for the time interval, the number of containers must be extracted from the Big Data platform.

Further segmentations of the containers can be performed, for data mining purposes. For instance, containers can be classified in categories such as import/export, transhipment, or hinterland. The global carbon footprint can then be calculated and evaluated separately for these three groups.

Regarding the KPI per weighted tonne, in this case the procedure is slightly modified. For each single container, its weight is needed. This information is available in TIC 4.0 from the cycle performed by each CHE, making use of any of the variable **cargo.weight.net,** available in the TIC 4.0 data model.

The **service** refers to the regular lines of container vessels, following regular routes of container transport. With the carbon footprint signatures from all the containers, classified into the different services at the terminal, **global carbon footprint signatures per service** can be computed (see Figure 5), allowing to differentiate between ECO from non-ECO lines, and providing the hints to further investigate on the reasons behind the rank obtained by any specific service.

Carbon footprint signature (logistic operative):

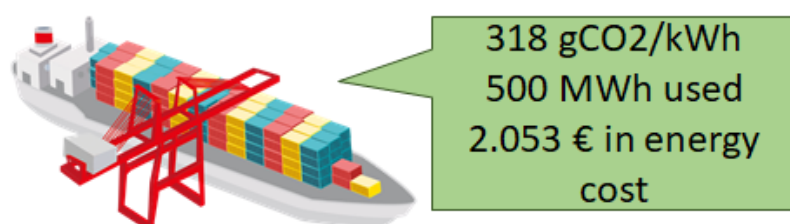318 gCO2/kWh
500 MWh used
2.053 € in energy cost

Figure 5. Example of real-time service level carbon footprint signature

In order to compute this KPI dynamically, **all the different containers (cargo) should be linked to a specific line or service**. Once the carbon footprints are obtained, the containers are aggregated by service, and the KPIs is obtained for each group. An average carbon footprint per container belonging to the same service can be also calculated and visualized. This information is available in the following TIC 4.0 variables: **cargo.line** and **cargo.service**.

3.1.3 Energy Label at Container level

Indicators at container level can have, as previously indicated, an individual **real-time carbon footprint signature**, that comprehends the dynamic carbon footprint, the energy used in each container handling and the cost associated to that energy.

Besides this result, however, this indicator can be used to compute a different variable with an added value, which is the **real-time energy efficiency label per container**, regarding its transport and logistics chain, very similar to, for instance, domestic appliances, with the main difference that, in this case, the labels are calculated continuously and can vary through time, allowing a number of future uses and applications (see Figure 6 as an example).
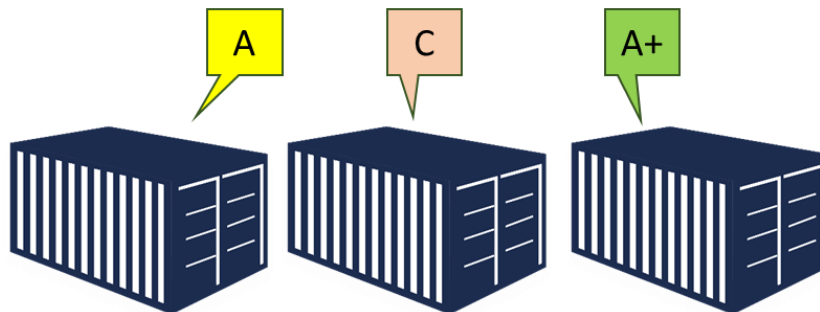
Figure 6. Example of real-time container logistics energy efficiency labelling.

The EEI (Energy Efficiency Index) for appliances, as defined by the European Commission, is usually obtained as a ratio between the annual energy consumption and a standard annual energy consumption from an appliance or load of the same type[7].

In this case, however, the time required to move each container varies; therefore, the first step is to obtain an equivalent measure of the work used to move each container per unit of time. This means that the total duration of the cycle for each cargo or container is needed. The following variables contain this information: **cycle.start.time.timestamp** and **cycle.end.time.timestamp**. Having the duration available, the procedure to compute the labels is the following:

1. Set the temporal window to compute the labels (e.g. the last day, the last month, the last year…)

2. Obtain from each container (cargo) the following information:

    a. The total energy consumed in its logistics operative.

    b. The total duration of the logistics operative (i.e. the total duration of all the cycles needed to move the container).

3. Obtain, for each container, the ratio of power per unit of time, as the quotient between energy consumed and duration.

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[7] European Commission. (2021). About the energy label and ecodesign. Retrieved from https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/about_en#:~:text=The%20energy%20labels%20provide%20a,gas%20emissions%20across%20the%20EU

As a result, values of power needed per unit of time for each container are obtained. These power ratios can now be compared among them and translated into specific energy labels, based on minimum and maximum values of power obtained, or on historical records of these values at the terminal.

3.1.4 Visualization

The strength provided by a common semantics language to describe movements and processes, serves as the basis to calculate and compare KPIs for any container or groups of containers at the terminal. Adding some extra information, such as the energy sources' carbon footprint and costs, allows operators to obtain a clearer view of what is really happening at the terminal in terms of energy efficiency and usage, giving not only the overall picture of the terminal in real-time, but also allowing to discriminate and compare among services and containers. Figure 7 depicts a visualization example of a dashboard with these KPIs, calculated in real-time for groups of containers segmented by areas in the yard.
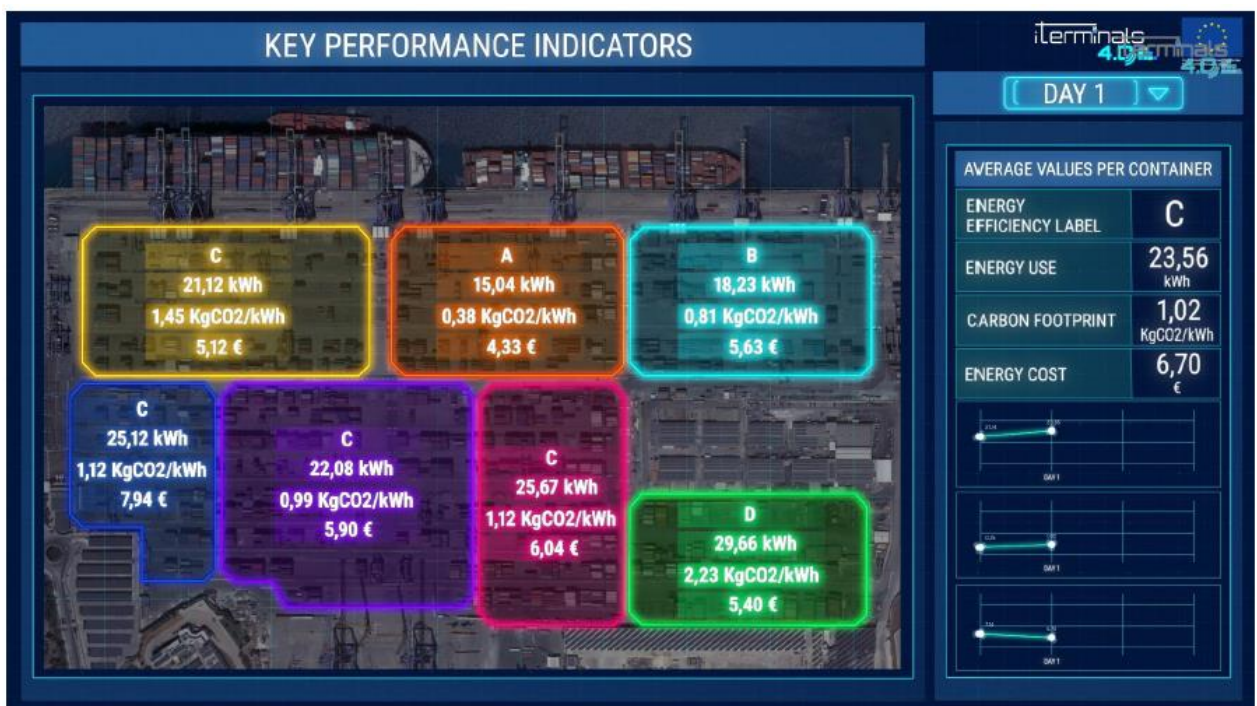
Figure 7. Dynamic Carbon Footprint KPIs grouped by areas at the yard, Malta Freeport container terminal. Dashboard Example.

4   Conclusions

The information on the carbon footprint of the processes that can be currently obtained is restricted by the availability of the data, being these usually scarce, or an average, or available on a monthly or yearly basis. This approach allows a detailed view of the insights of the processes machine by machine, having therefore a better understanding of the CHE behaviour. Thanks to the real time visualization of energy use and cost per cargo and per machine, terminals can derive conclusions on the real energy costs and carbon footprint incurred to each TEU and observe how the indicators evolve with time, evaluating trends and the impact of operational and activity-based cost allocation management decisions. Another benefit of the implementation of the dynamic carbon footprint calculation is the possibility of forecasting energy demand with a variable time horizon.

The iTerminals4.0 project has enabled the standardization of operational data and its implementation in port equipment through IoT technologies and digital platforms, especially developed to fulfil the needs and requirements of a Port Terminal. Having this IoT deployment connectivity, it is possible to study and develop new services and functionalities that provide a higher level of abstraction, built above a common semantics and ontology for container terminals operations, thanks to the telemetry systems that serve the data, and the middleware systems that convert them to uniform, standard and interoperable information. These new functionalities are provided to the terminal operators, allowing them to have an overall view of the container logistic operations in real time, helping them in decision making and providing an insight to the processes and operations that was not available before. This IoT & Big Data ecosystem is the basis which will help the terminals to build on top of this added value services like the dynamic calculation of carbon footprint presented in this paper.

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An exploration of the potential benefits of Transportation and Logistics innovations in Last-Mile Urban Deliveries: A case study approach

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Abstract:

Urban Last-Mile Delivery (LMD) is typically plagued with high uncertainty due to urban road traffic, parking spot unavailability and customer order handover process which in turn leads high operational costs accompanied by several sustainability challenges. Considering these issues, this study assesses the impact of innovative transportation and logistics strategies on LMDs. Specifically, this study examines the potential benefits emerging from the implementation of concepts such as the Physical Internet (in terms of complete collaboration) along with supporting paradigm technologies such as IoT in addition to the use of green logistics to address sustainability issues. Real data obtained from an E-commerce company operating in Madrid city center is utilized to create a simulated environment for evaluating the effects of order sharing and fleet sharing facilitated by urban consolidation centers and dynamic order reshuffling on operational, economic, and environmental indicators. In particular, an urban digital twin has been developed to assess the impact of such collaborative transport strategies on last mile deliveries. The results highlight the significant improvements that can be achieved in LMD performance including reduced delivery times, costs, and emissions. Furthermore, the research also provides valuable insights for urban planners and logistics companies looking to optimize last mile delivery operations in cities.

Keywords:
Physical Internet, Digital Twin, Agent-Based Simulation, collaboration, last-mile, Urban consolidation centers.

Conference Topic(s): distributed intelligence last mile & city logistics; logistics and supply networks; PI impacts; PI implementation; PI modelling and simulation; vehicles and transshipment technologies.

Physical Internet Roadmap: ☒ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks

1. Introduction:

In Last Mile Delivery (LMD), the design of the delivery rounds involves the pairing of each parcel delivery location with a vehicle, while respecting the time and operational constraints of the customer and vehicle drivers. Typically, in the last-mile, parcels located at central warehouses or distribution centers need to be distributed to customer locations all around the city. Urban LMD is typically associated with not only high uncertainty due to the busy city environment but also high operational costs as it accounts for around 30% of operators' costs (DfT, 2019) namely fuel, rental fee of consolidation centers, staff salaries, vehicle purchase, and other logistics' fixed costs such as insurance and maintenance. Furthermore, about 50% of the total delivery tour time in urban LMDs is not spent driving but spent while the vehicle is parked and the handover of orders to the final customers takes place (GLA, 2017; Allen et al., 2018). In other words, urban

delivery uncertainty arises from urban road traffic, parking spot availability as well as the handover process.

The delivery rounds are typically designed using the Vehicle Routing Problem (VRP) and its variants, a popular operations research problem with wide applicability, that has been extensively researched and documented in the literature since 1960s. The VRP is a well-known NP-hard problem because it includes the Traveling Salesman Problem (TSP) as a special case (Garey and Johnson, 1979). To address large real-world delivery round design instances, heuristics and approximate methods are typically used for identifying near optimal solutions. Furthermore, the mathematically optimized solution is frequently found to lack the implicit knowledge of the urban environment and its limitations, seasoned delivery drivers have. Recent advances in improving the accuracy of the VRP utilizing historical data and Machine Learning, attempt to address this issue (Merchan et al., 2022).

Current practices in LMD design and implementation are limited both by the lack of evidence as well as the unwillingness of operations to alter existing practices and go through the risk of changing processes that work. However, a ray of hope to change this is given by the rise of the Physical Internet (PI) concept. The Physical Internet seeks to transform logistics and supply chain management by applying the principles of the internet to the physical world. This approach involves creating a modular and interconnected network of transportation and logistics infrastructures that can enable more efficient, sustainable, and collaborative freight transportation, including LMD. Key aspects of the Physical Internet include the use of standardization, modularity, and interoperability, as well as the adoption of digital technologies such as the internet of things, blockchain, and artificial intelligence (Montreuil, 2011)

This paper focuses on the integration of collaborative and Physical Internet principles in LMD operations with the objective of enabling efficient urban logistics and to aid the transition towards a PI paradigm. Therefore, a simulated environment is established via the development of an urban digital twin, to examine the effects of order sharing and fleet sharing in three different scenarios. In the baseline scenario (as-is), multiple companies are delivering parcels to customers in Madrid city centre using their own distribution centres and fleet. In the second scenario (collaboration), companies' distribution centres are used as shared urban consolidation centres (UCC), in which orders can be redistributed and vehicles can be shared. Urban consolidation centres are logistics facilities located in an urban area that are designed to consolidate goods from multiple suppliers or distribution centres before delivering them to their final destination within the city. Moreover, a *dynamic reshuffling process* is established in this scenario, which matches delayed vehicles with vehicles that have buffer capacity to mitigate the impact of arising delays in daily operations. In the third scenario (collaboration + green vehicles), the collaboration setup is complemented by the use of green vehicles and cargo bikes to further drive down emissions and assess if there is an associated performance loss.

The findings clearly indicate that the integration of Physical Internet principles, particularly the collaboration on orders and fleets among competing companies, enabled by technologies such as IoT and blockchain, not only leads to cost reduction, thereby benefiting a company's financial performance, but also facilitates carbon footprint reduction for each participating company. By employing Urban Consolidation Centers (UCCs) and utilizing green vehicles within the PI vision, these enhancements can be achieved without compromising performance.

2. Literature review

Table 1 highlights the key articles reviewed in the field of carrier collaborations in last-mile deliveries with a special emphasis on the different technologies and logistics innovations considered and the methodologies used to address the research objectives

As can be seen from Table 1, limited number of studies explicitly address the use of different technology and logistics innovations for fostering efficient collaboration between carriers. While certain studies, such as Handoko and Lao (2016), Los et al. (2020), and Guo et al. (2021), emphasize the role of digital market platforms in coordinating logistics operations through order and capacity allocation, they do not delve into the examination of sharing and collaboration within the context of Physical Internet strategies. In Physical Internet strategies, collaborative sharing surpasses mere allocation facilitated by digital platforms and involves profound collaboration and coordination among participants. Although the extant literature recognizes UCCs as a common form of collaboration, studies like Handoko and Lao (2016) and McLeod et al. (2021) often assume that the responsibility of arranging fleet capacity for last-mile deliveries lies with the UCC operator. Furthermore, even

Table 1: Review of key extant literature

	Transportation Modes			Technology	T&L innovations	Collaboration Type			Methodology	Objective Type
	Trucks	E-vans	E-bikes			UCC	Carrier Fleet Capacity Sharing	Carrier Order Sharing		
Liu et al. 2010)	✓							✓	LSO	Empty vehicle moves (Min)
Handaku and Lau (2016)	✓				Platform	✓		✓	GT	CS(Max)
Wang et al. (2017)	✓				Platform			✓	LSO	P(Max) & fair P sharing
Chabot et al. (2018)	✓							✓	LSO	Costs,Emissions (Min)
Los et al. (2020)	✓				Platform	✓		✓	GT	Service, Profit (Max), Time (Min)
Guo et al. (2021)	✓				Reshuffling, Platform	✓		✓	LSO, GT	Costs,Emissions (Min
McLeod et al. (2021)	✓		✓	GPS		✓		✓	LSO	Costs,Emissions (Min
Current Study	✓	✓	✓	BC,IoT,	Reshuffling, PI enabled platform	✓	✓	✓	LSO	Costs (Min)

CS: Cost Savings, GT: Game Theory, LSO: Large Scale Optimization, Max: Maximization, Min: Minimization, P: Profit, BC: Block Chain, PI: Physical Internet, IoT: Internet of Things

though studies such as Chabot et al. (2018), Guo et al. (2021), and McLeod et al. (2021) consider the objective of minimizing emissions in the system considered, they do not capture the impact of using greener transportation options such as E-vans and E-bikes for last mile deliveries instead. This current study aims at filling the gaps highlighted above. The main research questions of this study are delineated below:

- <u>T&L innovation impact:</u> To what extent can an urban digital twin be used to analyze the influence of implementing a Physical Internet strategy, supported by paradigm technologies like IoT and blockchain, on the collaboration between logistics providers in terms of order and fleet-based coordination during the last-mile phase? In particular:
  - o <u>Order-Sharing:</u> What is the impact of implementing urban consolidation centers within a Physical Internet strategy on service performance?
  - o <u>Dynamic Fleet-sharing:</u> To what extent can the adoption of dynamic fleet-sharing strategies within a Physical Internet strategy mitigate uncertainties, such as traffic congestion and parking slot unavailability, that commonly affect last-mile delivery operations?
- <u>Green vehicles:</u> <u>To what extent does the replacement of conventional last-mile delivery vehicles with electric vehicles and cargo-bikes, within a Physical Internet strategy, impact the overall system performance considering the collaboration between logistics operators on orders and fleet management?</u>

3.   Methodology:

To address the main research questions of this paper, a scenario-based case study has been constructed in the city of Madrid. A digital replica of the Madrid urban city, referred to as the *urban digital twin* is developed to evaluate the magnitude of impact on last mile deliveries resulting from the different collaborative transport strategies considered. The digital twin comprises two key components: a dynamic simulation model and a route optimization engine. The dynamic simulation model utilizes multi-agent technology, enabling the digital twin to simulate the behavior and dynamics of entities within the system (hubs, vehicles, routes, and orders), thus, providing valuable insights into their interactions and performance. Through the simulation, detailed statistics are obtained, including aggregated and per-route/vehicle metrics such as distance, cost, emissions, on-time deliveries, and fill rate. The model is built on a standardized data model that efficiently collects essential information, including the number and position of hubs, fleet size, vehicle characteristics, as well as comprehensive details about orders, such as location, weight, and time windows. Additionally, effective communication is established between the simulation model and the route optimization engine, ensuring seamless integration between the two components. Through this digital twin, with strategic focus on urban logistics and commitment to the Physical Internet vision, answers are provided to the main research questions of this study, allowing users to make decisions based on the results of applying what-if scenarios.

The main assumptions are: three logistics companies operate in the city and hundreds of orders synthetically generated based on real demand data must be delivered during a normal day of operation. A description of each of the simulation scenarios is presented below:

(i)   Scenario 1. As-is

In the baseline scenario, the three companies operate in the centre of the city in the traditional, non-collaborative manner. Each company has a fleet of three conventional delivery vehicles, which start their routes from their company's hub located on the outskirts of the city, as shown in Figure 1 (left). The distribution of demand among the companies, represented by the different colours (where each colour represents the demand to be fulfilled by a single company) are also shown in Figure 1 (right).
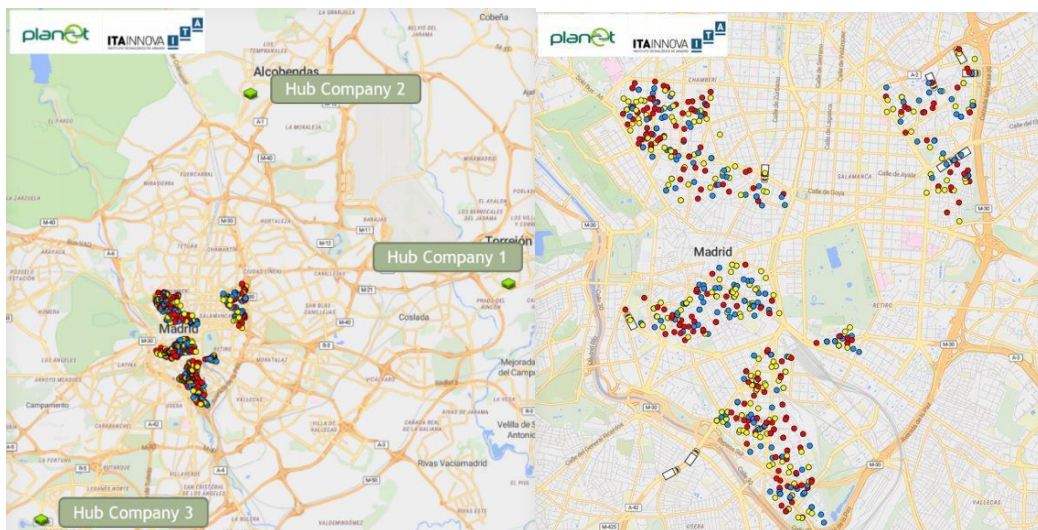

Figure 1: Companies' hub location and demand distribution

(ii)   Scenario 2. Collaboration across companies

To enable collaborative cargo distribution using the PI concept, two types of collaborations are implemented, namely,

1. Collaboration on orders through the implementations of **two** Urban consolidation centres. These facilities serve as centres for receiving parcels from the three firms,

sorting, and redistributing the parcels to their final destinations. The study assumes that the two UCCs are established and operated jointly by the three logistics players. Furthermore, rather than being located on the outskirts of the city as in Scenario 1, the two UCCs are assumed to be strategically located in and around Madrid's metropolitan city center, where the end-consumer demand is concentrated.

2. Collaboration on fleets. Fleet sharing between the companies can occur in two stages: static and dynamic. The static stage represents the start of the planning horizon where vehicles of each company are assigned delivery rounds comprising of parcels that have been sorted at the UCCs based on location proximities. The route optimization in the static stage is undertaken using the route optimization engine component of the digital twin. On the other hand, the dynamic stage represents the stage when the delivery operations by the vehicles are underway and a delay arises in at least one of the delivery rounds due to extrinsic factors such as traffic, parking spot unavailability etc. In such as case, a dynamic reshuffling service is responsible for identifying optimal help from any vehicle operating in the vicinity regardless of the company, re-assign the parcels and re-design the routes. In this scenario, a decision support algorithm is developed which is an automated process for addressing parcel delivery delays, that otherwise was undertaken manually (Scenario 1: As-is). The decision support algorithm tracks the progress of delivery vehicles through the digital twin, dynamically analyzes assistance and collaboration options, identifies optimal synergies and updates driver delivery instructions. The decision support tool focuses on effectively exploring all collaboration options in proximity for single or multiple operators, to alleviate late deliveries and non-completion of delivery rounds. Figure 2 further highlights the types and sequence of collaborations in the static and dynamic stages.

Through such collaboration, the system aims to reduce traffic congestion and emissions, as well as increase the efficiency of delivery operations.
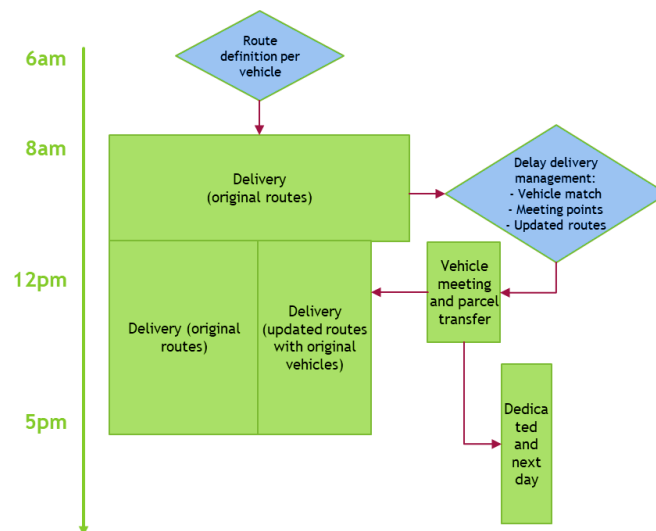

Figure 2: Sequence of events in the Static and dynamic collaborations stages

(iii)   Scenario 3. Collaborative urban hubs + e-vehicles

This scenario extends Scenario 2 by further assessing the potential of using electric vehicles and cargo bikes instead of traditional delivery vehicles in collaborative cargo distribution networks. (Figure 3). In this situation, while the number and locations of UCCs are the same as in Scenario 2, the two depots are designated for different vehicles: one for cargo bikes and one for electric trucks. The electric trucks have a similar capacity to the conventional trucks in Scenario 2 while the capacity of cargo bikes is lower. It is assumed that the vehicles have sufficient autonomy to operate throughout the day without the need for additional charging or battery replacements. These assumptions allow for a general exploration of the viability of implementing the PI

concept, while acknowledging that further detailed analysis may be required to account for specific cost factors and energy considerations.
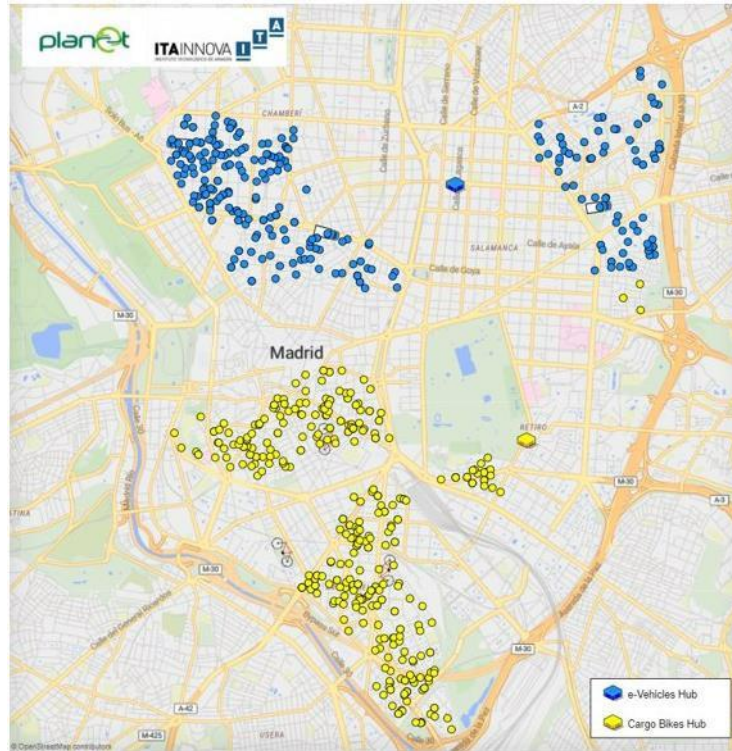

Figure 3: Collaborative urban hubs location and order-hub assignment

Table 2 Overview of technologies and logistics innovations modelled in each scenario

Technology/ Logistic innovation modelled	Characteristics considered	Scenarios		
		(i)	(ii)	(iii)
Physical internet	Open logistics environment to share asset (viz. trucks, depots) capacity, routes, and customer order data to improve the last-mile delivery performance.		✓	✓
IoT	End-to-end visibility over different operators and means of transport		✓	✓
Blockchain	Enabling technology for the Physical Internet, offering robust security measures and fostering trust in information exchange among operators		✓	✓
Optimized decision-making	•Vehicle routing Problem: Optimal routing of parcel deliveries in the last mile •Dynamic matching of delayed and non-delayed vehicles		✓	✓
Green Logistics (E-vans+cargo bikes)	Replacing the conventional diesel trucks with more sustainable vehicle options to carry out the last-mile deliveries			✓

4.   Results and Conclusion:

This work had the objective to assess the impact of adopting a Physical Internet strategy on last mile delivery performance.

In order to achieve this we developed an urban digital twin which allowed for a holistic analysis of the entire LMD system by enabling a close examination of the different logistics players and their processes. The unique aspect of the model examined is the application of different state-of-the-art PI enabling technologies such as IoT, Blockchain, AI/ML, and electric vehicles which replicate the actual progress observed in the last-mile delivery space.

Specifically, we assessed two different collaboration strategies within the PI paradigm: order sharing by implementing UCCs and fleet sharing by deploying dynamic parcel reshuffling (Scenario 2). Additionally, the impact of deploying green delivery vans and cargo bikes was analyzed (Scenario 3)

Results show that the two collaboration strategies lead to a drastic reduction of the average distance travelled and emissions, as shown in the comparison between 'As-is'-Scenario 1 and Scenario 2 in Figure 4. Hence, not only performance and utilization are improved, but also a great positive impact on sustainability is achieved. A smaller number of vehicles can serve the same demand, resulting in more efficient use of the resources of each company. The average route time remains constant, which indicates that performance improvements mainly stem from improved bundling of parcels across different companies in UCCs. The deployment of green vehicles and cargo bikes (Scenario 3) further drives down emissions as conventional vehicles with high emissions are replaced by low emission vehicles and zero emission bikes. The use of cargo bikes additionally leads to a higher fill rate as they can be deployed more flexibly with smaller loads. At the same, this does not come at the cost of longer distances travelled due to our optimization.
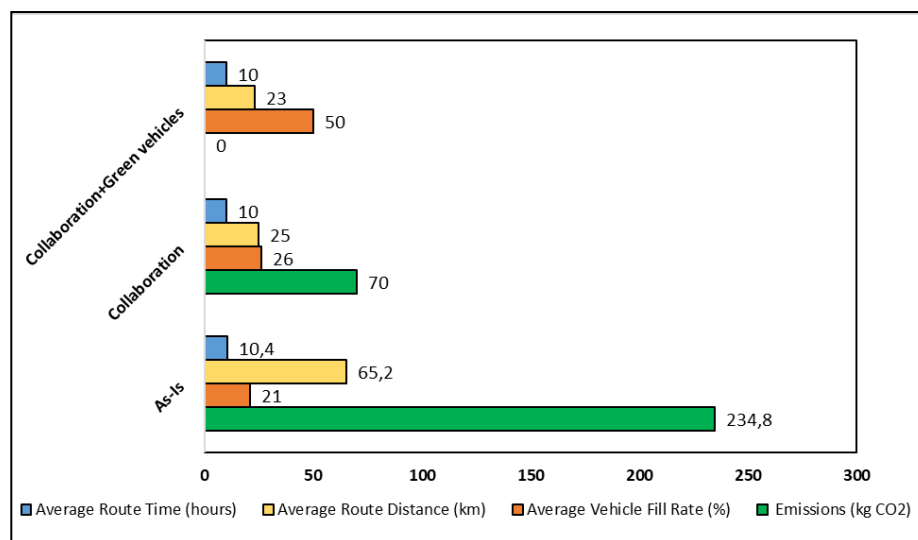
Figure 4: Comparison of Operational and environmental indicators across the three scenarios
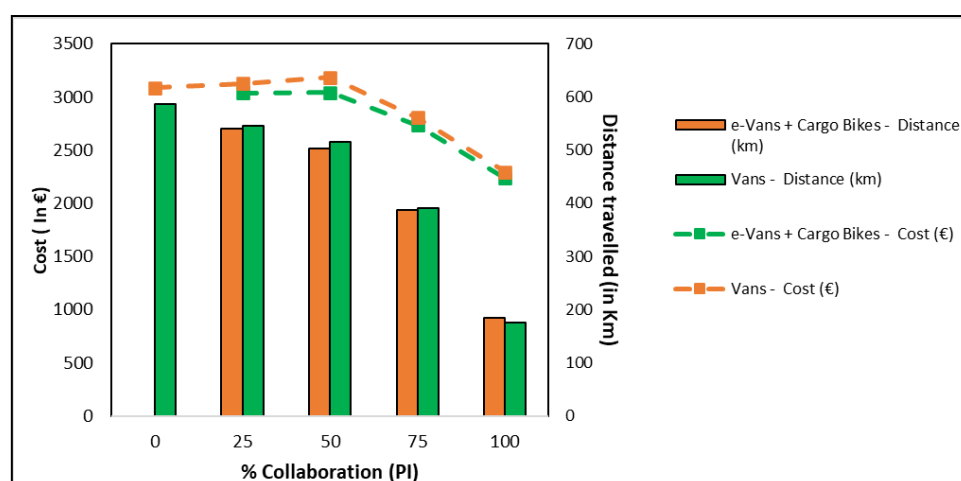

Figure 5: Comparison of Economic Indicators for different PI adoption levels

Figure 5 further highlights the extent of impact of different adoption levels of the PI concepton fixed costs, such as vehicle activation, as well as variable costs, such as fuel and driver expenses. Since the PI concept here refers to the extent of collaboration between the different last-mile delivery players, the different adoption levels represent various levels of information sharing, trust, and thus, overall collaboration on the logistics processes in the last-mile. In the case Scenario 2 depicted in Figure 5, 100% adoption

representing full or complete implementation of the PI concept leads to the most significant enhancement to the environmental performance along with better delivery performance for the whole system. In Scenario 3, the use of electric vehicles results in a complete elimination of emissions. This demonstrates that transitioning to alternative fuel vehicles can effectively reduce the environmental impact of transportation systems while maintaining or improving performance in other areas, such as cost savings.

The results of this study are based on a simulated environment, and further research is needed to validate the findings in real-world scenarios. Nonetheless, the insights gained from this research can be used to inform the development of collaborative transport strategies in a PI paradigm. Further, future research can also look at addressing the financial aspects of implementing the different collaborative strategies (i.e., UCCs and dynamic parcel reshuffling) by considering the capital investment costs, parcel sorting costs, electric vehicle charging and battery constraints etc.

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Environmental impact assessment of intercontinental transport network with digital twin under PI framework

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Abstract: *This paper evaluates the impact of collaborative transport strategies and emerging technologies on an intercontinental transport network with a digital twin. The study assesses the effects of applying Physical Internet (PI) concepts and enabling technologies, such as Internet of Things, blockchain, and artificial intelligence, on the performance of the transport network, including key indicators such as carbon emissions, delivery performance, and logistics costs. Results show that implementing PI concepts and integrating these technologies can lead to improvements in environmental and economic indicators. Despite these benefits, there are several challenges to overcome, including the integration of these technologies into existing logistics systems, coordination among stakeholders, security and confidentiality. Overall, the study demonstrates the potential of these technologies and concepts to contribute to sustainable transportation systems, but further research is needed to evaluate their feasibility and scalability in real-world transportation networks, as well as to develop strategies to address the challenges.*

Keywords: *Digital Twin, Agent-Based Simulation, Intermodal and Synchromodal Transport.*

Conference Topic(s): *PI impacts; PI modelling and simulation.*

Physical Internet Roadmap *(Link):* ⊠ *PI Nodes,* ⊠ *PI Networks,* ☐ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

1 Introduction

Supply chain disruptions could cost European economies around €920 billion of their gross domestic product by 2023, which corresponds to a loss of 7.7 percent of the eurozone's GDP in 2023 (Accenture, 2022). Over the past few years, there have been several significant events that have impacted global supply chains, including the well-known COVID-19 pandemic, the war in Ukraine, and the recent Evergreen vessel blockage in the Suez Canal. These events have highlighted the importance of resilient supply chains and the need for businesses to prioritize supply chain risk management.

Supply chain resilience and sustainability are closely related. Supply chain resilience is an important condition for supply chain sustainability at its three levels: social, economic and environmental (Zhu and Wu, 2022).

Based on the Internet of Things, standard coordination protocol, smart containers and other key foundations, the Physical Internet (PI) provides an interconnected, shared and adaptable logistics system, which has great potential to significantly increase the reliability and resilience of supply chains (Ben Neila and Nemeth, 2021; Peng et al, 2021). The PI concept roots its origins in the unsustainability in the long run from economic, environmental and societal

perspectives of the current global logistics and supply chain management practices that constitute the "worldwide global logistics sustainability grand challenge" (Montreuil, 2011). The PI is an integrative concept, which spans the boundaries between companies and therefore also necessitates substantial changes within and between organizations (Treiblmaier, 2019). The realization of the PI requires a fundamental re-organization in logistics that entails truly integrated processes and horizontal collaboration among organizations where collaboration among participating companies in the supply chain, third parties and externalities play a central role in its conception.

Technology can play a significant role in building resilient and yet still competitively cost-efficient supply chains enablers are intended to create an open, interconnected global logistics system (Zhu and Wu, 2022).

The ALICE roadmap to the physical internet explains the development of the PI over the next twenty years. The roadmap dictates the development path of five specific areas (logistics nodes, logistic networks, system of logistics networks, access and adoption, and governance) for the PI realization. The role of technologies is as enablers and facilitators of their development paths. This article explores the role of three specific technologies that enable the PI realization and increase supply chain resilience: Internet of things (IoT), Artificial Intelligence (AI) and Blockchain.

IoT devices are equipped with sensors and other hardware components that allow them to collect data such as temperature, humidity, motion, and location. Thus, the IoT enables the Physical Internet by providing real-time data of logistics goods and assets that can be used to optimize logistics operations. AI can enable the Physical Internet by providing real-time data analysis, predictive analytics, and machine learning algorithms that can optimize the logistics network (Radanliev et al., 2021). Blockchain helps track data transactions taking place between multiple networks owned and administered by various organizations as physical goods pass between points in the supply chain. It enables immutable data records and facilitates a shared data view along the supply chain. The blockchain can be used to alleviate risks inherent to supply chain management such as uncertainty regarding quantities of production, lack of transparency when a manufacturer changes supplier, unethical behavior of middlemen, and complicated inventory management (Treiblmaier, 2019). This technology offers a solution for fundamental barriers of the Physical Internet concerning the exchange of value and physical assets in logistics networks and decentralized leadership structures (Kuhn et al, 2019).

A supply chain digital twin is a detailed simulation (virtual representation) of real-world supply-chain entities and processes. Digital twins use real-time data to forecast supply chain dynamics and understand supply chains' behavior. Digital twins can help to optimize performance, predict outcomes, and test scenarios in a safe and cost-effective way. By simulating different scenarios of the supply chain, companies and governments can evaluate the impact of proposed changes before implementing them.

After a literature review to position this work in the current state of knowledge in the area, this paper evaluates the impact of PI strategies and emerging technologies on an intercontinental transport network with a digital twin based on multi-agent simulation techniques.

2 Literature review

The general interest in the PI concept is growing. Treiblmaier et al. (2016) identified a list of PI-related problems and questions yet to be answered by research. In this sense, the work carried out in this paper contribute to the area related to change in business models and culture trough the evaluation of the benefits and challenges of adopting a new paradigm in business practice.

Indeed, simulation techniques help evaluate the impact of various decisions on indicators of cost and emissions, showing the benefits of adopting more sustainable and efficient practices. Simulation techniques can thus support the transition to a low-carbon economy and society.

Digital twin, referring to the virtual representation of a physical object, is well-perceived as a key driver in the development of PI-based Supply Chain Management. Nguyen et al. (2022) concluded from their comprehensive review of the literature in this field that throughout the years, PI was investigated typically from the logistics and manufacturing perspective. Meanwhile, Digital Twin was mostly adopted as an enabler for smart manufacturing. Only most recently, it was adopted for supply chain resilience development in response to the COVID-19 pandemic and its consequences (Dy et al., 2022; Lv et al., 2022; Klöckner et al., 2023; Ivanov 2021; Burgos 2021).

Wang et al. (2022) highlighted the opportunities to build and improve the smart supply chain by building Digital Twins. In this regard Multi-Agent Simulation of PI supply chain networks is a common methodology to capture the diversity, dynamics, and emergent behaviors of the agents involved in a digital twin (Hakimi et al., 2012; Furtado, 2013; Sun et al., 2018; Chargui et al., 2020).

Recently, authors on the field have started to investigate opportunities of application of new disruptive technologies in the PI vision. Tran-Dang et al. (2019 and 2020) investigated the perspectives of PI under the impact of the Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), big data analytics (BDA), cloud computing and blockchain. In the studies, important perspectives were identified. However, it was pinpointed that since the PI is still in the initial stage of development and realization, the co-implementation of PI and the new disruptive facilitating technologies faces many critical challenges and barriers related to system, business, data, and policy issues. They concluded that besides the vital role of technologies, a mind shift in the business culture, policies, competition, and collaboration has a significant impact in the success of PI. Little has been investigated of the impact of combining different technologies in a PI network, as is the problem addressed in this work. This paper tries to close the gap related to the implementation of different disruptive technologies and new modes of transport in an intercontinental transport network applying PI related concepts.

3   Methodology

The maritime transport industry has experienced a surge in demand post-pandemic that exceeds the current supply, leading to a sharp increase in operating costs and a change in the rules of the game. Players are now required to control their economic risks much more rigorously, among other requirements. In 2021, China accounted for 63% of the volume of Spanish imports (1,487 thousands of tonnes) (Spanish Ports, 2022). The China-Spain container transport network was chosen as the case study for this research due to its significant size and complexity, making it an ideal representation of a typical PI. A range of transportation modes, including maritime, rail, and road transport, is involved, allowing the impact of enabling technologies to be evaluated. Additionally, valuable insights into how these technologies can improve the environmental and economic performance of the PI system on a global scale can be gained by analyzing the impact of enabling technologies on this network.

As the first step of the methodology, diagrams of the main processes involved in container shipping, such as port operations and the different modes of transportation were designed. This was undertaken to provide a comprehensive understanding of the different stages of the considered container transport network and to identify key areas where enabling technologies can be applied to improve performance. The process diagrams were also used to guide data

collection and integration into the digital twin. Figure 1 shows an example of a process diagram for road transport, including truck operations in the port.
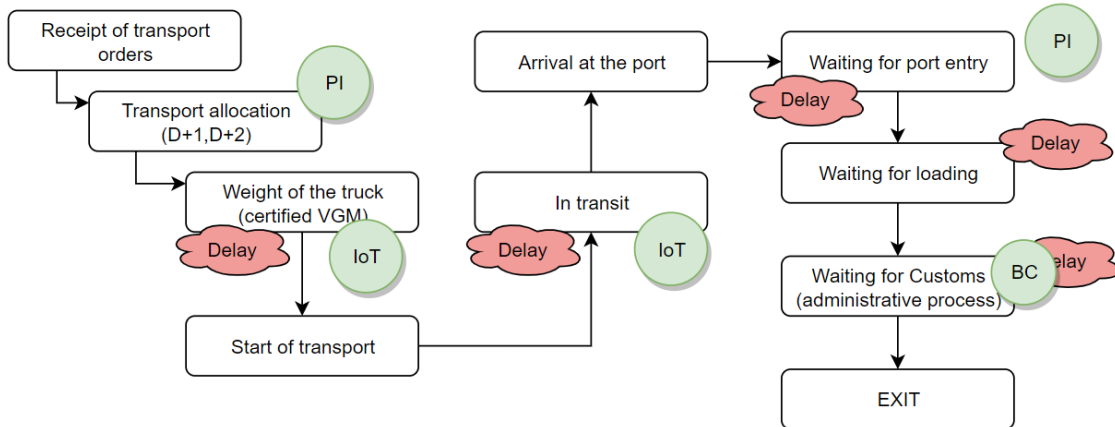

Figure 1: Process diagram for road transport, including potential impacts of enabling technologies

Following the development of the process diagrams, a set of logical rules was devised to represent the potential impact of IoT, blockchain, and artificial intelligence on the network.

Regarding IoT, the implementation of a track and trace service has been considered as a potential solution to reduce delays and the number of incidents in transportation. This service enables real-time monitoring of goods and vehicles, allowing for more accurate predictions of arrival times and better management of transportation resources. By providing greater visibility into transportation operations, the track and trace service can help identify potential issues before they escalate, enabling swift action to be taken to minimize disruption and prevent delays. Furthermore, IoT-based technologies, such as weight sensors, could be used to improve the efficiency of port operations. By verifying the weight of containers (VGM) in advance, these sensors could help to reduce waiting times and avoid additional movements during the entry and exit of the port, as shown in Figure 2.
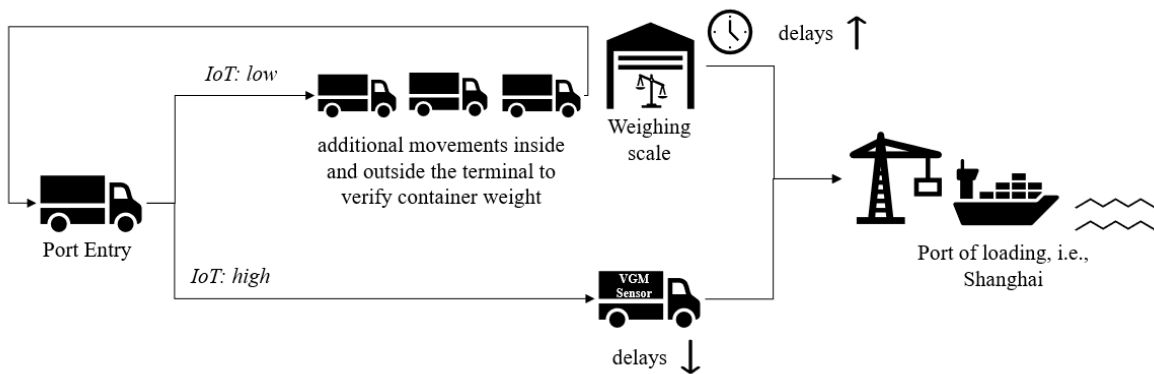

Figure 2: Potential impact of IoT on port operations

In the context of blockchain technology, one of the key applications being considered is the use of smart contracts to automate and streamline the contracting process. Smart contracts ensure that all parties involved in the logistics operation are in agreement and that the terms and conditions are met, which enables the customs clearance of seaborne cargo to take place at a dry port near the receiver/consignee, without any paperwork. This can help reduce queues and delays at customs clearance, as shown in Figure 3.
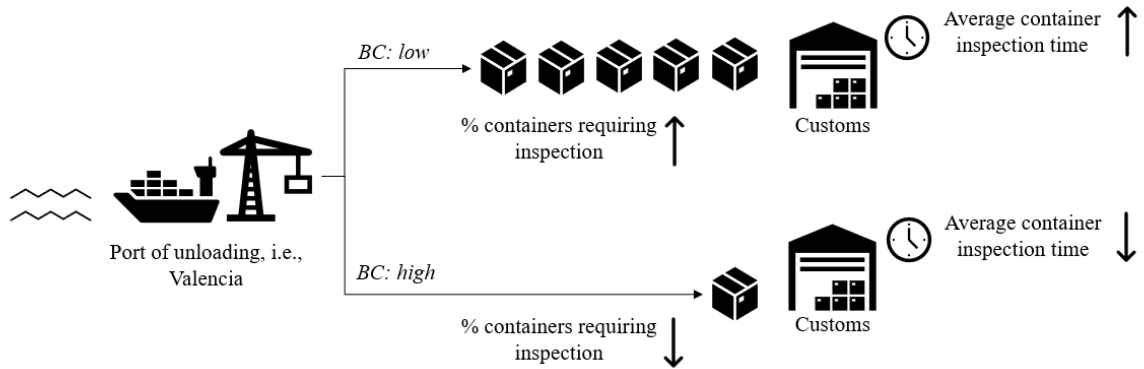
Figure 3: Potential impact of blockchain on customs clearance process

Artificial intelligence has been considered in this study as a potential technology to optimize liner shipping routes for containerships. Specifically, algorithms have been utilized to decide which ports to call at within the route. These algorithms take into account various factors, such as the costs of maritime and hinterland transport, port handling costs, and potential delays, in order to minimize the overall transportation cost. It is worth noting that when such algorithms are not employed, the destination port for the ship is typically predetermined from the origin, as shown in Figure 4.
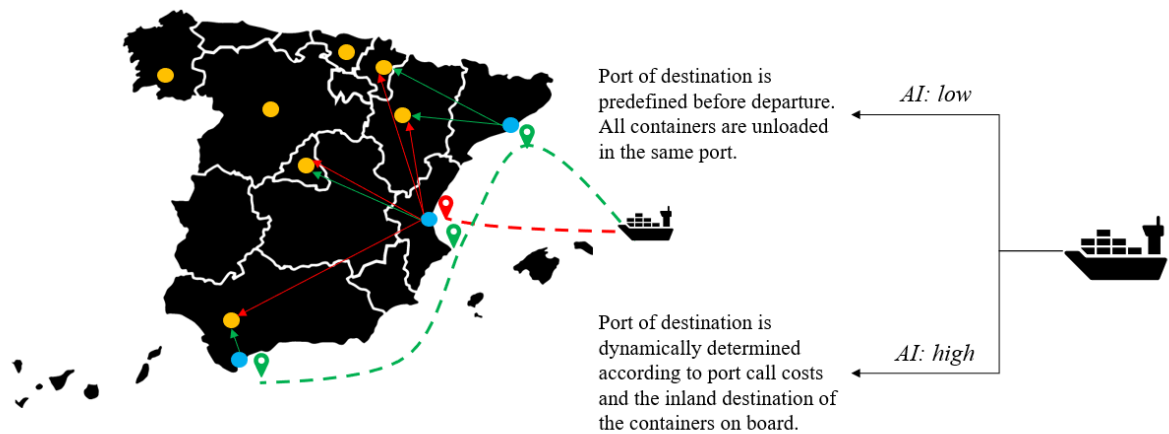

Figure 4: Potential impact of AI algorithms on containership routes

The integration of these advanced technologies described above paves the way for a transition from a traditional logistics network to a PI framework, where containers are "Smart Logistics Units" expected to make autonomous decisions at each node, such as selecting the optimal route to their final destination and the most suitable means of transportation for the next leg of the journey (Figure 5). By prioritizing collaboration and leveraging more efficient and sustainable transportation options, logistics providers can build a more agile and environmentally conscious supply chain ecosystem.
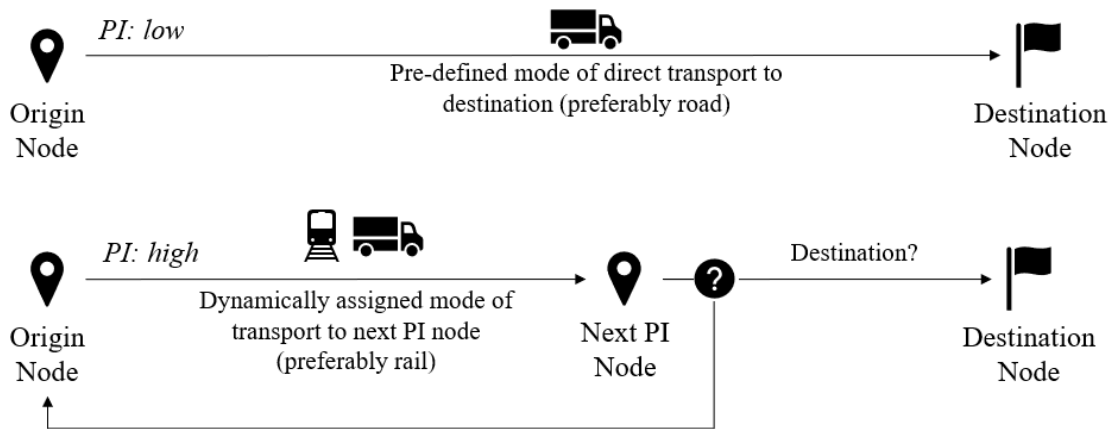
Figure 5: Conventional transport compared to PI-enabled transport

Based on the information gathered about the logistics network, the characterization of the relevant processes, and the definition of the parameters, algorithms, and logical rules that model the impact of the different technologies, a digital twin has been developed using multi-agent simulation techniques. This approach allows for the simulation of complex scenarios and the testing of potential solutions to logistical challenges. In the digital twin, agents representing different actors in the logistics network interact with each other, following the rules and processes defined in the model, and providing insights into the performance of the network under different conditions. The use of multi-agent simulation techniques allows for a more comprehensive and dynamic representation of the logistics system, enabling a better understanding of its behavior and potential for optimization.

In Figure 6, the main view of the digital twin (PI Network Simulator) is displayed. The dashboard depicts a map of the logistics network, with various transport services operating within it (maritime, rail, road). The digital twin allows for the dynamic collection of statistics, and on the right-hand side of the figure, several KPIs related to containers and transport services are presented, such as containers delivered on time, lead time or the distance, cost and emissions of the different hinterland transport modes. This information can be used to analyze the performance of the logistics network, identify potential bottlenecks, and test different scenarios to optimize its operation. The digital twin also provides a powerful tool for decision-making, as it allows logistics providers to evaluate the impact of different strategies and technologies in a safe and controlled environment.
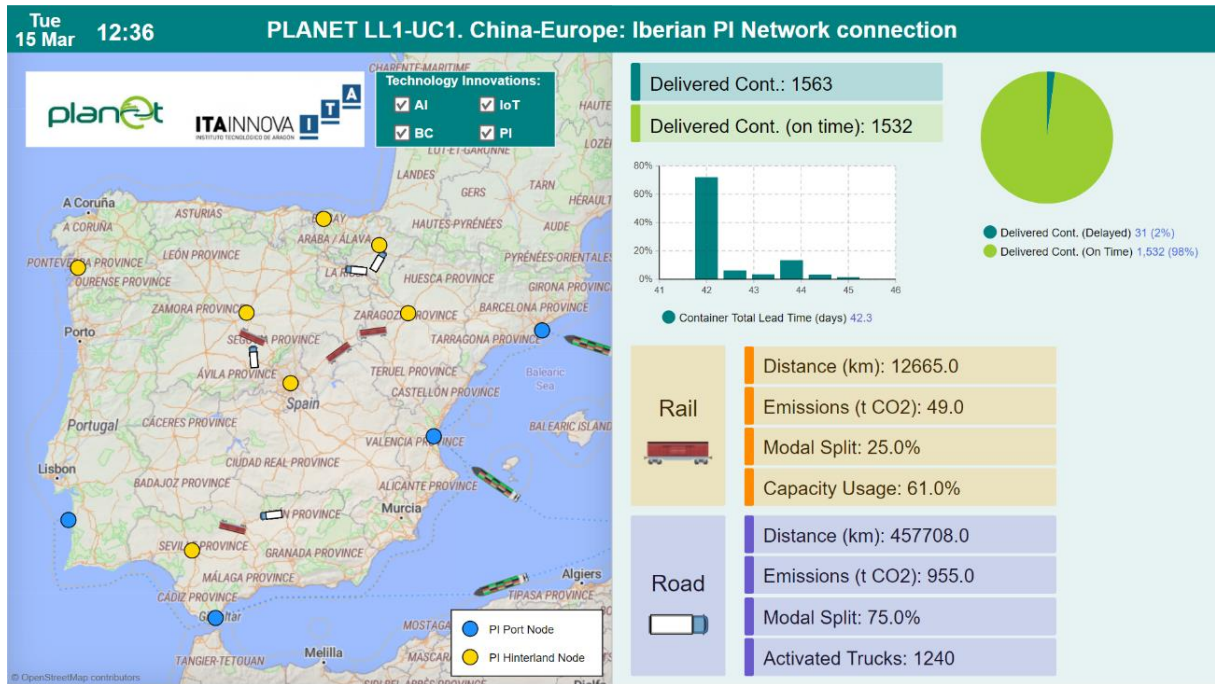
Figure 6: PI Network Simulator

4   Results

Two scenarios were considered in this study. The first scenario modeled the logistics network as it currently operates, while the second scenario simulated a network enabled by different technologies under the PI framework. Both scenarios were evaluated based on the demand data for container shipments originating from China and destined for the three most important ports in Spain, namely Valencia, Barcelona, and Algeciras, as collected in the statistical bulletins of the ports (Fundación Valenciaport, 2021; Port of Barcelona, 2021; Puerto de Algeciras, 2021). In order to ensure a comprehensive evaluation, a scaling factor of 10% was applied to the actual volume of container shipments between China and Spain. This resulted in a simulation of the total delivery of approximately 3,500 containers over the course of one week. Table 1 presents a comparison of the results obtained between the two scenarios evaluated.

Table 1: Comparison of results between scenarios

Scenario	Containers on-time	Rail share	Transport distance (km)	Transport Cost (€)	Transport emissions (t CO_2)
S1) Business as usual	87%	7%	621 250	940 625	1 825
S2) PI framework	99%	25%	420 000	700 000	1 230

The results clearly indicate that the scenario operating under a technology-enabled PI framework is considerably more advantageous. Notably, the scenario achieved a 12% increase in the on-time delivery of containers. This can be attributed to the positive effects of IoT in reducing delivery disruptions and delays and the efficiency of blockchain in streamlining procedures. Furthermore, the dynamic allocation of transport resources for containers allows for a more efficient use of available capacity, resulting in an 18% increase in rail share, a more sustainable mode of transport, which leads to a significant reduction in both distance and CO_2 emissions by 32%. Finally, by identifying and addressing inefficiencies in the logistics network,

such as empty trips or inefficient routing, the overall costs of transportation can be reduced by up to 25%.

It should be mentioned that, although the simulation included the maritime transport segment, the performance indicators were exclusively computed for the inland transportation part. Thus, a road transport cost of 1.57€/km and a rail transport cost of 498€ + 1.2€/km per container were assumed, according to data from the European Intermodal Association (2012) and AECOM (2014). In addition, regarding the calculation of CO_2 emissions, 150g/tkm has been considered for road transport and 20 g/tkm for rail transport, according to data from the European Environment Agency (2014).

5 Conclusions

This paper assessed the impact of collaborative transport strategies and emerging technologies on an intercontinental transport network with a digital twin. Through the case study of the China-Spain container transport network, the paper has demonstrated how IoT, blockchain, and artificial intelligence can improve the environmental, operational, and economic performance of the supply chain.

The study found that the implementation of IoT technologies, such as track and trace services and weight sensors, can lead to greater visibility and control over transportation operations. By identifying potential issues before they escalate, these technologies can help minimize disruption and prevent delays. Additionally, the use of weight sensors in port operations can improve efficiency and reduce waiting times, leading to better lead times and delivery performance.

With the adoption of blockchain technology, the contracting process can be automated and streamlined, guaranteeing consensus among all parties and ensuring compliance with the agreed-upon terms and conditions. As a result, it can contribute to minimizing waiting times and disruptions during customs clearance, ultimately leading to a more efficient supply chain.

Moreover, the study has demonstrated how artificial intelligence can optimize liner shipping routes for containerships. By using algorithms to decide which ports to call and in which order, the supply chain can be optimized to achieve the lowest possible carbon footprint while meeting customer requirements.

In addition to the benefits outlined, several challenges must be addressed in order to fully realize the potential of these technologies and concepts in an intercontinental transportation network. These include the integration of these technologies and concepts into existing logistics systems and infrastructure, the coordination and collaboration among various stakeholders, data privacy and security concerns, interoperability issues, and the need for new regulations and policies to support the adoption of these technologies and PI.

Furthermore, it is important to note that the success of these technologies depends not only on their technical capabilities but also on the mindset and culture of the organizations involved. A shift towards a more collaborative and innovative culture is needed to fully realize the benefits of the PI-based supply chain system.

Overall, this paper has contributed to the growing body of literature on the Physical Internet concept and the adoption of enabling technologies in supply chain management. It has demonstrated how the integration of IoT, blockchain, and artificial intelligence can lead to a more efficient, sustainable, and resilient supply chain system, but also highlighted the challenges that need to be addressed for successful implementation.

6 Acknowledgements

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Automating vessels berthing, docking and stevedorage operations: The MOSES project

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Abstract: About 74% of imports/exports and 37% of exchanges go through ports, making Europe highly dependent on ports for external and internal trade. In the European container supply chain, Short Sea Shipping (SSS) as well as inland waterways are not so well integrated in contrast to Deep Sea Shipping (DSS) ports (also referred to as Hub ports). MOSES is a European project, funded under the Horizon 2020 Work Programme, which aims to significantly enhance the SSS component of the European container supply chain by addressing the vulnerabilities and strains that relate to the operation of large containerships. The project develops a number of components that function as nodes of the Physical Internet, consisting of a number of data sources that when combined can lead to the development of meaningfull applications. Based on the technical innovations that are designed and developed, MOSES aims to reduce the environmental footprint for SSS and ports and improve the efficiency and end-to-end delivery times of SSS mode. In parallel, it will enable the promotion of smart port development with minimal investment and the development of concrete business cases.

Keywords: Waterborne transport; Container supply chain; Automated docking; Container handling; Horizontal logistics collaboration; Green logistics; Short-sea and deep-sea shipping

Conference Topic(s): autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms); logistics and supply networks; PI implementation.

Physical Internet Roadmap (Link): Select the most relevant area for your paper: ☒ PI Nodes, ☐ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.

1 Introduction

The physical internet is a conceptual vision for the future of logistics and transportation. It is a proposed network of interconnected physical infrastructures, such as roads, railways, ports, vehicles, vessels, trains and warehouses, that are designed to be more efficient, sustainable, and resilient than the current logistics systems.

The physical internet is inspired by the way the digital internet works, where data is broken down into small, standardized packets that can be easily transmitted and reassembled across a network of interconnected devices. Similarly, the physical internet would consist of a number of physical logistics nodes, producing and sharing data from a number of sources, that can be combined to produce meaningful applications for the optimization of the operation of the supply chain.It is perceived as a way to reduce transportation costs, increase resource utilization, and

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reduce environmental impact by minimizing empty or underutilized cargo space. The concept is still in the early stages of development, but several research initiatives and pilot projects are underway to explore its feasibility and potential benefits.

2   The Physical Internet and Short-Sea-Shipping

Short-sea shipping interconnectivity is a key component of the physical internet concept. Short-sea shipping refers to the transportation of goods by sea along the coasts and across the seas of a region, rather than by land. It is seen as an important element of the physical internet because it allows for the efficient transportation of goods over long distances, using standardized, modular containers that can be easily transferred between different modes of transportation.

Short-sea shipping is an important link in the physical internet because it provides connectivity between different logistics facilities, such as ports, vessels, warehouses, and distribution centers, which are all part of the physical internet network. The use of standardized containers, combined with efficient transfer mechanisms at ports and other intermodal facilities, allows for seamless connectivity between different transportation modes, including ships, trucks, and trains.

By leveraging short-sea shipping interconnectivity, the physical internet can achieve greater efficiency and sustainability in logistics operations, by reducing the number of empty or underutilized cargo spaces and minimizing the environmental impact of freight transportation.

The physical internet has the potential to significantly impact the future of maritime transportation and ports. As the concept is implemented, it could transform the way goods are transported, handled, and stored in ports and other maritime facilities. The increased use of automation and digital technologies could introduce a significant impact in ports and other maritime operations as well as reduced congestion and delays at ports and other maritime facilities.

3   The MOSES project and relevance to the Physical Internet

The EU-funded MOSES project will significantly enhance the SSS component of the European container supply chain by reducing total time to berth for TEN-T Hub Ports and by promoting the use of SSS feeder services to small ports with limited or no infrastructure. MOSES includes an innovative SSS feeder vessel outfitted with a robotic container handling system. It also includes a swarm of autonomous tugboats, an automated docking system for Hub Ports, and a machine learning-driven digital collaboration platform for logistics stakeholders.

Automated tugboats and automated vessel docking are two technologies that are relevant to the physical internet concept, as they can improve the efficiency and sustainability of maritime transportation. Automated tug boats are unmanned or autonomous vessels that can be used to assist larger ships in docking and maneuvering in tight spaces. These automated tug boats can be used to reduce the need for human pilots, improve safety, and increase efficiency in port operations. By automating tug boats, the physical internet concept can reduce the time and costs associated with manual tug boat operations.

Automated vessel docking is a technology that allows ships to dock and undock without the need for human intervention. This technology can be used to reduce the time required for vessels to dock and undock, as well as improve safety and reduce the risk of accidents.

Automated or remotely controlled container handling robotic arms facilitate the movement of goods between different modes of transportation. Automated container handling robotic arms can work faster and more accurately than human operators, leading to increased productivity

and throughput. They can also work around the clock without breaks, maximizing terminal utilization.

In the context of the physical internet, automated tug boats, automated vessel docking and automated or remotely controlled container handling robotic arms can improve the flow of goods through ports, reduce the time required for ships to load and unload cargo, and increase the overall efficiency and sustainability of maritime transportation. By reducing the need for human intervention in port operations, these technologies can also improve safety and reduce the risk of accidents.

Moreover, matchmaking logistics platforms can enable the sharing of transportation assets between different stakeholders, such as shippers, carriers, and logistics service providers. This can help to optimize the use of transportation infrastructure and assets, reduce congestion and emissions, and improve the overall efficiency of the logistics network. Matchmaking logistics platforms can also enable new business models and services within the physical internet with the introduction of on-demand logistics services, such as last-mile delivery or same-day delivery, by connecting shippers with local carriers in real-time.

Thus, the physical internet concept is closely related to the MOSES project since it aim at developing a modular, open-source logistics system, that consists of a number of data producing components that act as nodes of the physical internet and can be used to develop services and applications that optimize the operation of the supply chain. In the next paragraphs, the MOSES project and its components will be described in detail.

4   MOSES Components

MOSES aims to significantly enhance the SSS component of the European container supply chain by a constellation of innovations including innovative vessels and the optimisation of logistics operations:

   i.   For the SSS leg, an innovative, hybrid electric feeder vessel that will prevail from different vessel concepts that will be designed to match dominant SSS business cases and will increase the utilization rate of small ports. The feeder will be outfitted with a robotic container-handling system that is self-sufficient in terms of (un)loading containerised cargo and will simplify the process at the Hub Ports while improving the operational capacity of small ports;

   ii.   For DSS ports, the adoption of an autonomous vessel manoeuvring and docking scheme (MOSES AutoDock) that will provide operational independency from the availability of port services. This scheme will be based on the cooperation of (a) a coordinated swarm of autonomous tugboats that automates manoeuvring and docking with (b) an automated docking system based on an existing product and (c) the investigation of autonomous voyage/port entrance and mooring manoeuvre for the feeder vessel;

   iii.   A digital collaboration and matchmaking platform (MOSES platform) aiming to match demand and supply of cargo volumes by logistics stakeholders (shippers, forwarders, shipping lines, ports) using advanced analytics and data-driven assessment (availability of mode, cargo volumes, delivery times) to maximize SSS traffic.

The MOSES concept and relevant innovations are presented in Figure 1, while the following sections describe the main aspects of these innovations.
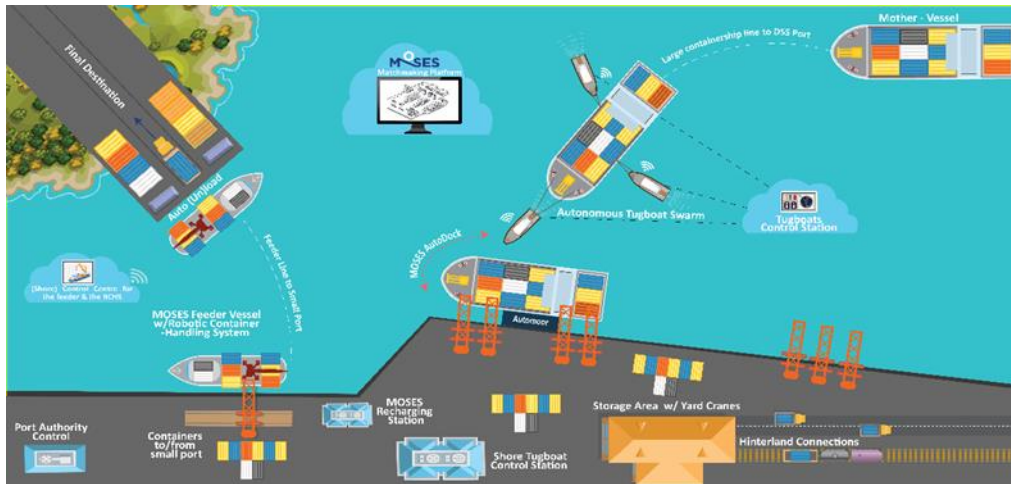
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Figure 1. MOSES concept and innovations.

4.1 Innovative Feeder Vessel and Robotic Container-Handling System

The innovations for the vessels are concentrated on two different directions, in which the innovations for the maritime industry are being developed and demanded by society. The first one is the ambition to reduce or eliminate harmful emissions by designing environmentally friendly vessels. The second one is the ambition to design a highly autonomous feeder vessel, that is able to sail large part of its route without human intervention. Main drive here is to reduce the number of accidents due to human errors followed by a reduction in cost. MOSES develops three different designs for the innovative feeder that are fit for purpose for the requirements of the MOSES business cases. Compared to existing container feeder vessels, the MOSES feeder includes the following innovative features: low cargo capacity (ranging from approx. 90 – 680 TEU), environmentally sustainable engine configuration; superstructures positioned at the fore and mid ships; enhanced maneuverability; and automated onboard crane. For achieving (near) zero emission operation, several engine configuration alternatives have been evaluated, with the selected ones resulting to an estimated 10% lower operating costs.

Furthermore, the concept design for the MOSES feeder is compatible with the MOSES AutoDock system (see Section 4.2) by including thrusters and azimuth propulsion, which provide enhanced maneuverability for the feeder and therefore minimize the required number of tugboats, while the hull form of the feeder has adequately large flat surfaces for facilitating the connection with the MOSES Automated Mooring System. It can also operate in parts of its voyage with a certain degree of autonomy. Due to the selected engine configurations, the MOSES Innovative feeder can have (partly) zero emissions throughout all operational phases, contributing to the reduction of the environmental footprint of SSS services from large container terminals to smaller ports. The feeder is also expected to reduce the environmental footprint within the port area and in its vicinity by: 1) having been designed to use its onboard battery systems and shore power connections for the required power while berthed, and 2) capturing part of the hinterland container traffic, currently moved by container trucks. A recharging station for automated vessels is also developed providing a fully automated shore power connection solution without the need for assistance from the vessel and ensuring the minimization of energy transfer losses from the port's electric grid to the ship.

In most port terminals, moored container ships are loaded and unloaded with shore cranes. In that case, a crane operator controls the crane based on their hand-eye coordination, knows which container to move according to the provided plan, finds the position of the container, estimates the distance between the spreader and the container, reduces speed if necessary and

hooks the spreader to the container, etc. The safety of the operation is ensured by a direct line of sight to the operation, relatively high degree of supervision by others and the creation of a safe and closed operational area. In contrast, many small European ports do not have their own terminal facilities. The port usually consists of a concrete quay or pier for the mooring of Roll-On-Roll-Off (RoRo) ferries for passengers, cars and trucks. The fact that these ports cannot accommodate a container service reduces the economic value and growth potential of these ports.

The solution envisaged within the MOSES project is that of a self-sufficient (autonomous) Robotic Container Handling System (RCHS). Mounted on and integrated with the MOSES feeder vessel concept, it enables safe container loading and offloading operations to small local ports without the need for additional terminal infrastructure. The RCHS innovation fits the MOSES-project aim to significantly enhance the Short Sea Shipping (SSS) component of the European container supply chain by implementing a constellation of innovations including innovative vessels and the optimization of logistics operations. The RCHS consists of a crane, software that drives it, a sensor suite that provides information about the operational area through object detection algorithms (e.g. the location of a container) to the crane software enabling autonomous operation, and a shore control centre from which operators remotely monitor and supervise the crane's operation. This makes the RCHS a collection of innovations – a system of systems (Figure 2).
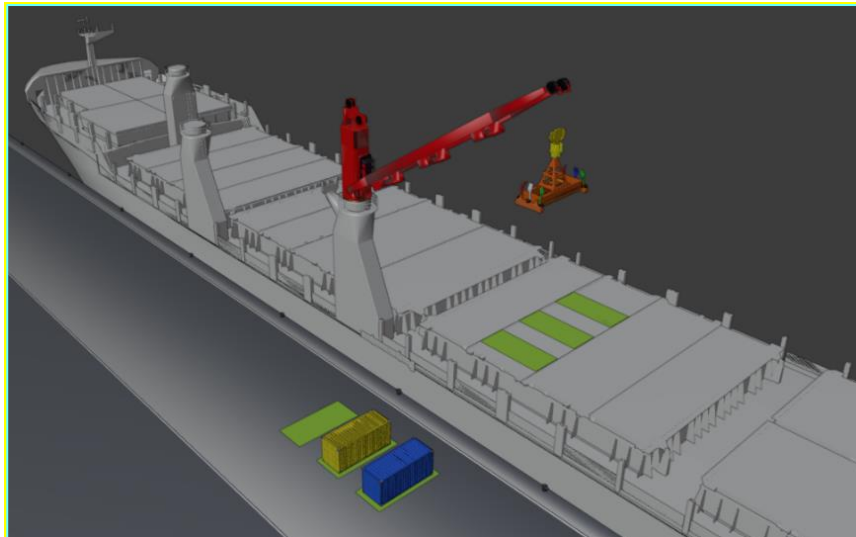

Figure 2. Innovative feeder vessel equipped with Robotic Container Handling System

The intended future operational scenario is the following: When the vessel with the RCHS arrives at its destination port, it receives a list of containers to unload and load. The loading and offloading operation is conducted automatically with the help of the sensor suite to monitor its surroundings and the control software that steers the crane. In parallel, the remote operator, who is potentially hundreds of kilometres away, supervises the process and is responsible to intervene when the crane or sensors experience difficulties of any kind. The sensor suite system acts as the sensing system of the crane and provides information over container position and orientation and is able to dynamically detect and classify objects like people and trucks. Its main role is to feed the necessary information to the control software of the crane to enable both the control of the crane and high-level decision-making (e.g., which container to pick up first and where to stow it on the vessel). It also conveys this information to the remote operator support system to enable it to timely bring the operator in the loop. The remote operator support system is developed for a shore control centre concept allowing multiple operators to supervise multiple autonomous operations effectively and efficiently. The combination of these

innovations supports a concept where dozens of small vessels can handle containers autonomously while being supervised by only a handful of remotely located operators.

4.2 AutoDock

The MOSES AutoDock system aims to automate the maneuvering and docking of large containerships in DSS ports, which is currently conducted with manually operated tugboats in a typically complex and time-consuming process. This is an intelligent system comprising autonomous tugboats operating in a swarm configuration at various levels of autonomy and supported by the MOSES Shore Tugboat Control Station (STCS), which will cooperate with the MOSES Automated Mooring System; a re-engineered version of Trelleborg's AutoMoor system (Figure 3). MOSES develops an architecture for autonomous tugboat operation that is compatible with existing equipment on conventional tugboats and therefore can be used for retrofitting. The architecture includes sensors that provide situational awareness to AI algorithms that control steering and propulsion. The automated mooring system is a vacuum-based system for hands-free mooring that includes rubber damping elements to allow and control surge motion of a connected vessel and energy harvesting systems. The MOSES STCS acts as a communication hub between the tugboat swarm and the mooring system, as well as a central platform for supervisory control of the process.
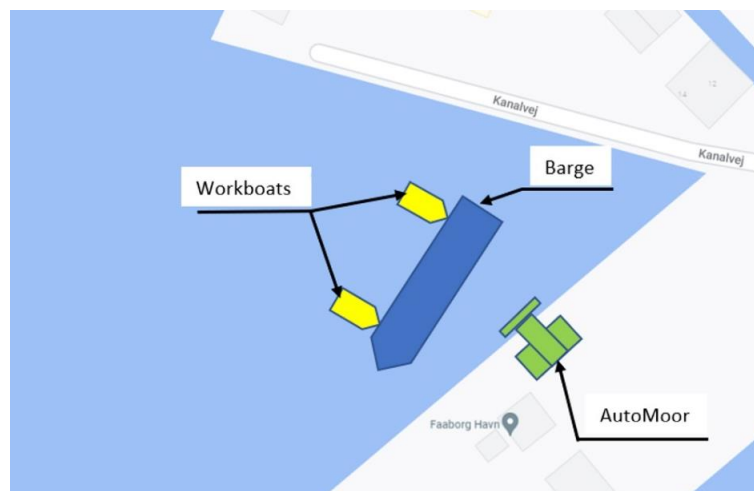

Figure 3. AutoDock system

More specifically, the AutoDock system supports the AI-optimized navigation and remote monitoring and control of the tugboats, enabling functionalities such as path planning and implementation, collision avoidance with static and dynamic obstacles, mission scenario management and achievement, fail-safe operation, compliance with navigational restrictions, situational awareness, switching between levels of autonomy, and fail-safe operation. The architecture consists of the following modules: 1) detection, 2) path planning, and 3) control. The detection module includes sensors and monitoring devices that feed data into the Data Acquisition Board, which consists of a data processing unit and a local database for storage. The sensors that have been identified for enabling autonomous operation are the following: AIS, Radar, IMU, Camera system with 360 FOV, SWATH Sonar, GPS, LIDAR, and an Engine and rudder monitoring system. The following sensors provide input to the AI navigation algorithm in real-time: IMU, LIDAR, GPS. The path planning module consists of the Auto Pilot unit that will host the AI navigation algorithms. The Auto Pilot receives data generated from the sensors as input to the AI algorithm and generates steering and propulsion commands that are passed on the control module. One of the main requirements for the Auto Pilot unit is adequate processing power for real-time operation, which has been satisfied by featuring a GPU

that results in significant faster execution of mathematical operations compared to a CPU. The control module is the part of the architecture that physically controls the steering and propulsion machinery systems installed on the tugboats.

The design for the MOSES autonomous tugboats targets a mixed autonomy level that consists of: 1) manual navigation with decision support by the remote operator in the STCS (Decision supported function), and 2) autonomous swarm operation with remote control capability (Self-controlled function, human-in-the-loop). With regards to the required software and hardware interfaces for integrating the different components of the architecture, one of the main requirements is the ability to exploit existing equipment that is typically installed onboard tugboats and required by regulation. This is satisfied by featuring multi-protocol data buses for ensuring interoperability with legacy systems. The wired interfaces mainly include ethernet connections, which are handled by an ethernet switch and ensure minimum latency in data transfer between the different modules. The wireless interfaces include 4G cellular modems that enable the communication of the tugboat with other external resources, such as the STCS and the re-engineered MOSES AutoMoor system. A CAN bus enables the communication between the different components of the architecture without a host computer.

As for the mooring process, the MOSES Automated Mooring System shall form an attachment between the terminal wharf and vessel hull. The system consists of a single mooring unit that can hold a vessel with a holding capacity of up to 5T, with an additional safety margin to accommodate for unexpected environmental or meteorological conditions. The control system shall consist of both the existing operator-based control module and an autonomous module that can send and receive appropriate signals to interact with other autonomous control systems such as the Tugboat system and the STCS. In parallel, the STCS serves as a central control platform that acts as interface between the tugboat's operator, the AutoMoor units and the port, supporting decision-making of the Port Control Authority. The main functionality provided by the STCS is to monitor the autonomous manoeuvring, as well as the real-time communications protocols with the Port Authority management systems, Port Community System (PCS), the Vessel Traffic Services (VTS) with the STCS.

In a future operational scenario, during the manoeuvring to/away from dock, the tugboat Captains manually navigate the tugboats in position and after communicating with the Pilot on the vessel establish the tow connection. The STCS switches the tugboat swarm to the autonomous navigation operational state and the swarm begins the vessel's manoeuvring process by conducting AI-optimised path planning and collision avoidance. In case an off-nominal situation is detected, the swarm transitions to either the Fail-safe/Emergency or the Hot-swap state. Once the vessel is approaching the berth, the automated mooring system requires notification of vessel arrival when the vessel is being manoeuvred by the pilot and/or the autonomous tugs. At this point, the system would shift into "ARM" mode. Following notification of imminent vessel arrival, the next signal the automated mooring system would require is that the vessel is parked in position against the fender-line, ready to be moored. At this point, the "MOOR" sequence would commence, the mooring units would form an attachment to the vessel and pretension as necessary to pull the vessel against the fenders. Once the vessel is securely moored, the mooring system would indicate to the pilot and the autonomous tugboat swarm that the mission has been completed, the STCS switches back to manual navigation and the tugboat Captains navigate back to base.

4.3 Matchmaking Logistics Platform

The Matchmaking Logistics Platform aims to offer match-making services to logistics stakeholders. It has been developed to support digital and horizontal collaboration among

shippers and carriers, aiming to maximize Short Sea Shipping (SSS) demand and balance backhaul traffic. More specifically, the Matchmaking Logistics Platform is a digital collaboration and matchmaking tool that aims to maximize and sustain SSS services in the container supply chain by matching demand and supply of cargo volumes by logistics stakeholders using data-driven analytics. It can dynamically and effectively handle freight flows, increase the cost-effectiveness of partial cargo loads and boost last-mile/just-in-time connections among the transport modes and backhaul traffic. In this way, its users can experience the benefits of a collaboration and optimization tool that prioritizes SSS and is able to deliver impactful results for all stakeholders involved. The platform advances current state-of-the-art by supporting cargo consolidation (at container level) and fully exploiting the bundling potential among different shippers to enable multimodal transport routes containing at least an SSS leg. This is done in existing but underutilized SSS routes, currently not preferred by shippers due to increased costs or low service frequency and reliability.

The platform focuses on collecting available information and datasets related to logistics supply and demand from relevant stakeholders, such as shippers, carriers, freight forwarders, shipping lines etc. Through the combination of these datasets, valuable information can be extracted, supporting the optimization of the logistics process. The main benefit of this analysis is the provision of multimodal transportation options, combining different transportation means and modes that can reduce the delivery time and the overall cost. In parallel, the combination of multimodal transport services with freight cargo bundling can increase the efficiency of transport operators and improve the management of empty containers. As already mentioned, the stakeholders that are involved in the logistics process may include shippers, carriers, freight forwarders, shipping lines and agents, etc. However, two discrete user groups have been identified as the main user roles of the platform based on their role in the logistics process and the supported interactions with the platform. These groups are the following:

- the logistics services supply group **(service providers)**, i.e. the owner of transport means (ships, trains, trucks) offering transport services;
- the logistics services demand group **(end users)**, i.e. owner of cargo to be containerized and shipped, placing transport requests.

Based on the involvement of each user group in the logistics process, specific functionalities are provided by the platform, in order to fulfil the needs of each user group and improve the shipping process. In a typical use case scenario, the platform is initialized by the data provided by the service providers, which inform the platform for vessel schedules for a rolling period of at least 2 months, with no major changes foreseen. End users can place transport orders and get notified once the service provider confirms the agreement for this order. The usage of the platform by a specific end user consists in the following sequence of steps/functions.

1. Any time an end user places an order, the platform is triggered to find feasible, optimal transport schedules satisfying the specification of the order.
2. The transport schedules found in the previous steps, along with already found transport schedules concerning other orders (i.e. the intermediate results) are used to find matching orders in the sense described above.
3. Once matchings are found, the end user is notified about them.
4. Service providers and end users involved in the matchings found in step 3 are notified.
5. As long as the order remains open, the end user is regularly notified in case new orders matching his/her order are found or if any of the already matched orders are fulfilled/closed or cancelled.
6. The platform aims at a near real-time to periodic response, i.e. end users are notified at periodic basis.

The architecture of the platform consists of the back-end module, the storage/database module and the front-end module. These modules include all the subcomponents of the platform, such as the optimization component, the user interface etc. More specifically, the structure is as follows:

- The back-end module is where the search and matching algorithms run and includes the server and optimization component.

- The database module is where all collected resources and intermediate results are stored.

- The front-end module is where all necessary information is collected and includes the available user interfaces that are provided to the users based on their role. In Figure 4, the platform's Dashboard is presented.
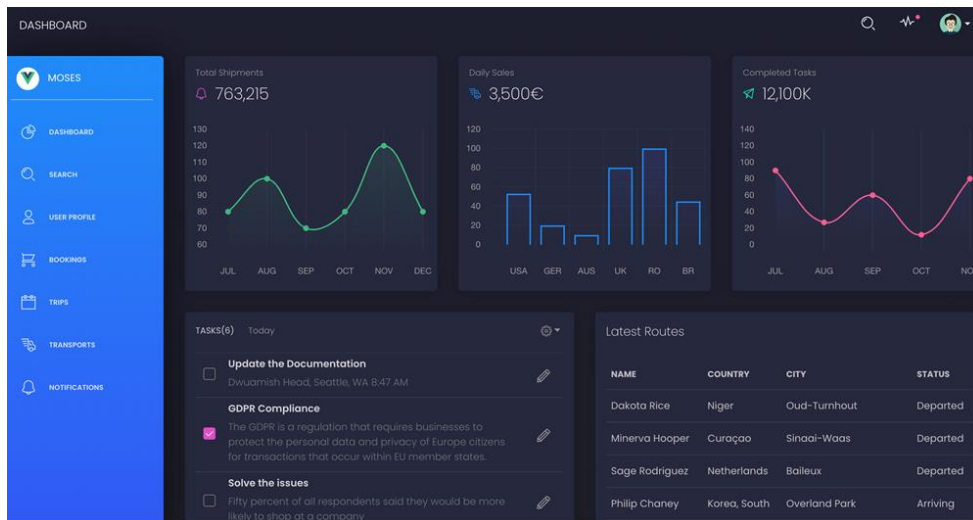

Figure 4. Matchmaking Logistics Platform Dashboard

Summarizing the above, the Matchmaking Logistics Platform is a cloud-based platform that has been designed and developed in order to support and maximise the provided services in the container supply chain by matching demand and supply of cargo volumes by different stakeholders using data analysis algorithms. Based on the user roles that have been identified, the platform usage is separated in two levels. The first one concerns the service providers, including different stakeholders like carriers, freight forwarders, shipping lines etc. which can use the platform in order to upload their routing schedules, see different system reports, examine customer orders and see a complete list of notifications. The second usage level concerns the end users and potential customers such as shippers, who can benefit from the optimisation and collaboration/matchmaking analysis that is made behind the scene, providing an analytic list of best available routes, based on their preferences (search criteria). This matchmaking functionality is the heart of the system and aims to provide to the customers the best options available by combining the transport services and means offered by different service providers.

5 Conclusion

Short sea shipping can play a significant role in the deployment of the physical internet, as it can provide an efficient and cost-effective mode of transportation for goods between nearby ports. By integrating short sea shipping with other modes of transport, such as rail and road, a

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seamless and interconnected logistics network can be created, similar to how the digital internet enables the transfer of data between interconnected devices.

MOSES innovative and automated components along with the use of the Logistics Matchmaking Platform can help to reduce congestion on roads and highways, lower carbon emissions, and improve overall transport efficiency, which are all key goals of the physical internet. The physical internet seeks to create a more sustainable and efficient logistics network, and short sea shipping can contribute to achieving this goal by providing a reliable and environmentally-friendly mode of transportation for goods.

Acknowledgement

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Hyperconnected Logistic Service Networks:
Bidding-Based Design Framework

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Abstract: In hyperconnected urban logistics, all components and stakeholders are connected on multiple layers through standardized interfaces and open networks to achieve seamless responsiveness, efficiency, resilience, and sustainability. Key for high performance is achieving coordination and cooperation of urban stakeholders. In this paper, we introduce the design of hyperconnected logistic service networks where associated logistic activities to move flows within an urban city are outsourced to third-party logistic service providers (3PL) via a bidding process to create service networks that are highly responsive and flexible at robustly responding to customer demand. We propose a framework for designing such networks that leverages a reverse combinatorial auction mechanism in which a logistic orchestrator serves as the auctioneer, putting out the logistic activities for auction and a set of participating service providers serve as bidders. We describe the design components of hyperconnected service networks and positions them into a comprehensive 3-stage design-making framework. Finally, we identify promising future research avenues for each stage in the proposed framework.

Keywords: Service Network Design; Hyperconnected City Logistics; Physical Internet; Combinatorial Auction

Conference Topic(s): networks; interconnected freight transport; distributed intelligence last mile & city logistics; logistics and supply networks; PI fundamentals and constituents; PI impacts; PI implementation; PI modelling and simulation;

Physical Internet Roadmap (Link): Select the most relevant area(s) for your paper: ⊠ PI Nodes, ⊠ PI Networks, ⊠ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.

1   Introduction

As a hyperconnected global logistic system aiming to serve efficiently, resiliently, and sustainably humanity's demand for physical object services, the Physical Internet (PI) enables a logistic web interconnecting multi-plane and multi-party meshed logistic networks serving the multi-tier logistic space (Montreuil et al., 2015). Such networks comprise multiple tiers of logistics hubs (e.g., access hubs (AHs), local hubs (LHs), etc.) and territorial clusters (e.g., unit zones (UZs), local cells (LCs), etc.) adapted to each plane as illustrated in Figure 1. This logistic web allows parcels to flow through each meshed plane using hub and cluster-based transport

operations characterized by openly shared access to logistics resources and service outsourcing, increased cooperation and coordination, and information exchange.
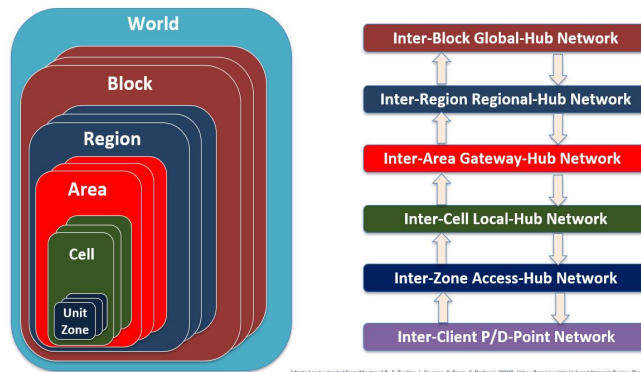

Figure 1: Multi-Plane Logistic Web Serving the Multi-Tier Logistic Space of the Physical Internet

Provided with a multi-tier set of interconnected logistic networks, our paper introduces a service network design approach for an urban transport system that outsources to multiple third-party logistic (3PLs) service providers, accounting for customers' expectations to receive fast and reliable services. A fair amount of literature has studied optimizing the design and operations of package express carriers' service networks, but most of the literature has focused on the service network design for intercity package flows rather than urban parcel delivery (Kim et al., 1991; Barnhart et al., 2002; Yildiz et al., 2022). For urban delivery systems, there recently has been several relevant works taking into account key characteristics of intra-city delivery systems. He et al. (2022) and Wu et al. (2023) studied a new service network design problem for an urban same-day delivery system with hub capacity constraints. Most of the service network design research is focused on first-party service network design (Bakir et al., 2021). Literature focused on designing service networks leveraging 3PLs is scarce. In the similar spirit to our paper, there is an extensive amount of literature that studied the application of combinatorial auctions in transportation procurement problem. A review of practical issues related to the execution of combinatorial auctions in transportation service procurement problem can be found in the work by Caplice and Sheffi (2006). Large amount of literature has studied decision-making problems in the combinatorial transportation procurement system from the shipper and carriers' perspective, respectively (Song and Regan (2003); Sheffi (2004); Song and Regan (2005); Guo, et al., (2006); Chen, et al., (2009)). Pan et al. (2014) introduces the use of Mechanism Design theory to make a business model of the logistic service providers where every transport service is auctioned and develops a simulation framework for auction-based transport service allocation process in PI. However, most of the literature does not specifically consider urban context and only considers single origin-destination pairs (i.e., lanes) of demand rather than logistic network perspectives.

Key contributions of our paper are threefold: (1) introducing a new research notion of PI urban logistic service network design where all hub logistic and cluster transport activities are outsourced to 3PL service providers through a combinatorial bidding process; (2) developing a combinatorial auction-based framework enabling to set service level agreements (e.g., time requirements) and determine winning service providers for each logistic activity, and (3) proposing a bidding scheme engaging multiple service providers and expressing price-time trade-offs (in the spirit of D'Amours et al., 1997).

2   Framework for Hyperconnected Bidding-Based Logistic Service Network Design

In this section, we introduce the hyperconnected bidding-based logistic service network design problem. We first introduce key decision-making stakeholders involved in designing hyperconnected service networks and discuss what decisions each of these stakeholders must make and what impacts their decisions. We then propose a conceptual design-making framework that leverages a reverse combinatorial auction mechanism to structure the design of such service networks in multi stages.

2.1   Problem Definition

We consider a reverse combinatorial auction involving a logistic orchestrator (the auctioneer) who is looking to outsource the logistic activities under its responsibility, and multiple logistic service providers (bidders) looking to win contracts to offer logistic services over a specified future period. We consider as a logistic orchestrator an urban authority, a logistic company, or a set of such organizations that desires to design a hyperconnected service network leveraging service providers via bidding process to timely and robustly transport shipments between a set of predetermined origin-destination (O-D) pairs in a way to minimize total outsourcing cost in a multi-tier set of interconnected logistic networks as illustrated in Figure 2.
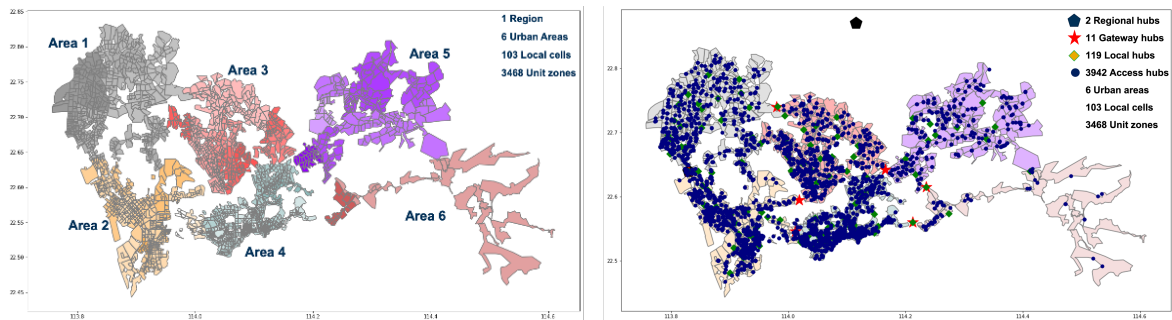

Figure 2: Hyperconnected Multi-tier Logistic Networks: (Left) Territorial Clusters. (Right) Multi-tier Logistic Hubs

We assume that the O-D pairs that the orchestrator offers transport services for are grouped into three types of shipments: (1) within-local cell (LC) shipments, (2) within-urban area (UA) shipments, and (3) within-region shipments. For example, within-region shipments travel from their origin to destination across the interlaced mesh networks through multiple planes using hub processing and cluster transport operations. Hub processing operations refer to a set of intra-logistic operations that take place in a hub to handle inbound parcels/containers to be ready for outbound shipment. Cluster transport operations refer to transporting parcels/containers between hubs within a specified territorial cluster as illustrated in Figure 3.
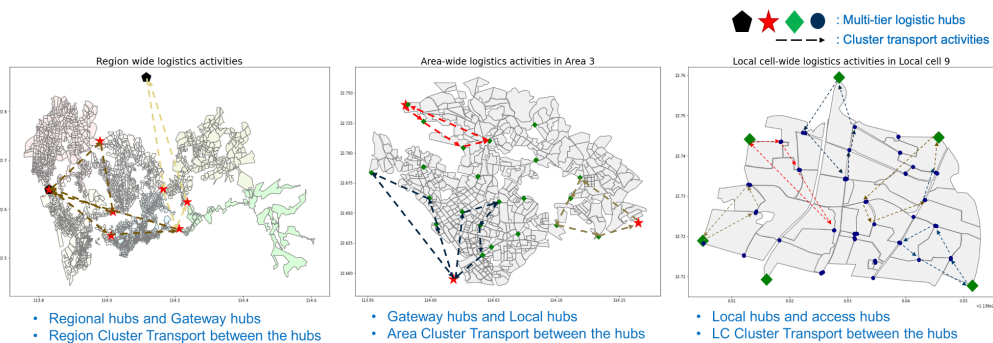

Figure 3: Logisitc activities in each plane: Region-wide activities (left), area-wide activities (middle), and local cell-wide activities (right)

We assume that each O-D pair is associated with a predetermined path consisting of a set of logistic hubs and clusters to traverse and is associated with target O-D service guarantees (e.g., 6-hour delivery) to be respected within a target reliability (e.g., 99%). The orchestrator uses standardized bidding languages (e.g., OR/XOR bids) that allow participants to formulate their bids and express bid requirements on their execution. For the bid requirements, the orchestrator specifies service level agreements (SLAs) for each logistic activity (e.g., 30 mins for local cell 1-cluster transport activities) such that the O-D target service guarantees are robustly met. The SLAs can thus be thought of as service capability expectations for service providers.

We consider a set of third-party logistic service providers (3PL) of two types respectively interested in offering services for hub processing and/or cluster transport activities within urban cities. We call such service providers "Bidders" throughout this paper. According to the imposed bidding language, these bidders make their bidding decisions in three stages: (1) they first select which logistic activity(ies) they are to bid on based on highest utility for them among considered activities, (2) then they evaluate what service capability in terms of time they can offer in accordance with the SLAs, and lastly (3) they determine what bid price to offer. Winning bids then result in contracts for the termed horizon (e.g., 3-year), subject to SLA clauses, to ensure persistent performance of the service network.

Given these decision-making stakeholders, as an alternative way to first-party service network design, the proposed research is to develop a design-making framework for designing and planning multi-stakeholder-engaged service networks inspired by the Physical Internet that will be able to robustly offer transport services across the multi-tier networks in a cost minimization manner by considering both the auctioneer's (orchestrator's) and bidders' (service providers') perspectives.

2.2   Design of Hyperconnected Logistic Service Networks

We structure the hyperconnected logistic service network design process in three phases which correspond to pre-auction, auction, and post-auction stages as shown in Figure 4, notably leveraging the work of Song (2003) on single round and multi-round combinatorial auctions: (1) Logistic Activity Selection for Auction and Bid Definition/Requirements, (2) Bid Construction, and (3) Bid Assignment.
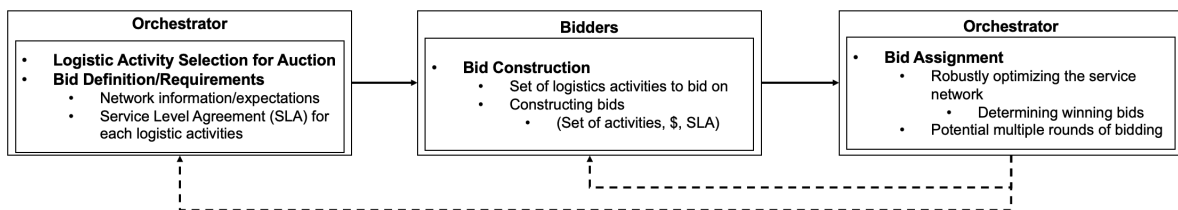

Figure 4: Proposed Hyperconnected Logistic Service Network Design Process

2.2.1 Phase 1: Logistic Activity Selection for Auction and Bid Definition /Requirements

In Phase 1, during the pre-auction stage, the orchestrator completes the following tasks: (1) forecasting the demand for the upcoming period's needs (e.g., 3-year) and selecting logistic activities for auction and (2) determining what information the bidder is required to submit back and abide by. In other words, the orchestrator collects demand information across the network and analyzes expected demand flow over the logistic activities. Then, they must determine which logistic to be serviced by its own capacity or to be outsourced through auction. The

orchesetrator then specifies bidding language that all bidders must use to encode their preferences and bid requirements for SLAs for logistic activities such that bids are defined to contain composite information for a single or set of activities to bid on, corresponding bid price, and service capability.

One of the key considerations that the orchestrator must consider during the pre-auction stage is the process of determining O-D service guarantees to offer across the network and SLAs for logistic activities, as such process impacts the overall business and service costs for outsourcing bidders. Such O-D guarantees can be estimated through simulation with historical data or with synthetic data from benchmarking competitors' service guarantees. Once O-D service guarantees are established for a given set of O-D pair transport services, SLAs for logistic activities must be determined such that each of the O-D service guarantee is met. The orchestator can simply select a combination of SLAs that satisfies O-D service guarantees. However, which SLA(s) the orchestrator imposes on logistic activities significantly impacts the bids that they receive from bidders at Phase 2 (and thus total outsourcing cost obtained at Phase 3). For example, for a given O-D pair-path traversing three logistic planes, one can simply allocate its service guarantee time equally among the planes of the path. However, some planes might expect huge fluctuation in demand, which makes it difficult for bidders to plan in accordance with the imposed SLA and estimate required number of resources, and possibly end up asking a significantly higher bid price as they might need to prepare additional resources (e.g., more drivers, external on-demand contracts) against unexpected events. This example motivates the orchestrator to smartly determine SLAs for logistic activities. To do so, it is clearly necessary to understand the characteristics of logistic activities and the capability of bidders. The orchestrator can obtain benefits from attempting to approximate bids from bidders a priori. In other words, the orchestrator may form an idea of bids from bidders at the pre-auction stage by mimicking the process of Phase 2 (bidders' bid construction) based on incomplete information on bidders, as bidders do not reveal sensitive information as illustrated in Figure 5. In practice, the orchestrator could access bidders' information on their operations, service coverage area, cost structure, and strategy from the industry community, or initial discussions with bidders on the aforementioned information before the auction stage, but only to a limited extent.
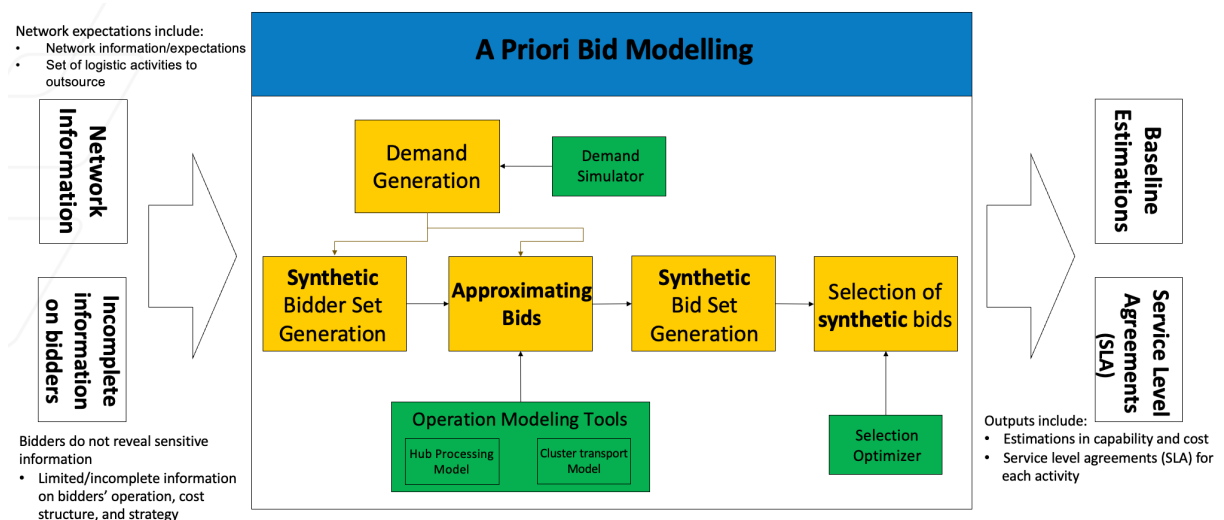

Figure 5: Schematic Description of A Priori Bid Modeling in Phase 1

To approximate bids of bidders providing cluster transport services, for example, one can employ a protocol-based vehicle routing problem (VRP) simulator. In the simulator, a set of

demand scenarios is generated, and each synthetic version of potentially participating bidders is created, equipped with an approximate cost structure (e.g., driver base cost, per-mile cost, profit margin rates) and service capacity/routing protocols (e.g., size of fleet, capacity of vehicles, operational constraints including the number of stops that can be made, route length), based on incomplete information. Then, the protocols of each synthetic bidder are applied to the set of generated demand scenarios to generate synthetic bids. The performance of each synthetic bidder is evaluated based on a predetermined set of KPIs, such as total outsourcing cost, service capability (e.g., parcel delivery time), and so forth. Not limited to simulation tools, one can also leverage MIP/IP-based optimization tools to achieve the same goal, yet in a more aggregate manner.

Once bids are approximated, given the service guarantees for each O-D pair, the orchestrator may draw a distribution of the generated synthetic bids for each logistic activity in terms of service capabilities and discretize the service capabilities into a finite number of potential SLAs. Assigning each a weight as a function of expected cost (e.g., average synthetic bid price) and frequency of each (i.e., number of corresponding synthetic bids), one can model the problem of determining SLAs using integer programming (IP) as an assignment-oriented model that assigns one specific SLA option to each activity such that the O-D service guarantees are met while optimizing the sum of weights. Since the service capabilities at this stage are approximated ones based on incomplete and estimate information and the mathematical model is often a simplification of the real business problem. So, there might be a gap between its solution and reality. Such a model may have left out details that are difficult to quantify and express. Thus, the orchestrator can consider multiple SLA options for logistic activities. To do so, one can consider generating multiple solutions including optimal, near-optimal solutions for the proposed IP model, encoding resulting solutions into mutiple SLA options for logistic activites.

2.2.2 Phase 2: Bid Construction

After the orchestrator has defined the set of bids, bid requirements, and SLAs for each logistic activity, these are commnuicated to the bidders. In Phase 2, each participating bidder tries to address three problems: (1) deciding which logistic activities (service contracts) to bid on (i.e., the most valuable activity bundles), (2) what service capability to offer (i.e., which SLA to bid on), and (3) deciding the bid price for each bundle. When bidders determine the set of profitable logistic activities to bid on, they attempt to make full use of their capacity to decrease overall costs, with different activities having different costs. We differentiate two contexts in which bidders provide logistic services: (i) bidders provide dedicated services (e.g., sub-fleets) assigned to individual clients (e.g., dedicated fleet services for the orchestrator) and (ii) bidders already have pre-existing commitments to other contracts prior to the auction so new logistic activities have to be integrated into a bidder's current operations. In the absence of considering pre-existing commitments, bidders just need to deliberate over their bidding plans based on combinatorial opportunities among new logistic activities. However, in the presence of pre-existing commitments, bidders not only need to consider the combinatorial opportunities among new logistic activities but also need to optimize how these new activities can fit into their current operations while still protecting the pre-existing commitments, which requires making more complicated decisions. In addition to considering the existence of pre-contracted services, bidders must also consider economies of scope when determining which logistic activities to bid on. When cluster transport service bidders decide which cluster activities to bid on, their economics are not solely based on the volume of one-way demand in a cluster. They must optimize the utilization of their resources and balance their needs for equipment and drivers.

An important factor contributing to a cluster transport service bidder's transportation costs (and therefore bid prices) is associated with empty vehicle repositioning. Hub processing service bidders should also consider economies of scope in determining which hub activities to bid on. To exploit economies of scope, hub service bidders can consider relocating resources such as labor, modular capacity over time between a set of hubs to adapt to dynamic demand more efficiently (Faugere and Montreuil, 2017; Faugere et al., 2020).

The set of logistic activities a bidder participating in the auction ends up serving is uncertain due to the participation of other bidders (e.g., competitors) in the auction. The probability that a bidder wins a certain logistic activity/set of activities depends on the bidder's bid, competitor's bids, and the SLA that will be imposed on the activity(ies). That is, each bidder should take several factors into account: (1) SLAs imposed on the logistic activities that they are to bid on, (2) type of auction mechanism employed such as first-price auction or second-price auction, (3) the bidder's own cost structure, and (4) the competitor's bidding strategies.

To determine bids, bidders first need to consider modeling their operations for logistic activities that they are to bid on. Cluster transport bidders may use a VRP model to evaluate their capability in their desired activities. Hub processing bidders may develop a sort plan design/cross-docking assignment model. In addition to modelling operations, bidders also need to incorporate modelling game-theoretic decisions in their bid construction. In case of multiple SLAs offered for logistic activities, bidders need to consider which SLA will eventually be selected for their desired logistic activities by the orchestrator in Phase 3 in order to decide on which SLA(s) to select and how much bid price to ask. The bidder's bid price must be high enough to make serving the logistic activities profitable, but low enough to beat competitor's prices. In practice, it is very difficult, indeed almost impossible for bidders to access competitor's strategies. One way to incorporate the competitor's strategies is to consider lowest price offered for logistic activities previously offered (Kuyzu et al., 2015; Yan et al., 2018).

2.2.3 Phase 3: Bid Assignment and Service Network Optimization

Once each bidder forms their bids with associated bid prices, these are submitted to the orchestrator. In Phase 3, the orchestrator determines the winning bid among the bids submitted by all bidders (and the selected SLA in case of multiple SLA options) for each logistic activity in a way that minimizes the total outsourcing cost, as illustrated in Figure 6. The orchestrator models this winning bid determination problem using integer programming as an assignment-style model, where one specific bid is assigned to each logistic activity such that the service guarantee of each O-D pair is guaranteed in a cost minimization manner. This indicates the final assignment of SLAs to logistic activities, and bidders to logistic activities, and results in contracts for the termed horizon.
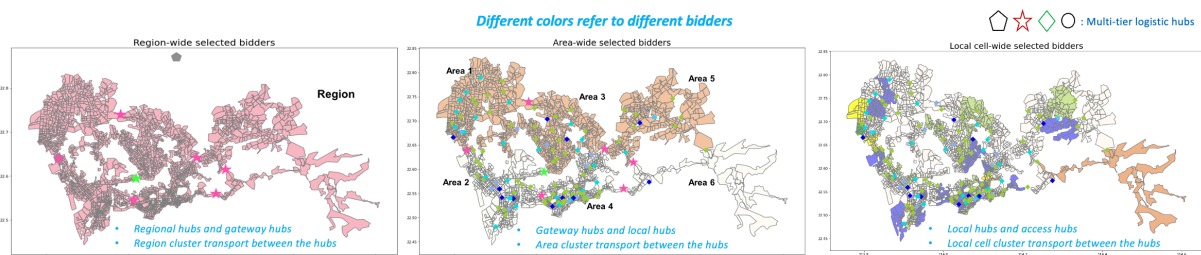

Figure 6: Example of Output of Phase 3

In practice, the orchestrator would face uncertain values of parameters such as future demand volume and bidders' service capability/reliability, and it is not always possible to predict or estimate them accurately. Now that the main logistics goals are to deliver the right items to the right place, at the right time under the right conditions, when allocating winning bids to logistic activities, the orchestrator must ensure that the resultant bid-activity assignment leads to robust O-D service guarantees that are stable and less sensitive against possible uncertainties in a cost minimization manner. One common way to consider such robustness is to employ a probabilistic way of handling probabilistic uncertainty aforementioned. For example, the orchestrator may consider an on-time arrival probability of meeting the requirement of the O-D service guarantees. In other words, the orchestrator wants to guarantee the probability (e.g., 99.99% robustness/reliability) such that the robust solution feasibly ensures the O-D service guarantees. One can model this using a chance-constrained model where the probability that O-D service guarantees are met is constraind. The orchestrator will still make sure that the optimal selection of bids leads to planning that are not overly conservative or too costly, which also depends greatly on the SLAs as discussed.

3   Conclusion and Future Research Avenues

In this paper, we apply an auction mechanism concept to the design of logistic service networks by outsourcing logistic activities to third-party logistic service providers (3PLs) via a bidding process. We leverage the three-phased combinatorial auction (CA) mechanism that is well-used in the transportation service procurement process, further incorporating it with O-D service guarantees within an urban city and service level agreement (SLA) for each logistic activity. Throughout this paper, we provide the decision-making process of each stakeholder in each phase with modelling ideas that are to be researched and concretized. Introducing the concept of SLAs for logistic activities to the problem adds another dimension of complexity to the decision-making process in each phase, such as considering the reactions of other decision-making stakeholders, and creates another decision perspective view, which makes the proposed problem novel in the context of service network design.

Subsequently, the proposed framework opens future research avenues. Each of the stages in the proposed framework involves optimization and modelling challenges that are related not just limited to the operations of vehicles in clusters and those of hubs, but also to determining SLAs, the reactions of other decision stakeholders, and robustness in the O-D service guarantees. In the combinatorial transportation service procurement auction literature family, the three phases in the proposed framework are often represented as the Shipper Lane Selection Problem (SLSP) for Phase 1, the Bid Construction Problem (BCP) for Phase 2, and Winner Determination Problem (WDP) for Phase 3 (Song, 2023).

When it comes to SLAs, most of the literature on the three problems is only focused on satisfying demand volume (e.g., forecasted volume of packages) and does not address time-aspects of services (e.g, x-hour transport). In addition to time-aspects in the service, most literature considers a single-tier network consisting of a set of origin-destination pairs while we base our framework on the hyperconnected multi-tier mesh networks where parcels move from their origin to destination by traversing multiple planes through multiple logistic activities. This adds another layer of combinatorial complexity. The paper marks key decisions and required capabilities, revealing capability gaps that will be left for future research steps.

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Hyperconnected Urban Parcel Delivery Network Design with Tight Delivery Service Requirements

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Abstract: The advent and growth E-Commerce has led to not only a huge increase in demand for rapid and guaranteed transport/delivery services, but also in the numbers of vehicles entering and leaving urban cities to deliver goods and services, clogging the roads and polluting the air. Seeking efficient usage of resources is inarguable. Motivated by these challenges, this paper studies the design of hyperconnected parcel network design in line with the Physical Internet initiatives, modelling it as a coalition-formation game. The objective is to design a cooperative parcel delivery network among multiple delivery actors such that the actors within the same coalition can share resources. We develop a case study of La Poste to understand the impact of coalitional decisions and cost-sharing methods on the global and individual network design cost.

Keywords: Network Design; Hyperconnected city logistics; Physical Internet; Coalition-Formation;

Conference Topic(s): autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms) business models & use cases; networks; interconnected freight transport; distributed intelligence last mile & city logistics; logistics and supply networks; PI fundamentals and constituents; PI impacts; PI implementation; PI modelling and simulation

Physical Internet Roadmap (Link): Select the most relevant area(s) for your paper: ☒ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☒ Governance.

1 Introduction

Over the past decade, the exponential growth of the e-commerce industry has led to an exponential increase in the volume of smaller yet faster and more frequency parcel deliveries, causing increased commercial traffic, congestions, and hence pollution in areas with dense population. Many companies, especially those operating in densely populated urban areas, already introduce a new design of their delivery networks to include satellite facilities/micro-

hubs with sorting capability within the urban center close to their customers to better serve them, and sustainable initiatives using electric vans/cargo bikes (CBs) as an alternative to carry last-mile delivery (Winkenbach et al., 2016). Furthermore, inspired by the Physical Internet concept enabling open asset utilization, many are open to change their way of business toward collective actions and cooperative strategies by mutualizing data and resources (Kim et al., 2021). With such multiple delivery actors within an urban city, there still are some remaining challenges: (1) lack of available logistic space to build such micro hubs and (2) congestion of alternative modes of transport including CBs.

In this work, we consider the case of La Poste, French national postal company, that is motivated by the challenges above to redesign their logistic network. La Poste consists of several subsidiaries of parcel delivery actors, each of whom is an independent firm and offers different delivery time service levels (e.g., x-hour delivery) between fixed origin-destination (O-D) pairs in their own dedicated network. Motivated by the case of La Poste and further generalizing it, we study in this work the design of a hyperconnected network for a logistic firm in a similar setting to La Poste where its subsidiary actors are allowed to cooperate and share with others their network components including vehicle resources and micro-hubs to seek tight delivery service requirements in a sustainable manner while maximizing their own profit as a result of their coalitional decisions. We propose a coalitional decision-making framework and shared network design model where both input demands and transportation plan decisions are modelled as a frequency per time (e.g., 1000 parcels per week, 50 cargo bikes per week) in a flat network (not space-time). The proposed framework leverages the network design model to model the coalition-formation decisions of delivery actors to determine whether it is beneficial to stay stand-alone or form a coalition with others, and how to form it.

2 Framework for Hyperconnected Urban Parcel Delivery Network Design

In this section, we present a conceptual framework for the proposed hyperconnected urban parcel delivery network design. We first introduce key decision-making stakeholders involved in designing hyperconnected parcel delivery networks and discuss the main objective and key decisions of each one. Then, we discuss what it means for these stakeholders to form a coalition with others, what is to be cooperated and shared under a formed coalition, and what is to be globally expected from that coalition.

2.1 Problem Description

We consider a coalitional game for the shared network design involving a set of independent parcel delivery actors who are offering a range of parcel delivery services between a predetermined set of its origin-destination pairs (i.e., commodities) in the same geographical urban area. We assume that each of these actors has its own dedicated parcel delivery network and offers a set of service levels (e.g., 6-hour delivery, same-day delivery) in that network. Origins and destinations served by the delivery actors are represented as demand zones which can be thought of as a set of demand points in an urban city where parcels are picked up and dropped off. The parcel delivery network of each actor is structured as a multi-echelon network comprising existing and potential (not opened yet) micro hubs (MHs) within the city that are equipped with sorting capability and distribution centers located in peri-urban areas.

Each commodity is associated with expected revenue and a service level requirement that specifies the maximum amount of time allowed to transfer from its origin to destination. We assume that the delivery network of each actor allows shipments to be transferred between vehicles at intermediate micro hubs. That is, commodities are transported from the origins to

destinations via one or more intermediate micro hubs while abiding by actors' operational constraints. Therefore, the main goal of each delivery actor is to optimize its parcel delivery network such that all commodities are feasibly served in a cost-minimization manner. We assume that the overall profit of each actor is defined as the difference in total revenue from serving its demand commodities and total cost incurred to optimize its parcel delivery network. Thus, in order to maximize its profit, each actor must minimize the cost of optimizing its parcel delivery network.

To increase individual's economic benefits, one can consider forming a coalition with other delivery actors. Forming a coalition with other delivery actors means horizontal cooperation. Horizontal cooperation offers the opportunity for actors to access other actors' additional capabilities and capacities and share their own resources with others when underutilized. In this work, we assume that resource sharing includes micro hub sharing and vehicle sharing. Resource sharing is meant to allow other actors to access underutilized resources. As a result of cooperation, micro hubs can share resources such as sorting capability or dock doors and vehicles can be loaded with flows of different actors. For example, suppose we have a vehicle moving from one hub to another and assume that it is 70% full. Then, we may allow other actors who are interested in sending flows in the same direction to access the underutilized vehicle by filling the remaining 30% with flows of other interested actors.
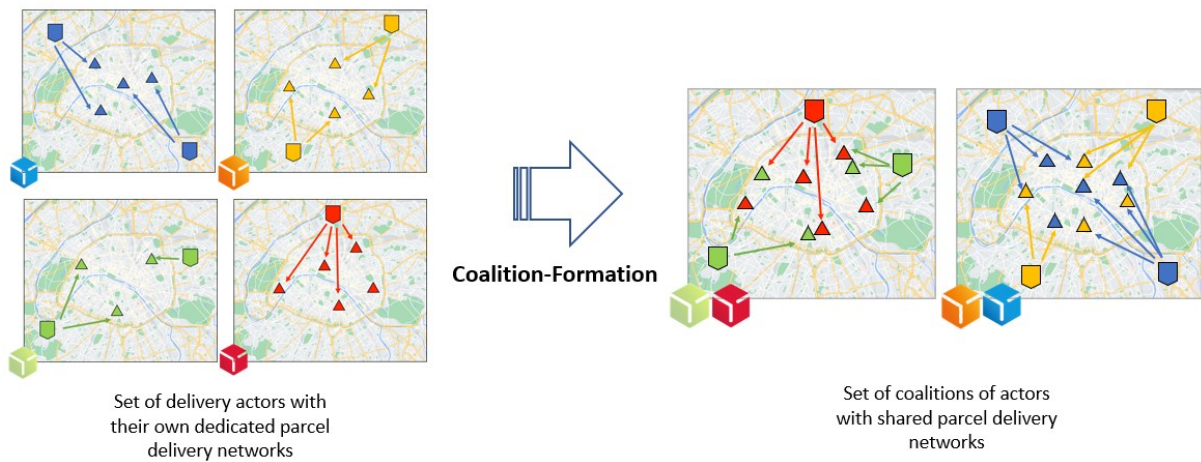

Coalition-Formation

Set of delivery actors with
their own dedicated parcel
delivery networks

Set of coalitions of actors
with shared parcel delivery
networks

Figure 1: Example of Coalition-Formation of Multiple Parcel Delivery Actors

It is clear that some actors could gain benefits from forming coalitions, yet this opportunity still must be investigated. To do so, several questions must be addressed: Can the actors improve their individual economic performance when they coalesce with others? If so, what is the best coalition for each actor to form so that the profit of each cooperating actor is increased? Even if the global economic performance of a given coalition is larger than the sum of the individual economic performance of actors in that coalition when they stand alone, actors would not form the coalition if their cooperative individual performance is smaller than their stand-alone individual performance. Also, it needs to be addressed how the actors will react to cooperation according to the cost sharing method proposed.

2.2 Coalitional Decision-Making Framework

We propose a coalitional decision-making framework for the proposed hyperconnected urban delivery network design. The proposed conceptual framework shown in Figure 2 takes as input the dedicated parcel delivery network of each actor and consists of two interrelated steps: coalition-formation and shared network design model. We model the problem as a coalition-

formation game where the shared network design model is proposed to evaluate the payoff of each possible coalition. The payoffs obtained from the network design model are used to determine the solution of the coalitional game in terms of stable coalition structure (i.e., a set of stable shared parcel delivery networks).
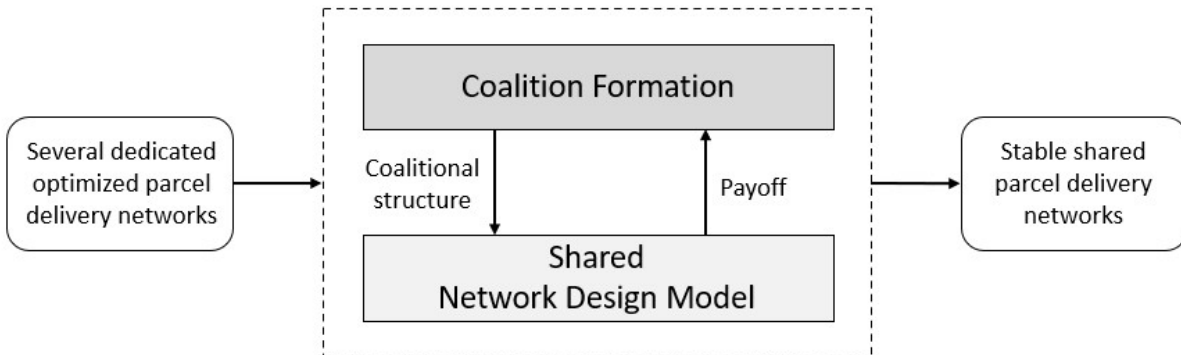

Figure 2: Coalitional Decision-Making Framework

We address (1) which profitable coalition each actor should form, (2) how the shared network of each coalition should be designed to offer timely delivery of each actor in that coalition, and (3) how the joint costs of the shared network should be allocated between actors. To answer (1) and (3), we model the coalitional game of the problem in the stand-alone scenario as a benchmark where actors do not interconnect with each other, and shared scenarios where actors are allowed to interconnect. Actors possibly refrain from coalescing with others when such a coalition does not improve their individual economic performance, regardless of the benefit that the coalition might provide the global system. Thus, the coalitions formed should be desirable from both the global coalition level as well as the local actor level. We use principles from cooperative game theory to identify the most profitable coalitions and to determine the portion of cost that would be allocated to each actor to guarantee the stability of the formed coalitions. We employ different cost-allocation methods such as Shapley's value as different cost-allocation mechanisms could lead to different outputs for the actors (Basso et al. 2020).

2.2.1 Shared-Network Design Model

In this section, we introduce the shared urban parcel delivery network design problem for a coalition of actors. We consider a strategic hub selection problem within the context of service network design. Note that all possible coalitions include a single-actor coalition (i.e., stand-alone case) and thus the proposed model can be used to evaluate the payoff of a stand-alone parcel delivery network. We formulate the shared network design problem as a path-based mixed integer programming (MIP) and frequency-based model on a flat network incorporating time aspects of parcel delivery. In flat networks, demands are modeled as average demand rates per time for each origin-destination pair. The proposed model takes demand rates as input. The goal of the proposed model is threefold: (1) choosing the hubs that encourage consolidation opportunities the most, (2) selecting a joint set of time-feasible paths for all commodities, and (3) along with the paths, allocating required number of vehicles to be dispatched between facilities per time (i.e., vehicle dispatch frequencies) to guarantee the desired timely service levels for O-D pairs in a cost minimization manner. For each commodity, we express its dwell time at intermediate hubs along its (potentially) assigned path using vehicle dispatch frequency variables and link it with its corresponding service level.

For a given coalition s, which can be a subset of actors or single actor, let $(\mathcal{N}^s, \mathcal{A}^s)$ define the coalition's network. The node set $\mathcal{N}^s$ denotes the set of existing and potential locations in the network; these include the set of demand zones that originate shipments, $\mathcal{N}_O^s \subseteq \mathcal{N}^s$, the set of those that are destination demand zones for commodity shipments, $\mathcal{N}_D^s \subseteq \mathcal{N}^s$, , and the set of potential and existing micro hubs where shipments can be sorted and consolidated, $\mathcal{N}_I^s \subseteq \mathcal{N}^s$. Furthermore, each hub $i \in \mathcal{N}_I^s$ has an associated opening cost g_i and specifies an associated lower and upper bound $Q_i^{\min}$ and $Q_i^{\max}$ on the throughput capacity when opened/activated (i.e., minimum and maximum number of vehicle dispatches required). The directed arc set $\mathcal{A}^s$ consists of the set of potential transportation legs linking pairs of locations. Each arc $a \in \mathcal{A}^s$ has an associated travel time t_a and a per-vehicle dispatch arc cost c_a corresponding to a vehicle movement of capacity v. We define $\delta^+(i)$ and $\delta^-(i)$ as a set of incoming/outgoing arcs to/from hub $\mathcal{N}_I^s$.

Origin-destination demand is modeled as a set $\mathcal{K}^s$ of commodities. Each commodity $k \in \mathcal{K}^s$ has an associated origin $o_k \in \mathcal{N}_O^s$ and destination $d_k \in \mathcal{N}_D^s$, demand volume rate q_k representing aggregated average shipment quantity from o_k to d_k per time unit (e.g., 1000 parcels per day), expected revenues, and service level τ_k in terms of delivery time requirement from o_k to d_k (e.g., 6-hour, same-day, two-day deliveries). Let $\mathcal{P}_k$ denote the set of potential paths for commodity k, where each potential path consists of a set of pair of locations connecting origin o_k and destination d_k. Thus, for each commodity k, a unique path out of the set must be selected. As the problem is more of a strategic nature, we assume that any fluctuating demand do not significantly affect the feasibility of the consolidation plan. Moreover, although shipments for each commodity k, can be sent from its origin to destination through different hubs over time in practice (i.e., taking different paths over time), we assume that such shipments follow the same path defined by the chosen consolidation plan.

We hereafter introduce a base optimization model for the shared urban parcel network design problem. We define for each $i \in \mathcal{N}_I^s$ binary variables x_i to indicate whether hub i is opened/activated and integer variables y_a to represent the integer dispatch frequency of vehicles on arc per time unit a, $\forall a \in \mathcal{A}^s$ (a dispatch frequency of 10 is interpreted as 10 vehicle dispatches per time unit i.e., 100 vehicle dispatches per week). Let binary variables z_p^k indicate whether commodity k uses path p, $\forall p \in \mathcal{P}_k$. As each commodity has an associated service level (i.e., delivery time requirements), each potential commodity path must be time feasible. That is, the shipment lead time along each commodity path must satisfy the service level. To capture such time aspects in our proposed frequency-based model, we assume that each commodity $k \in \mathcal{K}^s$ arrives at o_k and all vehicles are to be dispatched between locations according to a uniform distribution. We then use a similar approach in the work by Greening et al., (2022) and Dayarian et al., (2022) for network design problems to handle the time requirements of commodities in a frequency-based model. We suppose that the shipment lead time of commodities is determined by the arcs and intermediate hubs along each route. The times spent traversing the arcs and hubs along each path include travel time across arcs, handling time, and dwell time at each intermediate hubs along the path. Therefore, a potential path for each commodity k is said to be time-feasible if and only if the sum of travel times of all arcs along the path, the handling times at all its intermediate hubs, and expected dwell times at the hubs along the path does not exceed the service level, τ_k In other words, for each commodity $k \in \mathcal{K}^s$ and each path $p \in \mathcal{P}_k$, the following must be satisfied:

$$\sum_{a \in p} t_a + \sum_{i \in p \setminus \{o_k, d_k\}} h_i + \sum_{i \in p \setminus d_k} \mathbb{E}\left[w_{ip}\right] \leq \tau_k$$

$$\rightarrow \sum_{i \in p \setminus d_k} \mathbb{E}\left[w_{ip}\right] \leq \widehat{w}_p^k = \tau_k - \sum_{a \in p} t_a - \sum_{i \in p \setminus \{o_k, d_k\}} h_i \qquad (1)$$

, where h_i denotes fixed handling time at hub i independent of commodity flow, and $\mathbb{E}\left[w_{ip}\right]$ denotes the expected dwell time at intermediate hub $i \in p \setminus \{o_k, d_k\}$, and $\widehat{w}_p^k$ denotes the maximum allowable dwell time along path p for commodity k. Expected dwell time at hub i along path p depends on the outbound dispatch frequencies along the arc leaving hub i along path p. We assume that given the vehicle dispatch frequency y_a on arc a, vehicles are dispatched every $\frac{1}{y_a}$ time units. With the uniform distribution assumption, the expected dwell time at intermediate hub i along path p can be modeled as $\mathbb{E}\left[w_{ip}\right] = \frac{1}{2} \cdot \frac{1}{y_a}$. We can formulate this model as follows:

$$\min \sum_{i \in \mathcal{N}_I^s} g_i \cdot x_i + \sum_{a \in \mathcal{A}^s} c_a \cdot y_a \qquad (2)$$

$$\sum_{p \in \mathcal{P}_k} z_p^k = 1, \qquad\qquad \forall k \in \mathcal{K}^s \qquad (3)$$

$$\sum_{k \in \mathcal{K}^s} \sum_{\{p \in \mathcal{P}_k : a \in p\}} q_k \cdot z_p^k \leq v \cdot y_a, \qquad\qquad \forall a \in \mathcal{A}^s \qquad (4)$$

$$\sum_{a \in p} \frac{1}{2} \cdot \frac{1}{y_a} \leq \widehat{w}_p^k + M \cdot \left(1 - z_p^k\right), \qquad\qquad \forall k \in \mathcal{K}^s, p \in \mathcal{P}_k \qquad (5)$$

$$\sum_{a \in \delta^-(i)} y_a \leq Q_i^{max} \cdot x_i, \qquad\qquad \forall i \in \mathcal{N}_I^s \qquad (6)$$

$$\sum_{a \in \delta^-(i)} y_a \geq Q_i^{min} \cdot x_i, \qquad\qquad \forall i \in \mathcal{N}_I^s \qquad (7)$$

$$\sum_{a \in \delta^+(i)} y_a \leq Q_i^{max} \cdot x_i, \qquad\qquad \forall i \in \mathcal{N}_I^s \qquad (8)$$

$$\sum_{a \in \delta^+(i)} y_a \geq Q_i^{min} \cdot x_i, \qquad\qquad \forall i \in \mathcal{N}_I^s \qquad (9)$$

$$\mathbb{x}, \mathbb{z} \in \{0,1\} \qquad (10)$$

$$\mathbb{y} \in \{0,1\} \qquad (11)$$

The objective function (2) minimizes the total cost including micro hub opening cost and variable costs incurred along the operated arcs. Constraints (3) ensure that one path per commodity is selected. Constraints (4) allow flow along each arc only if there is vehicle dispatch and enforce an aggregated vehicle dispatch capacity. Constraints (5) assure that enough vehicle dispatch frequency must be allocated along each arc of the chosen path for each commodity so that the maximum allowable dwell time along the path is not violated. Constraints (6)- (9) set required vehicle dispatch frequency for each hub opened. To avoid such

nonlinearity in Constraints (5) we propose two linearization approaches along with the model: (1) allocating the maximum allowable dwell time equally among the arcs of each path and (2) introducing a discretization of the domains of vehicle dispatch frequencies along each arc as proposed by Cancela et al., (2015).

2.2.2 Cost-Allocation Methods

As mentioned before, whether an actor wants to coalesce with others depends on how much benefit they receive from forming a coalition with others compared to the case where they stand alone. Actors would want to form a coalition with others if the cost allocated to them in the shared scenarios is less than or equal to the cost allocated to them in the stand-alone scenario. In other words, the cost-allocation method impacts the decision of actors to form coalitions. An essential requirement is that the resulting allocations satisfy the individual rationality condition for all actors, that is, the profit obtained from forming coalitions exceeds the individual profit. Note that different cooperative game solution concepts for allocating joint costs as different sharing mechanisms could lead to different outputs for the actors (Basso et al. 2020). We here focus on three most well-known cost allocation mechanisms: Shapley value, Proportional allocation (PA), and Egalitarian allocation (EA) which are among the most used cost allocation mechanisms in the literature on collaborative transportation (Guajardo et al., 2015). We refer to the work of Jouida et al. (2021) for the definition of each cost-allocation method above.

3 Preliminary Experiments

To test the modelling and understand the impact of coalitional decisions of actors, we apply the developed framework, optimization model, and three cost-allocation methods to a large-scale urban network instance of the La Poste group for case study. We show how the proposed framework can be leveraged to evaluate network's service capability of each actor such as at what cost their desired service level goals can be reached in stand-alone and shared scenarios, respectively. We consider 3 delivery actors, subsidiaries of the La Poste Group, serving an urban city with 412 demand zones expecting a weekly demand on the order of 1.6 million parcels weekly across 52,000 origin-destination (O-D) pairs. We consider each delivery actor offers 3 different service levels and the weekly demand for each actor is derived according to their historical market share for the given urban city. We assume that all the micro-hubs of actors are homogeneous in terms of capacity/size. Tables 1 and 2 summarize the network and demand information of delivery actors and possible coalitions, respectively. Default values for parameters used in the model are set according to the historical practice of La Poste.

Table 1: Summary of Delivery Actors

Delivery Actor	No. Micro-hubs	Market Share	No. O-D Commodities
1	25	60%	35591
2	3	10%	6162
3	8	30%	18105

Table 2: Summary of Possible Coalitions

Coalition	No. Micro-hubs	No. O-D Commodities	Description
(1,)	25	35591	Standalone
(2,)	3	6162	Standalone
(3,)	8	18105	Standalone
(1,2)	28	41301	Coalition of Actors 1 and 2
(1,3)	33	52472	Coalition of Actors 1 and 3
(2,3)	11	24044	Coalition of Actors 2 and 3
(1,2,3)	36	57968	Grand Coalition

The aim of this preliminary experiment is to understand the impact of coalitional decisions of actors on the global network design performances and the impact of the cost-allocation methods on the coalitional decisions of actors. For the global network design performance indicators, we consider the total overall network design cost and overall usage of transportation resources in terms of number of dispatches for each possible coalitional structure. For the coalition performance indicators, we consider the number of cooperative actors, number of profitable coalitions, and cardinality of the optimal coalition structure for each cost-allocation method (denoted respectively with No. Cop. Acts, No. Prof. Coal, and |Coal| in Table 3).

Figure 3 reports the global network design cost and total resource usage in terms of number of vehicle dispatches per possible coalitional structure. As shown in Figure 3, forming coalitions leads to the reduction in the overall network design cost and number of dispatches, and the best performance is achieved when the grand coalition is formed, that is, when all actors belong to the same coalition. However, coalitions can only happen when the rationality condition holds for all actors. That is, the actors will coalesce only when the overall profit achieved from forming coalitions exceeds the individual profit from working standalone, which depends on how the joint costs are allocated.
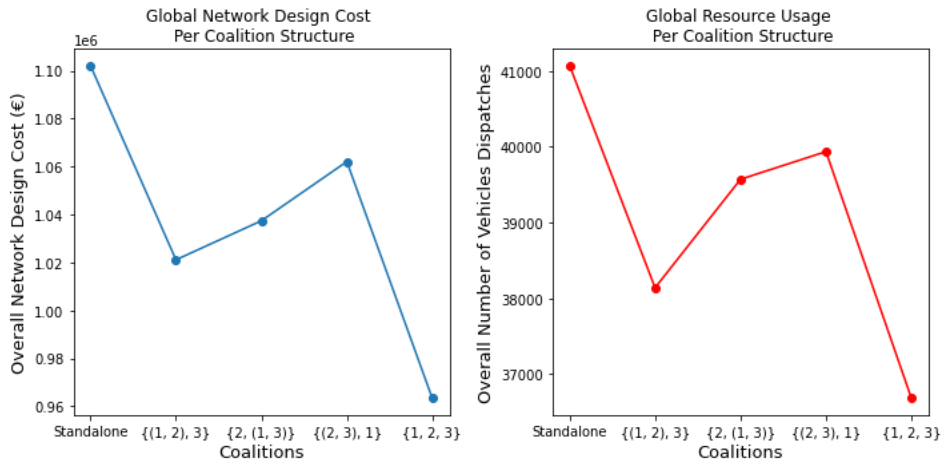

Figure 3: Global Network Design Performance

Table 3 reveals that the Shapley allocation and PA methods lead to the formation of more coalitions than the EA method. For the EA method, all the actors prefer to work standalone as joining coalitions is not beneficial to them while the Shapley and PA methods lead to all actors willing to coalesce. The cardinality of the optimal coalition structure indicates that the actors are willing to form a grand coalition. Detailed results of the impact of cost-allocation methods on all actors are shown in Figure 4. This phenomenon can be explained by the characteristics of the instance considered in the preliminary experiment. The market shares of the actors are not well-balanced; actor 1's market share is dominating the others. In this case, The EA method which does not account for marginal contribution of actors would be significantly beneficial to the dominating actor while it would be detrimental to the other actors, leading to them wanting to work standalone. Different instances with different market shares among actors and parameters will lead to different coalitional structures. These results still underline that the cost-allocation method incentivizes the actors' decision to coalesce.

Table 3: Summary of Coalitional Decisions per Cost Sharing Method

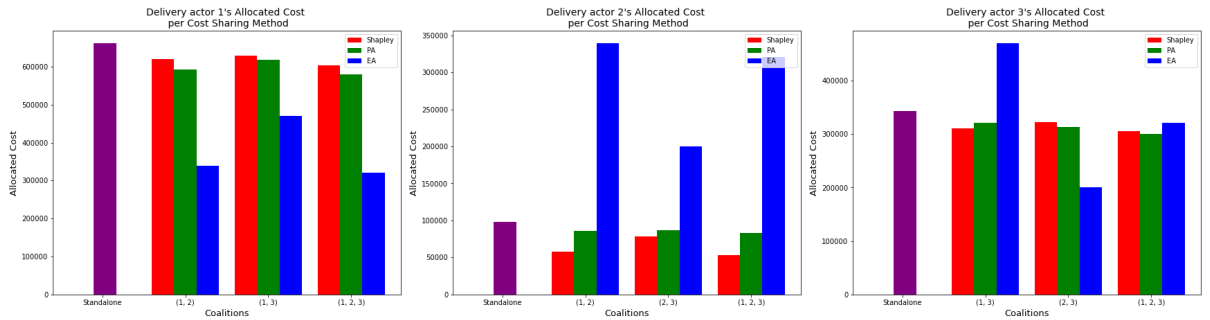| Tot. No. Coal	Shapley			Proportional (PA)			Egalitarian (EA)		
	No. Cop. Acts	No. Prof. Coal	|Coal|	No. Cop. Acts	No. Prof. Coal	|Coal|	No. Cop. Acts	No. Prof. Coal	|Coal|
7	3	5	1	3	5	1	0	0	3

Figure 4: Allocated cost to actors per cost-allocation method

4 Conclusion and Future Research Avenues

The network design problem studied in this paper considers designing a cooperative parcel delivery network in which multiple actors coalesce to efficiently serve a number of transport demands and maximize their profit. Cooperation is viewed as a concept aiming to pool resources by seeking better resource utilization through smart consolidation to maximize one's profit. In this paper, we motivate the resource-sharing concept in the realm of the Physical Internet initiatives in the context of the urban parcel delivery network deisgn. Furthermore, we leverage a cooperative framework to model the problem as a coalition formation game. The preliminary experimental study highlights the importance of horizontal cooperation in the pursuit of actors' profit growth and sustainability. It also observes that forming coalitions depends on the cost allocation method used. Indeed, using various cost sharing methods, we observed that different methods can lead to different coalitions.

Future research steps could include adding more dimensions such as problem size, network configuration, different hub sizes, different cost structure to analytically see how the

cooperative decision conditions can be derived according to the cost-sharing methods considered. For modelling, this paper assumed that arriving demand and vehicle dispathces between hubs follow a uniform distribution and derived Equation (5) for the delivery service requirements. However, this would imply that the commodity travelling along its path arrives at its destination on time with probabilty of 0.5. Future works could remove this assumption and address robust perspective in the commodity lead-time requirement.

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Why Fair Benefit Sharing is Crucial for a Successful Implementation of Cooperation and How it Could Work.

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Abstract: Within this paper, we discuss benefit sharing in modern freight logistics. We propose to introduce transport management platforms for organising intermodal transports. As this idea is not new at all, we focus on the sharing of (costs and) benefits within these platforms as in our understanding one main obstacle in collaborative logistics is the willingness of people (decision makers) to collaborate with (potential) competitors. Although in a future world where collaborative logistics are well-established there might be no need for such strategies, we think that during transition a fair sharing among participants which does not advantage one of them is crucial. A simple, yet fair calculation method is presented. Impacts and future works are then discussed.

Keywords: fair benefit sharing, horizontal cooperation, coopetition

Conference Topic(s): business models & use cases; technologies for interconnected logistics (digital twins, collaborative decision making)

Physical Internet Roadmap: ☐ PI Nodes, ☒ PI Networks, ☐ System of Logistics Networks, ☐ Access and Adoption, ☒ Governance.

1 Introduction

Climate change is one of the major challenges of our generation. According to international figures [1], about 10% of global CO_2 emissions are related to the freight transport sector. Even more, up to 12%, if activities in hubs are included. Most of the emissions are related to road-based transport. It is therefore crucial to focus on a global reduction of transports. Those transports which cannot be avoided should be shifted towards more climate-friendly modes of transportation like the (inland) waterway system or rail system. The rest should be improved with respect to CO_2 emissions as much as possible. Possible technologies are (battery) electric vehicles and/or hydrogen trucks – as long as the energy/hydrogen is produced via renewable energy sources. However, replacing all trucks with electric trucks lets us face the same other challenges related with road transportation, which are, amongst others, congestion, soil sealing (for roads and parking places), noise, road safety, lack of truck drivers, driving time regulations, etc. Completely avoiding transportation is, however, not feasible from an economic point of view. Even though local production might be beneficial from different point of views, disadvantages are connected with it. E.g., not all raw materials are available in all regions. So, either certain areas around the world would have to deal without specific products, or transportation of raw materials, or manufactured goods is indispensable.

Taking a closer look at these aforementioned reasons, intermodal transports are to be intensified on a large scale. The basic principle of an intermodal transport is to split the transport into three legs: the first mile, the main run, and the last mile. While the first mile and the last mile are typically road-based, the main run is either completed via vessel or train. Obviously, capacities along the main run are much higher than on the first and last mile. Therefore, bundling has to take place in order to be economically viable. In addition, the first and last mile will most probably be below 150km. This is a distance for which state-of-the-art electric trucks can already be utilised. Therefore, intermodal transports contribute to all three aforementioned strategies in reducing CO_2 emissions: avoidance of transports (via bundling), shifting towards vessel/train, and electrification of those parts which have to be realised along the road.

Even though intermodal transportation seems to be a viable solution to an increasing freight transport demand, the question arises whether it is applicable on a large scale: As already mentioned, one crucial point is that critical masses of freight need to be transported along the same track as otherwise the usage of trains/vessels is not economically viable. This, however, implies (on a first glance) that only large companies with large amount of freight for the same route can utilise intermodal transportation. This is only partly true. Due to bundling of different freight flows, it is possible to generate the needed demand for transport along the main run on train/vessel. The coordination amongst the relevant stakeholders, i.e., the individual companies, is mostly done by carrier that order trains at railing companies that than take over the actual transport. Please note, that there is a number of various other constellations which, however, lead all to a similar structure: the actual transport executing company (operator) takes order from an intermediary (freight forwarder) that sells the capacities of the train to individual companies with "less than train" loads of freight.

All in all, this concept of transport bundling works quite well – from an economic point of view as well as from an individual point of view for smaller companies. However, the full potential is not reached yet by far. On the one hand, the modal split shows that road transport is still the most used mode of transportation – especially for intracontinental transportation, cf. [2]. On the other hand, the utilisation rate of individual trains and vessels differs and is not as high as it should/could be, cf. [3]. Goal of this work is to discuss how especially intermodal utilisation rates can be improved.

2 Proposition on Benefit Sharing

Within this paper, we propose the following: Instead of hoping that the current freight transport system will somehow improve over time, we propose to actively shape it. As outlined in the previous section, intermodal transports seem to be one major opportunity to overcome negative climate impacts from freight transportation (obviously, in combination with a lot of other measures, some of them not originating in the transport sector). As outlined, intermodal transportation relies on bundling of freight flows for the main run. Bundling, however, can be seen as horizontal collaboration between shippers. As (currently) this bundling is done via freight forwarders (or carriers), this is realised quite efficiently. However, if a freight forwarder (or carrier) does not gain enough orders to economically operate a train, it is most likely that all transports are realised on road. We suggest that in such cases, freight forwarders and carriers should (horizontally) cooperate with each other. For convenience only we outline our ideas for train operators only. Of course, the same mechanics apply for inland navigation.

2.1   Strategies for Horizontal Collaboration

Suggesting that freight forwarders and carriers cooperate with each other with respect to intermodal transportation, we outline the basic idea. The concept refers to the collaborative use of trains along the main run.

Based on expected freight volumes, individual freight forwarders should pre-order trains. First, they should pre-order trains for the main run on relations that will most probably be utilised on an economically viable level. In some cases, these trains will be fully utilised. In other cases, the utilisation will be close to economic inviability. However, the economic risk is low.

Second, trains should be ordered for relations, where companies themselves have a considerable volume even though the volume might not be enough for economic viability as long as others (i.e., competitors) have enough volume such that a joint transportation is economically viable. For those relations where the own volume is not considerable, the goal is to find operators which already ordered a train and put the own freight on that train, too.

So far, the proposed strategy is straightforward and only the joint transportation for relations where not enough volume for one company is available is cooperative. Even in this simple case, it is necessary to consider the benefits (e.g., saving time, saving costs) that are gained with such a strategy, and how these benefits can be fairly distributed amongst the participants.

At first glance, this need seems to be not mandatory, as the one company ordering the train (and then selling empty spaces to others) could make some money out of it. But to be honest, it can be expected that those companies in need of slots on a train are not willing to pay to their competitors. If, however, the costs and benefits are fairly distributed amongst all participants, the likelihood for cooperation can be assumed to be higher. We call this concept "Fair Benefit Sharing".

Please note that normally, train schedules are not planned for just one trip, but for a recurring roundtrip for a longer period of time (e.g., one year). There might be some relations where all participants together do not have enough volume to justify such a block train. In such cases, a re-routing of transport units, i.e., containers, might be an interesting option. This means that instead of booking a slot on a direct train, slots on trains with a via-point are booked, e.g., instead of going from A to B, trains from A to C and C to B could be chosen. The operators of those trains do not necessarily be the same. The idea of such a re-routing of containers is depicted in [4]. First algorithms for optimising the decision which container is to be transported on which train are presented in [5]. With respect to benefit-sharing, this application scenario is just a multiple application of the above-described use case.

Another application case to be considered is the parallel operation of trains in the network. With parallel trains, we denote trains booked from different companies on the same relation/track. Over the course of a year, it is very likely that sometimes one of the two trains is full (or over-booked) while the other one has still some slots for containers left. In these cases, a shifting of non-transported containers for one company/train towards the other one (with still open slots) is beneficial as more customers can be satisfied while the utilisation rate of the second, non-fully booked train can be increased. Again, sharing costs and benefits among all partners will most probably increase the likelihood of cooperation among the competitors.

2.2   Benefit-Sharing

First of all, it is necessary to define what benefits are, exactly. In our understanding, benefits are the profits companies make with the transportation service. Please note, that other benefits, e.g., reduced environmental emissions, might be considered as well. For convenience only, we

focus on monetary benefits only in this paper. Contrary to the benefits are the costs which are the production costs of the transports, i.e., the fees for the tracks, the salaries of the train driver, the costs for the energy used, etc. With respect to share the benefits among all participants, we discussed several different formulas and ideas. Our considerations on how to distribute and share the benefits, led to one observation: Everyone has to bear its own costs. The benefits are then distributed proportional to the share of costs. I.e., someone with a 10% contribution to the costs, gets a 10% share of the benefit:

$$s_i = \frac{c_i}{\sum c_j}$$

The share s_i of participant i of the overall benefit is the fraction of their costs (c_i) and the overall costs of all participants ($\sum c_j$).

To ease computations of contributions and benefits, one can easily add up all costs (and profits) of each individual transport, i.e., the costs of the non-cooperative or status-quo approach. In addition, the costs (and profits) of the cooperative transports are calculated. The costs of cooperative transports are those costs that occur for all partners together when cooperative transports are applied. The difference between the overall individual transport costs and the overall cooperative transport costs is then the overall benefit. However, if the benefit is negative, i.e., the cooperative solution costs more than the individual ones, it is obvious that no cooperative transport will be executed. Please be aware that if for one participant cooperation is beneficial, it is beneficial for all participants when following this approach.

3 Expected Impacts and Future Work

We expect that this transparent and open calculation of benefits and the sharing of them will positively effect collaboration in the transport sector. Everyone participating in such a cooperative environment benefits proportional to his/her contribution. That is, no one is advantaged. On the contrary, the benefits are not only for the participants themselves who mainly benefit on a financial basis. The benefits are for all of us since the overall outcome are more environmentally friendly transports. That is, a positive contribution towards climate action. At the same time, the needed distribution of goods can be retained.

Even though in theory the solution is quite easy, the actual implementation is challenging. The most important issue is to build up trust among the participating parties. As some individual examples among different players show, such cooperations can be generated over time. However, they will always be on a rather small level. Therefore, we request that more effort is put into providing up technological support for trust-building. There are different transport management platforms on the market that allow booking, contract management, the recording of transport routes, availability display, usage times of assets, the search for offers for the customer, or documentation and evaluation of all desired events. One major need is that these platforms are neutral in the sense that they are not related to any transport companies. I.e., they are not operated or owned by transport companies (or some related to them). In addition, it is necessary that these platforms are transparent in how collaboration is facilitated and how benefits are shared amongst participants. Finally, they need to be open, i.e., all parties who want to participate, do get easy access. Of course, some quality and anti-fraud checks need to be integrated into them, but they should not limit access to the platform for well-meaning and honest players.

4 Conclusions

Within this work, we briefly discussed the need for fair benefit sharing in the freight transport sector. The presented approach is based on the observation that a distribution of benefits gained through distribution should be shared among the stakeholders proportional to their contribution (i.e., individual costs). This leads to the observation that either collaboration benefits for all participants, or for nobody. The latter will, obviously, result in a non-collaboration approach. It is, however, important to note that the decision whether (or not) collaboration is beneficial, can be made on a per-case level. I.e., for each possible collaboration, a new decision can be made. As this decision making will be time-demanding when manually performed, we propose to utilise transport management platforms. They need, however, to be neutral (i.e., not owned or operated by any company interested in the transports themselves) and open (i.e., anyone who wants to participate is able to do so – as long as the party is well-meaning and no fraud).

It may be argued that (in a future) scenario there will be no need for (complex) benefit sharing algorithms as most of the transport will be organised via concurrent protocol-based cooperations. Although we think that this statement is true, we have two remarks to add. First, we think that benefit sharing will be one component of these future protocol-based cooperations. Second, and most probably more important, we think that a transition towards a future set-up is necessary. And this transition phase will require transparent benefit sharing algorithms, as the freight transport sector currently is marbled by mistrust. We are, however, positive that once the transition phase started on a large scale, very soon the mistrust will change into trust and the anticipated positive impacts will soon take place.

5 Acknowledgements

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Hyperconnected and Autonomous Distribution System for Societally Critical Products

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Abstract: Societally critical products are crucial for maintaining people's well-being and ensuring the continuity of vital societal operations. However, disruptions can severely impact their supply chains due to increased demand and supply chain disruptions. The paper defines the importance of these products and presents a conceptual framework for a hyperconnected and autonomous distribution system that encompasses physical, organizational, information, and operational aspects. We present the results of research at Georgia Tech during the COVID-19 pandemic, which involved designing and operating an innovative system for efficiently distributing personal protection equipment. The study provides the foundation for a systemic approach to distributing societally critical products, integrating autonomous operations and hyperconnectivity based on Physical Internet concepts. The paper also discusses the challenges of large-scale adoption, implementation, and operation of such a distribution system.

Keywords: Physical Internet, Hyperconnected Distribution, Autonomous Operating Systems, Multi-Agent Systems, Societally Critical Products, Personal Protection Equipment

Conference Topic(s): autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms) business models & use cases; logistics and supply networks; Modularization; PI fundamentals and constituents; PI impacts; PI implementation; PI modelling and simulation; machine learning,

Physical Internet Roadmap: ☐ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.

1 Introduction

Societally critical products (SCP) refer to products that are essential to the well-being and functioning of society. The world recently experienced an unprecedented outbreak of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), commonly known as COVID-19, declared a pandemic by the World Health Organization on March 11, 2020. As a result, educational institutions across the United States, ranging from elementary schools to universities, temporarily suspended in-person classes and research activities. Although reopening was widely recognized as important (Panovska et. al, 2020), institutions lacked the strategies to do so safely (Dibner et. al, 2020). The Center for Disease Control (CDC) issued reopening guidelines that included consistent prevention strategies, such as universal and properly fitting masks and physical distancing. As a result, there was a surge in demand for critical supplies such as personal protective equipment (PPE), including gloves, masks, sanitizers, and disinfectants, while the supply was limited due to production constraints. Many organizations and individuals prioritized securing a sufficient stockpile of PPE during the COVID-19 pandemic, with concerns about price or other factors often taking a secondary role.

The COVID-19 pandemic has demonstrated that everyday products we rely on can become SCPs during pandemics and epidemics, underscoring their critical role in safeguarding public health. The ability of regular products to become societally critical products highlights the importance of having a robust and adaptable distribution system that can quickly respond to changing needs and demands during times of crisis. Ensuring that essential goods and services are available and accessible to all can help mitigate the impact of emergencies and build more resilient communities.

In the first part of the paper, we define and stress the importance of societally critical products (SCPs). We present the synthesis of our action research at Georgia Tech during the COVID-19 pandemic on the design, implementation, operation, and continuous improvement of an innovative system for enabling the efficient, seamless, and resilient supply and distribution of personal protection equipment. In the second section, we expand on our research and propose a comprehensive systemic approach for SCP distribution, which combines autonomous operations and hyperconnectivity, in accordance with Physical Internet (PI) principles, extending beyond PPEs. We present a conceptual framework for the hyperconnected and autonomous distribution system for SCPs, concentrating on the physical, organizational, information, and operational layers. Finally, we conclude the paper by highlighting further research, innovation, and field experimentation opportunities, and emphasizing the importance of integrating the supply and distribution of societally critical products seamlessly.

2 Societally Critical Products (SCP)

Essentials are necessary for the population and the economy at large to sustain a satisfactory quality of life and work, including ensuring supply chain continuity, given the circumstances. Essentials cover a broader spectrum of products than societally critical products (SCP). Essential products, which include food, consumables, and non-pharmaceutical medicine, can become societally critical products in certain situations, such as during natural disasters or other emergency situations where supply chain disruptions can have significant consequences on society. Demand for SCPs can also change rapidly depending on the circumstances, and ensuring their availability is crucial for maintaining societal stability and well-being.

Given the lack of a clear definition of key attributes for SCPs in existing literature, we propose a set of defining characteristics (Figure 1) as a novel contribution to the field:

1. Essentiality: SCPs are products or materials that are indispensable for human survival, health, or safety. They are critical for meeting basic needs such as food, water, shelter, sanitation, and healthcare and ensuring social and economic stability.
2. High Demand: SCPs are prone to experience a surge in demand during situations such as emergencies, crises disasters, and pandemics.
3. Limited Availability: SCPs may have limited availability due to various factors such as supply chain disruptions, production constraints, or transportation difficulties. This can lead to shortages and competition for these products, notably resulting in price hikes or rationing.
4. Equitable Distribution: SCPs must be distributed equitably and made accessible to everyone who needs them, especially vulnerable populations such as the elderly, children, and those with disabilities or chronic illnesses. This requires cooperation and coordination between various stakeholders, including governments, NGOs, and the private sector.
5. Time-Sensitive: SCPs must be delivered in a timely manner to be effective. Delayed or inadequate delivery of SCPs can have serious consequences for public health and safety.
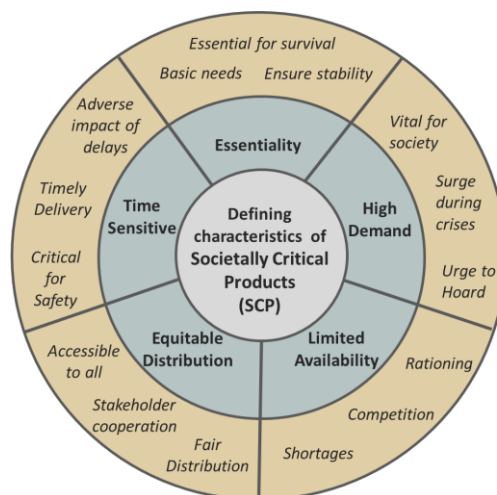
Figure 1: Characteristics of Societally Critical Products (SCP)

SCPs become even more important during a pandemic as their demand surges and their supply chain ecosystem may be disrupted. The scarcity of SCPs can lead to panic, hoarding, and a lack of access to the products for those who need them the most. The sudden surge in demand for these common products during the COVID-19 pandemic highlighted their critical importance in protecting individuals and preventing the further spread of the virus. For example, face masks, hand sanitizers, and cleaning products became SCPs essential to public health and safety. Without these products, the pandemic could have been much worse. Similarly, during outbreaks of other contagious diseases, regular products like disinfectants, tissues, and personal protective equipment also become SCPs crucial to limit the spread of the disease.

In times of scarcity or crisis, it may be necessary to ration these products to ensure that they are distributed fairly and equitably among the population. Rationing is the process of limiting the distribution of a product or service to a specific amount or group of people. Rationing societally critical products can ensure fair access, manage demand during scarcity, and prioritize distribution to those in need. It prevents hoarding and panic buying, ensuring an even distribution of the available supply. Rationing may become necessary to ensure that essential goods and services are available to everyone.

In summary, SCPs are products or materials necessary for meeting basic needs and maintaining social and economic stability during emergencies, disasters, or crises. Their essentiality, high demand, limited availability, equitable distribution, and time-sensitivity make them unique in terms of their importance and the challenges associated with ensuring their availability and distribution during times of crisis or emergency. Regular products may not have these distinctive features or may not be as crucial for maintaining societal stability and well-being.

3   Living Lab Initiative

Before the COVID-19 pandemic, Georgia Tech (GT) used a decentralized model for sourcing and replenishing PPEs and cleaning supplies, with each department managing its own stock and re-ordering as deemed pertinent. However, during the pandemic, this model proved to be inefficient and risky due to supply scarcity, uncertainty, and a lack of preparedness among lab teams to manage decisional complexity. In response, GT's Supply Chain & Logistics Institute implemented a hyperconnected supply chain and distribution system that leveraged a distributed network of software agents capable of autonomous prediction and decision-making, along with human-centric operations that relied on users for consumption information. The system successfully served researchers in over 200 labs across 40 buildings on campus throughout the pandemic, managing the distribution of massive quantities of PPEs, including 450,000 units of

gloves across sizes and types and 200,000 units of disposable masks, without any significant stockouts or urgent requests for several months.

Drawing insights from the living lab initiative, the initial model for sourcing PPEs and cleaning supplies was revised and enhanced by integrating state-of-the-art advancements in supply chain management and engineering, such as autonomous prediction and decision-making mechanisms. The resultant generic conceptual model, characterized by its scalability, extends beyond PPE applications and is adaptable to various domains and industries, offering a structured approach to enhancing SCP inventory management and distribution processes. This model achieves efficiency through the implementation of cutting-edge technology and minimizes the reliance on human-centric operational procedures.

4 Conceptual Framework of the Proposed System

Our proposed concept envisions a fully automated and interconnected network of systems that can efficiently and effectively distribute essential goods and services to people and communities around the world. This section describes the framework focusing on the physical, organizational, information, and operational layers. Each layer plays a critical role in creating a seamless and efficient operating system that can respond quickly and effectively to changes in the business environment.

4.1 Physical Layer

We propose a topological multi-tier physical network structure, where physical nodes represent the facilities that are active in the system. The physical nodes are organized into tiers based on their location and function. At the lowest tier, there are tier-0 physical nodes, which are locations of specific active users or small groups of users who consume critical products. These nodes could be workstations of researchers, medical professionals, or employees in a manufacturing facility who require specific products to carry out their work. Next are the tier-1 physical nodes which correspond to facilities that include several tier-0 nodes and/or include a product depot. These nodes are larger than tier-0 nodes and serve as hubs for the distribution of critical products within a specific area, mostly within a building. Examples of locations for tier-1 nodes include healthcare centers, research centers, and manufacturing centers.

Tier-2 nodes correspond to buildings that host a set of tier-1 physical nodes. These buildings could be distribution centers, warehouses, or logistical hubs that manage the distribution of critical products on a larger scale. Tier-3 nodes correspond to a space grouping a set of tier-2 nodes. These could be large warehousing complexes, industrial parks, or campuses. Higher-tier nodes can be defined at local, regional, country, continent, and planetary tiers. Physical flows of products between physical nodes result from the organizational and decisional layers defined in the system. This topological multi-tier physical network structure enables the system to run autonomously and adapt to changing circumstances in real-time.

The physical layer also embodies the physical realization of the logical paths between nodes. This model assumes that the lead time of transportation between nodes can be approximated. We form the inter-relationships of the components in the physical layer in the organizational, information, and operational layers.

4.2 Organizational Layer

The organizational layer of the distribution system establishes a network of functional nodes, each with specific responsibilities. This system is designed to operate autonomously and adapt to changing circumstances in real-time. The system comprises multiple tiers of functional nodes, all hosted within physical nodes. The number of tiers in an actual distribution system may vary

according to context and requirements, and the following model based on five-tier network serves as a conceptual example:

- End Users (Tier-0 Functional Nodes): As the final consumers in the system, end users may maintain a small autonomy stock for uninterrupted workflow.
- Nano-Fulfillment Centers (Nano-FCs, Tier-1 Functional Nodes): Situated near end users, these centers provide direct services and maintain an autonomy stock, continually restocking from the subsequent tier.
- Micro-Distribution Centers (Micro-DCs, Tier-2 Functional Nodes): These centers are responsible for autonomy stock maintenance and nano-fulfillment center replenishment. Each group of Tier-0 nodes is served by a single Micro-DC and its corresponding physical node.
- Distribution Center (DC, Tier-3 Functional Nodes): Tasked with aggregating and distributing resources to micro-DCs, the distribution center manages supplies between tiers and upholds an autonomy stock for smooth network operation.
- Supply Center (Tier-4 Functional Nodes): This center sources and procures materials from external suppliers, replenishing the DC while maintaining its own autonomy stock.

In this system, functional nodes are housed within physical nodes—actual locations where distribution functions occur. Each functional node exists within a physical node, with tier-0 functional nodes occupying one or more tier-0 physical nodes. Meanwhile, functional nodes within tiers 1 through 4 are situated in corresponding physical nodes. Each unit that houses tier-0 nodes is assigned a singular tier-1 functional node (Nano-FC) and its corresponding physical node. In essence, Nano-FCs operate as small-scale fulfillment centers, serving end users directly, whereas Micro-Distribution Centers cater to the Nano-Fulfillment Centers.
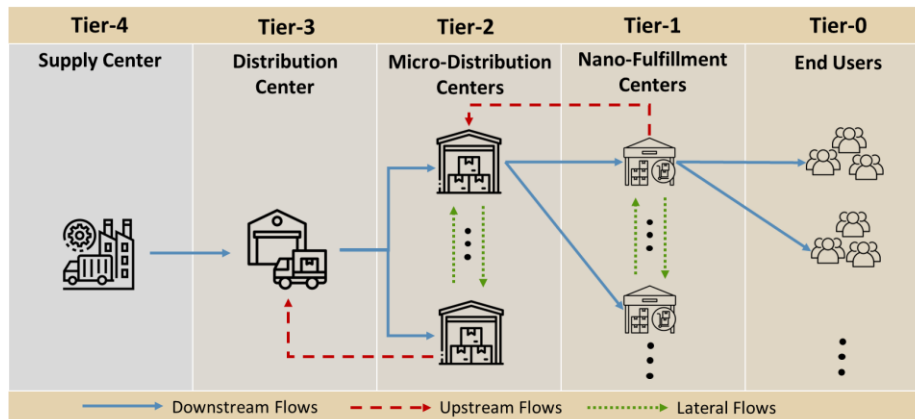

Figure 2: Typical flows within and across functional nodes

The distribution system's organizational layer combines functional and physical nodes to create an adaptive and efficient network that can respond to real-time changes. Each tier contributes to maintaining a continuous supply and distribution flow and fulfilling the end users' needs. The actual number of tiers in a distribution system will depend on various factors, and the distribution network can be designed to accommodate specific requirements.

In a multi-tier distribution network organization, the primary flow of products and resources is typically downstream, from higher to lower tiers. However, under certain circumstances, lateral and upstream flows may also be allowed to optimize the network's efficiency and adapt to changing requirements (Figure 2). Lateral flows facilitate redistribution within a functional tier, while upstream flows enable the retrieval of stock from lower tiers. Such flows may be necessary if a node no longer requires specific items or if a node is scheduled for closure.

4.3   Information Layer

Our proposed multi-tier shared distribution system relies on sharing resources and information across supply chain levels. Emphasizing information sharing, the proposed architecture aims to coordinate across and within tiers. Collection and analysis of user consumption data and resource burn rate are for example key to maintaining efficient inventory levels and resource availability.

Innovative methods for seamless data collection and user confidentiality include electronic key card systems, which offer secure, contactless access. These systems use encrypted communication to prevent unauthorized access and can be configured for different user access levels. Data from key card usage aids in pattern identification, resource allocation, and security improvements. The system also utilizes smart dispensers to track consumption and enable resource distribution. These dispensers feature remote monitoring, adjustable configurations, and automated inventory management. User authentication integration helps manage resource allocation and minimize waste.

Smart lockers, as proposed by Faugere (2017), provide an efficient way to record usage of critical products while minimizing contact and potential contamination. Critical product containers can be exchanged without physical contact, reducing the points of contact and potential contamination. The smart locker system tracks usage and provides data for efficient inventory management and allocation. Dynamic vision sensors using Time-of-Flight (ToF) technology collect accurate, real-time resource usage data in common areas. By analyzing depth information, ToF sensors inform restocking decisions, while gesture recognition capabilities yield deeper consumption pattern insights. These sensors can be combined with infrared or thermal sensors for comprehensive environmental and resource usage understanding.

Integrating advanced technologies and traditional practices offers comprehensive distribution network visibility and traceability. Balancing information sharing with sensitive data protection is crucial, requiring clear data access protocols, robust database security measures, and stakeholder awareness of proprietary information safeguarding responsibilities. This multi-faceted approach ensures a seamless, secure, and efficient multi-tier shared distribution network.

4.4   Decisional Layer

The decisional layer is a crucial aspect of the proposed multi-tier distribution network. It employs advanced decision-making technologies and processes, including predictive analytics, machine learning, and simulation modeling. These tools facilitate real-time decision-making in response to shifting dynamics in the economic environment, ensuring efficient inventory management and distribution.

Our model is demand-driven and encompasses several tiers of functional nodes, as well as a supply layer connecting suppliers to the primary supply center. The usage log of each user is employed to update demand forecasting models, enabling accurate consumption predictions for each location. Periodic evaluations of inventory levels against the forecast are conducted to determine the robust-days-of-inventory, a metric that accounts for both current stock and consumption rates. When inventory levels drop below a predefined threshold, it triggers inventory replenishment and re-ordering from suppliers at the supply center level. The decisional layer also accounts for uncertainty in lead time when placing orders with suppliers, ensuring that the distribution network remains responsive to fluctuations in demand and supply conditions. In the following subsections, we describe the various facets of the decisional layer. These components' technical details and models are published in independent research articles.
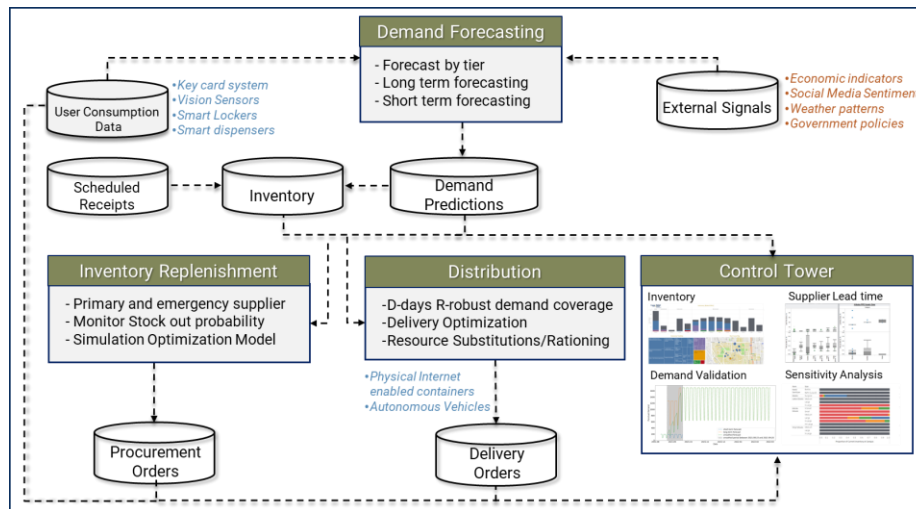
Figure 3: Conceptual Framework of the Decisional Layer of the Proposed Model

4.4.1 Demand Forecasting

The dynamic and adaptive data-driven model used for demand prediction in the lowest tier of the distribution network ensures accurate forecasting of critical items' requirements as formulated in Yim et al. (2021). Long-term and short-term decision forecasting for critical products involves leveraging user resource burn rate data to create accurate predictions of future demand, ensuring that adequate supplies are available when needed. Both forecasting methods are essential for keeping efficient inventory levels and facilitating effective decision-making within the distribution network.

Short-term decision forecasting focuses on predicting demand for critical products over a relatively brief period, such as days or weeks. This forecasting method is crucial for addressing immediate needs and ensuring that resources are readily available for users. Short-term forecasting employs user resource burn rate data and other real-time variables, such as seasonal fluctuations or sudden changes in consumption patterns, to generate accurate predictions. This information is vital for making quick adjustments to inventory management and replenishment strategies to maintain optimal stock levels and avoid shortages.

Long-term decision forecasting aims to predict demand for critical products over more extended periods, such as months or years. This method is essential for strategic planning, as it enables organizations to anticipate future requirements and make informed decisions regarding procurement, capacity planning, and infrastructure development. Long-term forecasting utilizes historical user resource burn rate data, as well as external factors such as market trends, economic indicators, and regulatory changes, to create projections of future demand. This information is critical for making informed long-term decisions regarding resource allocation, supplier contracts, and investment in distribution infrastructure.

External signals must also be incorporated into the data-driven model used for demand prediction of critical items. External signals stem from any data sources outside the organization that can provide valuable insights into the factors that impact demand. Incorporating external signals, such as market trends, economic indicators, government policies, social media sentiment, and weather patterns, into the forecasting model can improve the accuracy of demand predictions. External signals such as government mandates requiring everyone to wear masks in public places, and lockdowns or social distancing measures, can significantly impact demand for critical consumables like masks, food, cleaning supplies, and medical equipment; and social media sentiment analysis can also provide insights into potential surges in demand for products like medical supplies, cleaning products, or non-perishable foods.

By incorporating both short-term and long-term decision forecasting methods, along with the external signals, organizations can effectively manage inventory levels for critical products and adapt to changing demand patterns. This approach ensures that resources are available when needed while minimizing excess inventory and associated costs. Ultimately, this proactive strategy helps to create a more resilient and efficient distribution network for critical products.

4.4.2 Inventory Replenishment

Managing the inventory replenishment process for critical consumables is a complex task. Several challenges arise, including increased demand uncertainty, deteriorating supply capacity, fluctuating prices, extended lead times, and the impact of product unavailability on the functioning of facilities. Addressing these challenges, we develop a simulation-optimization-based inventory replenishment algorithm for the primary distribution node, which serves as the main source for inventory distribution to all downstream nodes. This algorithm leverages demand forecast to determine optimal replenishment strategies for both regular and emergency suppliers.

Regular suppliers replenish inventory through a low-cost but slower transportation mode, resulting in longer and variable lead times. The primary distribution node periodically reviews the stock levels and places orders with the regular supplier based on the demand forecast. However, this may result in occasional delays in delivery due to unforeseen circumstances or supply chain disruptions. In these situations, the primary distribution node relies on emergency suppliers that provide expedited shipments through a faster, albeit more expensive, transportation mode. This emergency supplier contribute toward ensuring the availability of critical consumables, even when regular supplier orders face delays. Due to the higher procurement costs and varying shipment frequencies, it is essential to establish separate review periods for regular and emergency orders.

Leveraging both regular and emergency suppliers enables the primary distribution node to maintain adequate inventory levels while minimizing procurement costs and lead times. This approach ensures continuous availability of critical consumables, promoting efficient facility operations during challenging times.

4.4.3 Distribution System Design

The proposed distribution strategy sheds away from the conventional approach in which individual units within a network are solely responsible for procuring critical resources. In the proposed novel approach, individual entities no longer need to place orders for essential resources as long as the number of active users, resource consumption, and inventory are known. This necessitates the conceptualization and implementation of a seamless, quasi-autonomous, demand-driven resource distribution system, incorporating decision-making algorithms and live connections to demand and inventory databases and stakeholders.

4.4.3.1 Targeted T-R Autonomy and Inventory Optimization

In our suggested approach, each node in the network maintains a targeted T-R autonomy, corresponding to T-time R-robust demand coverage. This implies that the strategy aims to have sufficient stock in each node to cover realized demand with at least an R% probability over the next T time periods, For example, target autonomy may be T= 3 days at R= 99%. In a higher-tier functional node, the targeted stock takes into account both the inventory within that specific node and the inventory in each subordinate functional node it serves.

The system triggers a series of delivery tickets across various nodes to periodically adjust inventory levels to reach the T-R autonomy target, given current inventory status and demand predictions. Consequently, most of the time, personnel within the network do not need to reorder

resources. The system accommodates special orders in cases of significant staffing level changes or events that drastically reduce on-hand inventory. The T-R targets are regularly updated to adapt to current system state and projections.

While maintaining high inventories at each node may seem like an easy solution to ensuring high availability, it is inefficient and does not encourage careful resource usage during times of supply scarcity and supply/demand uncertainty. Instead, the system and its underlying algorithms manage supply uncertainty and scarcity at the main inventory level, maintain lean inventory at distribution nodes, ensure adequate autonomy without promoting hoarding behavior, and facilitate efficient resource delivery.

4.4.3.2 Distribution Planning, Execution, and Resource Substitution

Distribution planning algorithms optimize lean inventory autonomy levels in smaller and larger units, postponing the dedication of shared resources to maintain high responsiveness to unforeseen changes and minimize the overall network-wide inventory necessary for smooth distribution and continuous availability. Distribution execution algorithms optimize delivery timings across the network, employing smart routing and vehicle/cart loading to minimize overall delivery efforts. These algorithms generate delivery tickets for distributors to replenish units within the network.

We propose the implementation of smart dispensers and lockers as a key part of the distribution strategy. These technologies offer several benefits, including precise consumption monitoring and control, access restrictions per user, and limitations by units and time (Phade et al., 2021) (Zainudin et al, 2022). They allow for splitting stock-keeping units (SKUs) into smaller portions, streamlining distribution and improving consumption monitoring. For example, a box of 100 face masks can be split into individual masks or smaller packs, enabling better resource allocation and more accurate usage tracking, which facilitates distribution and ensures precise consumption monitoring and control. Smart lockers can be customized with security measures like biometric authentication and environmental sensors for optimal storage conditions. Smart lockers also integrate with the larger network, providing inventory level updates and usage pattern notifications.

Handling critical resources involves managing the scarcity of commodities. In addition to rationing techniques that limit the number of items accessible to each user, it is essential to have substitution protocols for scarce products. These protocols allow for the reassignment of resource usage based on product preference and availability, ensuring that the distribution network can continue functioning efficiently even in times of resource scarcity.

4.4.3.3 Physical Internet-Enabled Containers and Autonomous Vehicle Integration

In our distribution strategy, we propose using Physical Internet-enabled modular containers (Montreuil et al., 2015) to store and transport critical products. These containers protect the encapsulated products and enable smart, reliable, and efficient tracking, such as RFID on containers (Jiang et al., 2021). Real-time traceability of containers provides visibility of the location of assets at any given time. For critical products, close tracking of inventory is essential due to the higher risk of pilferage and unauthorized use. Furthermore, the proposed modular containers have composition-decomposition and interlocking properties, which protect the constituents of the container, making it difficult to access compared to a box on a pallet.

During critical and urgent situations, workforce and physical resources supply may decrease due to factors such as work absenteeism or planned capacity reductions to protect labor force and public health. To address this constraint, we propose leveraging a degree of vehicle autonomy. With a strong startup ecosystem in the robotics space (e.g., Starship robots, Nuro, and KiwiBots)

and evolving legislation, these technologies present robust opportunities to automate the distribution system with minimal human intervention. This approach may reduce the margin of error, resulting in fast and accurate deliveries and 24/7 availability.

In scenarios such as pandemics, deploying autonomous shuttles can strengthen infection prevention and control by significantly reducing social contact while simultaneously saving time and effort. Combined with Physical Internet-based modular containers, seamless distribution can be achieved using π-totes that can be interconnected with or placed inside sidewalk delivery robots. Fleets of automated delivery robots and drones already provide service worldwide on a small scale, with battery capacity and flight regulations typically restricting the service radius. However, the continuous operational availability of these technologies offers advantages over human-centric operations.

4.4.4 Control Tower

We propose the implementation of advanced shared control towers as a strategic component, providing real-time visibility and fostering collaboration among all stakeholders. The control tower serves as a unified information source, facilitating trust and collaborative efforts across enterprises. Consequently, supply chain participants can achieve objectives, such as cost reduction and service improvement, beyond the capabilities of individual entities. Enhanced supply network visibility and transparency reinforce trust in the system and enable stakeholders to capitalize on numerous benefits. Furthermore, a supply chain informed by timely and accurate data optimizes overall operations and mitigates the risk of disruption.

The proposed control tower design aims to deliver comprehensive end-to-end visibility throughout the supply chain while maintaining a central dashboard displaying key metrics of the overarching system and network. The dashboard assists in identifying and addressing issues while refining decisions. The control tower affords direct insight into inbound and outbound orders at each tier node, along with delivery notifications confirming order receipt. Moreover, it offers real-time intelligence for managing inventory, including insights into imbalances, shortages, and stock-outs. Monitoring supplier lead time and on-time delivery of supplies within the control tower is also essential. Finally, the dashboard facilitates comparison between forecasts and actual consumption, aiding in the ongoing evaluation and improvement of forecasting algorithms.

5 Conclusion

This paper has introduced a definition of societally critical products and has presented a comprehensive conceptual and analytical framework, elaborating on underlying principles, components, and relationships. It has then introduced a conceptual framework for a hyperconnected and autonomous distribution system for these critical products. These frameworks form the foundation for future research, development, and implementation, enabling the exploration of potential benefits, limitations, and opportunities for improvements.

The large-scale adoption of the proposed distribution system for critical products presents several challenges, offering opportunities for future research and innovation. Key areas to explore include technological integration and interoperability, data privacy and security, and regulatory compliance. Potential research directions could involve the development of advanced simulation models to assess the feasibility and performance of transitioning from human-centric to autonomous operations, accounting for the dynamic interplay of human behavior. Additionally, executing further pilot studies to evaluate the proposed system's viability and performance, as well as investigating the system's resilience to both simulated and real-world disruptions, represent significant and relevant research avenues.

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Automated high-speed Hyperloop cargo transportation for a sustainable logistics network

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Abstract:

Hyperloop cargo transportation in an evolving Physical Internet does have the potential to contribute major advances in sustainable, high-speed freight transport. The low-pressure tube transport (LPTT) solution realistically enables a viable zero-emission high-speed transport system to come to market quickly with rather low levels of investment in infrastructure. Switching and merging technologies for cargo pods are the key to a LPTT network, providing much greater flexibility for the TEN-T network. The integration into intermodal cross-docking hubs including the use of standardized transport units and synchromodal algorithms predicting and distributing transport flows is a key characteristic for the success of the implementation of new and more environmentally friendly transport modes to the Physical Internet. Modelling and simulation as well as Life-cycle performance assessment for an industrial use case supplying an ingrown industrial area in an urban environment highlights the benefits of a LPTT connection between an ePI node and an automotive plant.

Keywords: Hyperloop, Low-Pressure Tube Transport, cross-docking, DES, modelling, LCPA, automation, tube network

Conference Topic(s): autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms); business models & use cases; manufacturing networks; PI impacts; vehicles and transshipment technologies

Physical Internet Roadmap (Link): ⊠ PI Nodes, ⊠ PI Networks, ⊠ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.

1 Introduction

Today's logistics is one of the major contributing sectors to greenhouse gas (GHG) emissions in the European Union. Electrification will reduce pollutants such as NO_x and direct CO_2 emissions, but cannot cut down noise and light emissions as well as particle emissions produced through e.g. tire wear. Additionally, the energy demand and thus pollutant emission will increase with the projected increase in transport demand which is estimated to be up to 300% by 2050 (IFT, 2019). The last decades have shown that the demand for faster transportation of

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goods across the globe has increased significantly and thereby caused correspondingly higher energy consumption. While new powertrain generations could improve direct emissions and efficiencies, they cannot eliminate aerodynamic losses or lower the underlying energy demand of movement.

LPTT technologies such as Hyperloop and CargoTube tackle the problem at its root by operating in a reduced pressure environment within a tube to drastically reduce air resistance and thus energy consumption. By operating at a pressure of only about 1% to 0.1% of normal atmospheric pressure, losses can be reduced by 90%. (cf. Oh et al., 2019, Zhou et al., 2022). CargoTube offers a unique advantage by introducing innovation to the Hyperloop approach and providing an intermodal combination with existing transportation technologies to be rapidly deployed.

The assessed use case in production logistics evaluates the CargoTube connection of two main Physical Internet Nodes (ePI nodes) - a production plant and a Logistics Service Park (LSP). This will greatly improve the congested road infrastructure in the city, which is currently in use to deliver required cargo via trucks to the industrial plant. Additionally, the new LSP ePI node and CargoTube branch of the network shall introduce multiple benefits, commonly observed with the Physical Internet approach such as re-batching along with last mile just-in-time delivery. This avoids only partially loaded trucks, as can often be the case in production logistics due to specific deadlines. The economic and environmental impacts are evaluated through discrete event simulation (Duin et.al., 2023) and Life Cycle Performance Assessment (LCPA).

2   The CargoTube Technology

The CargoTube LPTT transport solution not only brings in new Hyperloop technology such as the introduction of a low-pressure tube environment and a linear motor but combines these innovations with established technologies such as the wheel-rail interface. Velocities between 100 km/h and 200 km/h are the design target for system operation, tuned to the demand curve in production. CargoTube complements emerging Hyperloop standards and has the advantage of quick deployment without requiring further research into levitation or propulsion technologies, which would only be necessary at higher speeds.
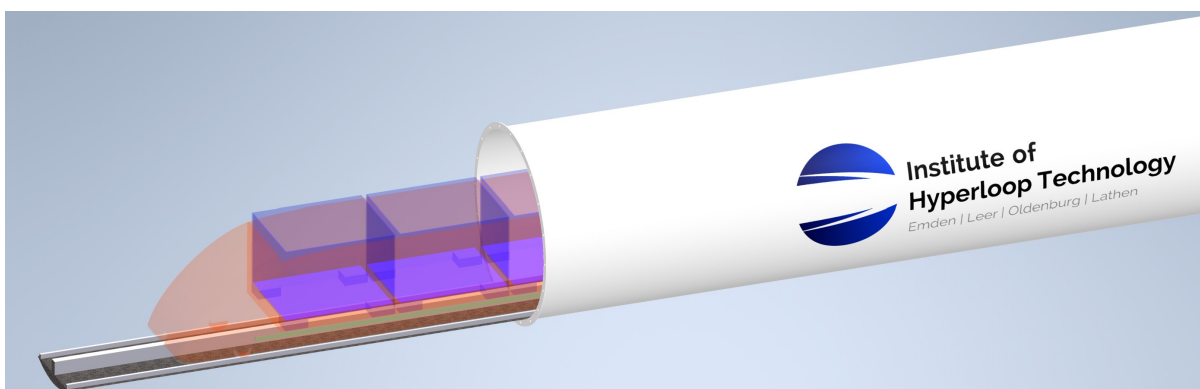

Figure 1: Basic principle of CargoTube: Design sketch using a wheel-rail system with linear motor for acceleration and recuperation for a vehicle with several standardized transport boxes

Figure 1 shows the automated vehicle (pod) inside the tube environment, which can hold up to 10 standardized transport boxes of approximately (1x1x1) m^3 volume each. The system is designed to connect the two ePI nodes completely autonomously. In combination with packing robots in the LSP and an automated loading and unloading process, this connection of two ePI nodes is capable of 24/7 operation. High frequencies resulting in a high capacity means of

transport in the smallest possible space are at the heart of CargoTube. Finally, limitations only arise from safety distance considerations and emergency scenarios.

Airlocks are used to transfer the pods from normal atmospheric to low-level pressure levels. Ongoing research aims at advanced airlock designs such as a combination of the pod with the airlock. With this approach, there is no necessity of bringing the complete vehicle out of the low-pressure environment, which can substantially reduce cycle times while simultaneously minimizing wear and extending the lifetime of the vehicle.

The system is optimized and adapted for the respective intermodal connections with regard to Key Performance Indicators (KPI) concerning the environment and transport requirements. Digital Twin Technology is employed and a test facility is under construction at the Campus of the University of Applied Sciences Emden/Leer to generate physical data sets necessary to evaluate simulations and modelling approaches presented in this paper. (Neu et al., 2023)

3 CargoTube Production Logistics use case

While cities and urban areas are growing, industrial sites and production plants formerly located at the outskirts of the cities are nowadays embedded in the growing cities thus sharing the infrastructure network for both, residential and industrial cargo traffic (cf. Figure 2). This poses a major challenge for the constant flow of production supplies in the new Physical Internet and requires solutions to provide sufficient transport capacity for both simultaneously.

Figure 2: Illustration of a shared residential and commercial urban region with an industrial hub in a larger metropolitan area such as the VW automotive plant inside of Wolfsburg, Germany (Google 2022)

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Figure 2 is an aerial view of the city of Wolfsburg encompassing the Volkswagen (VW) plant. The automotive plant is supplied by more than a thousand trucks daily according to data from autumn 2022. These trucks, which are on the road in addition to the normal volume of traffic, regularly encounter major traffic jams on the highways, while the entry and unloading of trucks at VW's internal freight hubs are subject to tight schedules. In addition, there are many citizens' groups complaining about pollutant emissions affecting air quality, as well as noise and light pollution at night. A stakeholder and requirements analysis for the Wolfsburg plant's major logistics center revealed the importance of small footprints of logistics areas which are currently competing with the limited capacity of production areas.

A LSP is being considered to consolidate inbound goods and reduce delays and turnaround times of inbound trucks, increasing individual truck productivity and saving valuable driver time. In addition, a more consistent and reliable supply of goods will be realized for the plant, which has proven to be a bottleneck during the recent parts shortage in the automotive industry. Transport of standardized boxes from the LSP to the VW plant can best be realized with a CargoTube connection, which allows for a significant reduction of direct emissions (e.g., GHG, noise, light and particulate emissions) within the city and relieves the burden on local residents. The system is designed for s certain type of standardized box that is used for a majority (approx. 80%) of inbound logistics. One logistics hall is taking delivery of around 10.000 standardized boxes a day, which is the target for the CargoTube simulations. Any freight outside of these dimensions is not considered in this use case. CargoTube can operate around the clock as a highly reliable transport system that delivers goods to the production site while minimizing the space required for storage, logistics or truck parking at the production plant. An additional feature in a LSP is the temporary storage or buffering capacity of sparce goods in the combined CargoTube LSP-facility. This enhances resilience to supply chains disruptions that otherwise lead to sudden parts shortages and costly production shutdowns.

4   Logistic Service Park integration

The integration and implementation of a CargoTube handling system also requires a focus on processes carried out by logistics service providers. A LSP has a secured gated area to handle and control inbound and outbound traffic that is either road or possibly rail. The fenced area (approximately 30,000 square meters) has an ideal rectangular shape to ensure optimal use of the functionality of the LSP, which combines several logistical functions. These include e.g., truck parking lots, trailer yards, empty container storage, control points, and last but not least a Cross-docking (CD) logistics system attached directly to the CargoTube station. Cross-docking is an almost inventory-less distribution process in which shipments (if possible) are no longer (temporarily) stored. The LSP with integrated CD hall has various spatially separated loading/unloading points for inbound and outbound logistics processes and crossdocks in covered hall areas called unloading tunnels, which are used specifically for unloading megatrailers (cf. Figure 3).

The shipments can usually be unloaded from the trucks using industrial trucks/floor conveyors and transported directly to the relation areas (corresponding to the individual unloading points in the production plant). CD is usually executed with little or no storage, so that no further steps are necessary between the automated unloading / loading of trucks and pods. Nevertheless, an automated high bay storage can be added if necessary or advantageous to the supply chain. Subsequently they are loaded into pods at precisely the right cycle. In principle, this process bears the possibility to be partially carried out in an automated manner, especially if the pods are on the same ground level in the CD hall. The essence of the cross-docking approach is that shipments have already been pre-picked by the suppliers. To handle deliveries which are either

not or incorrectly pre-picked, CD systems have so-called "clearing" areas on the outskirts of the hall. To ensure a permanent supply to the production plant, it is also advisable to set up a "buffer area" in the middle of the hall, which serves as a short interim storage or "reserve".
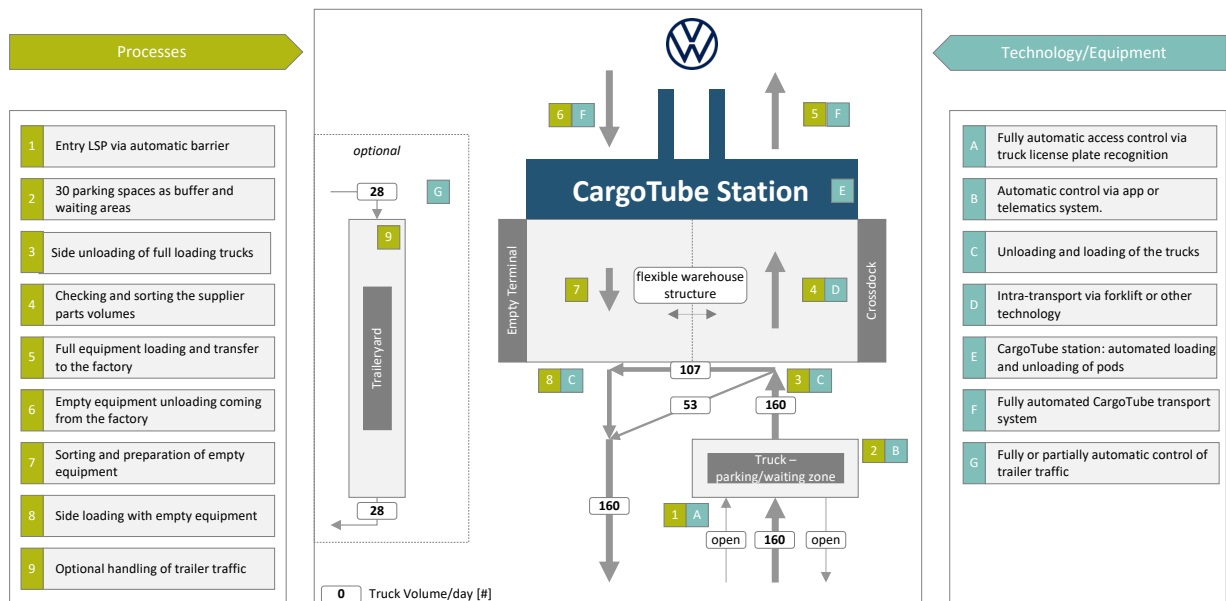

Figure 3: Integration of Hyperloop into a combined CargoTube LSP facility with illustration of the process-oriented steps (left column) and listing of the technological implementations (right column)

Shipments can then be delivered from the relation areas (exit areas) to the plant by the CargoTube system. Another functional area of the LSP includes a trailer yard used for any larger freight transports that cannot be fitted in the standardized box. These therefore cannot be transported with pods and will be transported from the LSP facility to the production plant via megatrailers with high utilization through consolidation processes at the LSP. Very large freight that is transported with other means than trucks such as railways or ships is not addressed in this process. A further area for handling the various smaller VW transport containers and returning empty boxes from the production plant is very important as well. Unloading of the trucks and/or pods at the plant then depends on the internal logistics processes. Spatially separate unloading zones for trucks and pods could play a role here.

5 Modelling and Simulation - Performance Assessment

CargoTube case: The questions to be answered by the simulation relate to the comparison of the Hyperloop transportation link with traditional approaches for a specific set of KPIs and the analysis of effectiveness. A discrete simulation model is created using the JaamSim simulation system (King and Harrison, 2013). Figure 4 shows the basic layout for that simulation model. The central elements are the two tubes that connect the LSP bidirectionally to the production plant. On each side there are six bays which can be switched on and off individually (e.g., for simulating maintenance). In each of the bays the single pods are cycling through a process of waiting (when the bay is in use), repressuring, unloading and/or loading, and evacuation. When the process in a bay is finished the pod is sent into the tube keeping a safety distance of 1,000 m to the previous pod. The handling process on the side of the production plant is the same with the exception that empty boxes are loaded to be sent back.

Initial simulations employing that model reveal the following results:

- The whole system is capable of transporting more than 16,000 boxes from the LSP to plant using six bays on each side and running fully loaded (no waiting times).
- The maximum number of pods in the system fully loaded is 33.
- With only five bays in operation on each side, the system is still capable of handling more than 13,600 boxes per day at full capacity.
- With only four bays in operation on each side, the system is capable of handling more than 10,900 boxes per day at full capacity.
- With a specific demand curve, where the demand of the plant is not equally distributed throughout the day (typically with peaks around noon and lower demand during the night), there are a few waiting times which do not last longer than 60 minutes.
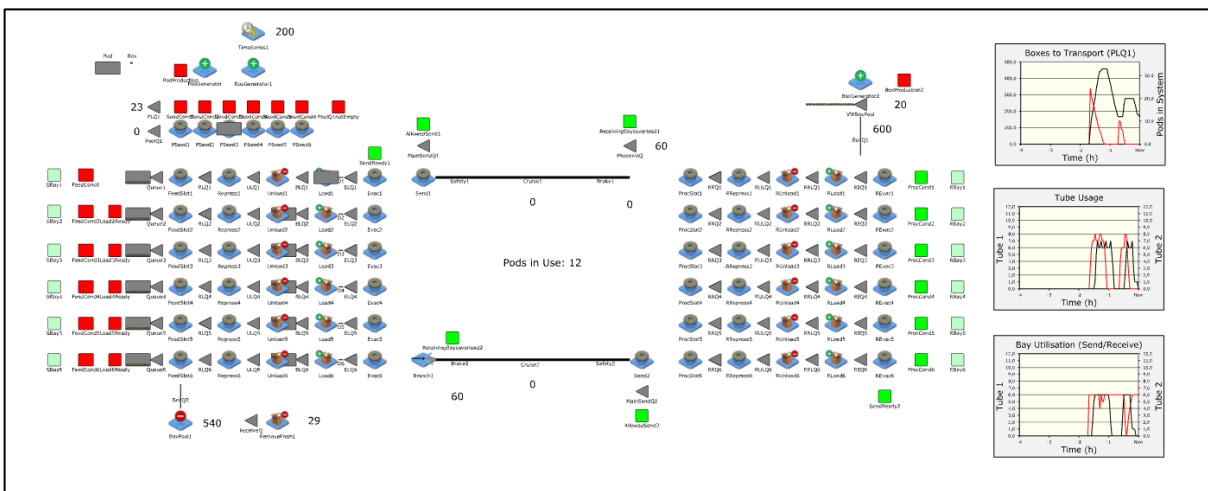

Figure 4: Simulation sketch visualizing the Integration of Hyperloop in a LSP

Truck case: Since truck electrification is widely discussed, the paper also includes simulations comparing conventional diesel and potential electric trucks. However, this does not reduce certain environmental impacts or nullify air friction losses. Using a universal model created on the basis of AnyLogic simulation software (Borshchev, 2013), various scenarios with both diesel and electric trucks are studied and modeled. 135 standard truck units are needed to transport cargo from the LSP to the VW production plant. This number decreases to 108 when using consolidated cargo on mega trailers, which are not electrified yet. In the developed simulation model, indicators of the transportation process are estimated. An analytical spreadsheet model is developed for preliminary calculations.

The main conclusion is that, assuming it is possible to charge several times per day, it would be most effective to use electric trucks with customized small battery packs of rather low capacity and thus low weight in combination with wireless charging technology. The use of the most advanced wireless charging technology eliminates time-consuming pre- and post-processing, i.e., the typical plugging and unplugging of charging cables.

6 Life cycle assessment

In addition to the positive environmental aspects, cost efficiency or simply a quick return on investment (RoI) of a CargoTube system is of immense importance. For the assessment of the financial and environmental impacts of the CargoTube connection, a LCPA is performed. The analysis focuses on a subset of the available KPIs. Financial aspects are mainly covered by CAPEX, OPEX and NPV, while the environmental impact is represented by the GWP (Global Warming Potential), measured as a CO2 equivalent.

Three scenarios are compared: The use of diesel trucks shuttling cargo from the LSP to the industrial plant is the current method of performing the transport task. An innovative CargoTube connection will be compared against this baseline scenario in order to calculate the differences in financial and environmental impact. However, since the realization of a CargoTube prototype will most probably take several years, battery electric trucks will be considered as a third scenario as current developments show that a widespread use of these vehicles might become the baseline scenario by the time the LSP will be built. For a more detailed analysis, a combination of both truck scenarios might be considered as well.

Relying on the Basic Data Calculations some key results are highlighted for the LCPA. For the setup of one tube for each direction of the approximately 10 km distance, the current material choice results in approx. 14,000 tons of steel and 11,000 tons of concrete, which are making up the primary emission expenditure during construction. Pod and infrastructure costs are estimated to sum up to approximately 51 million € in 2022. On the other hand, it is assumed that for the same transport task, 25 trucks are needed with a monthly leasing rate of 2,100€ (diesel) and 4,200€ (EV). While the setup of new infrastructure of CargoTube is included in the calculations, only the maintenance of roads is considered, not the construction of new roads itself, which estimates to be 50 million € for one lane of 10km (Hahn and Hoppe, 2022; Fritz et al., 2022). The graph in Figure 5 shows the costs over net present value and operating costs, while Figure 6 shows the lifetime emissions (carbon dioxide equivalent) for the three scenarios.
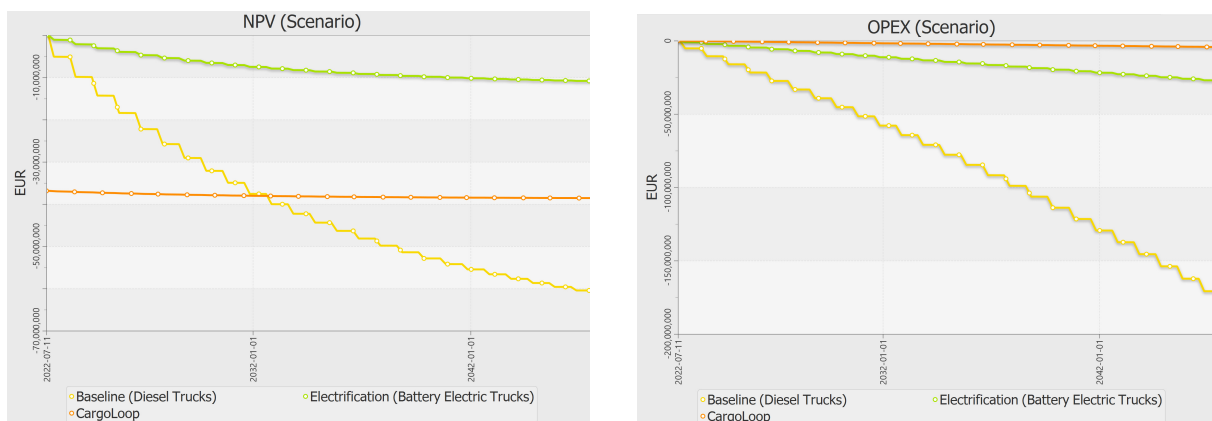

Figure 5: Comparison of NPV and OPEX for Hyperloop, diesel, and electric truck connections between a LSP and the VW production plant

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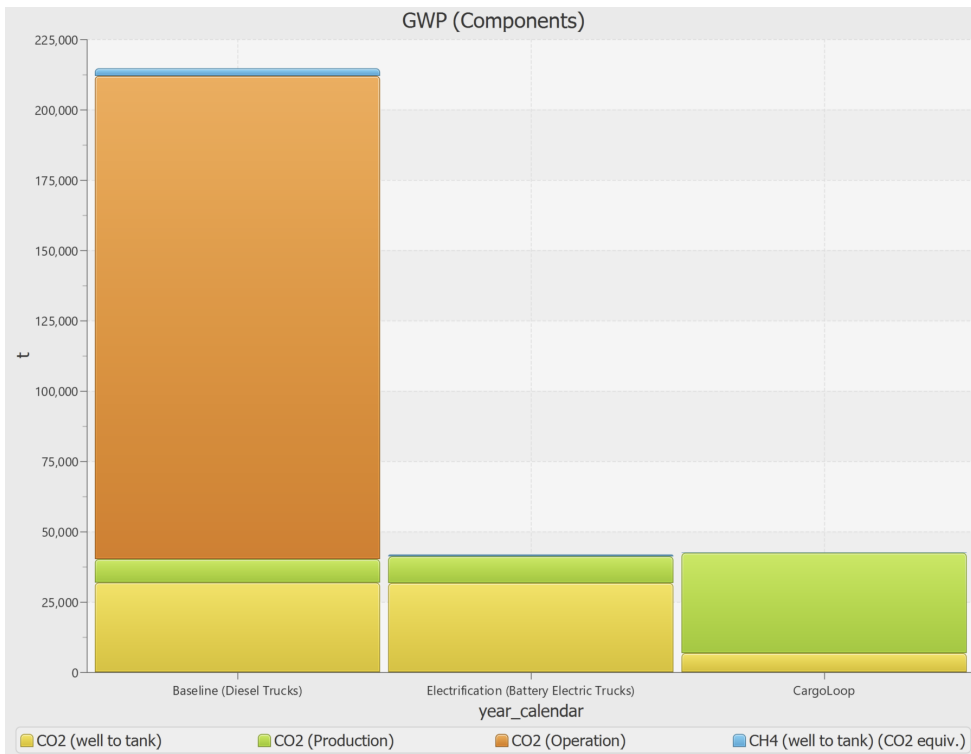

Figure 6: Lifetime emissions (carbon dioxide equivalent) for the Hyperloop, diesel, and electric truck solution

These preliminary numbers will be updated and refined as more accurate data is collected during the development of the demonstrator, assuming scenarios with different projections for fuel prices, energy prices and energy sources (e.g., EU mix for electricity vs. sustainable energy only). As seen fit, new developments in civil engineering will be modelled so that enhanced and low impact construction methods such as circular concrete, carbon neutral steel and low impact asphalt will be added to the model.

Currently, both CargoTube and battery-electric trucks perform much better in terms of NPV and GWP. However, both innovative approaches emit nearly the same amount of CO_2 over a lifetime of 25 years, the NPV is still better for electrifying the trucks. The main reason for this is the high investment cost which dominates the values. Nevertheless, considering infrastructure additions for more capacity on roads could equal the two approaches and will be investigated in future scenarios. When only considering the OPEX it becomes apparent that the CargoTube solution causes less costs than the truck in the operational phase. The emissions for both approaches are mainly bound to the installation phase. In the operational phase, a CO_2 neutral operation is possible when using sustainable energy sources.

Approaches of Hyperloop applications such as CargoTube show environmental benefits that even electric trucks cannot offer. Due to the enclosed environment of the tube, no noise or light pollution disturbs the outside environment, i.e., residential areas, during its 24/7 operation. Particulate/fine dust emissions from tire abrasion and brake pads, which are still by far the most important source of particulate emissions today and especially in the future, are also avoided. Finally, operation has no impact on social aspects such as local traffic congestion and is independent of external environmental influences such as snow or ice. Studies to demonstrate these impacts and improvements to the system, such as the implementation of a linear motor in the infrastructure, will be conducted in a later phase of the ePIcenter project as part of the transition to full life cycle analysis (LCA). (ePIcenter, 2023)

7 Interconnected CargoTube in the European Physical Internet

The creation of a Hyperloop network will take into account all the important logistical aspects, such as the integration of digital twin technology to control and monitor virtual pod traffic, the high flexibility and large capacity throughput between nodes, the distributed storage capabilities, the fully automated mode of operation and the closed system without additional security controls. Intermodal transport and cross-docking enable logistics node to destination transport in small batches with direct connection to last mile transport. This Hyperloop freight network can evolve from small node connections to a comprehensive intermodal networked European transport system. In general, a European network for passengers and freight would benefit and drive the most use cases, as it connects the most nodes and thus achieves the best network effects. Direct and indirect network effects are achieved by connecting new ePI nodes to the network, increasing value, usage, and the number of possible routes. Operating a small network with high throughput and low capital investment can demonstrate the feasibility, design, and deployment of a use case for connecting a larger manufacturing plant with a number of smaller industrial centers and a network of suppliers in a regional context. Nevertheless, as stakeholders of this project are discussing standardization of Hyperloop technologies in JTC 20 of CEN/CENELEC. A European wide freight network can only be realized through standardized technology including all mayor stakeholders.

CargoTube Physical Intranet. Such a Physical Intranet could, for example, connect several of a company's production facilities with its network of suppliers in the region, dramatically reducing the number of just-in-time truck connections and the environmental and socioeconomic impacts. In addition, there is the possibility for trusted shippers to collaborate in a network without the need for security checks or waiting times in such a highly automated logistics system with advanced scheduling algorithms. Intelligent ePI nodes can connect the Physical Intranet to the Physical Internet on demand to allow incoming goods into the CargoTube Physical Intranet system.

Direct network effects are realized when existing users directly benefit from the addition of new users. Any direct network effect is proportional to the number of users connected to the transport network. Indirect network effects arise when users of the original transport network increase because of some complementary ePI nodes that trigger the use of additional serviceable connections. If the value of the transport service is higher than the price, the customer base is expected to increase. New adopters are attracted to that service because of the extra value they are getting. Unfortunately, there is a huge dependency on prior adoption to critical mass level.

The CargoTube ePI nodes could be fully integrated with the Electronic Freight Transport Information (eFIT) and the European Technology Platform (ETP). Such digital IOT technologies allow for faster transfer of freight within the European network. Essential for large scale networks are innovative and disruptive technologies such as ultrafast Hyperloop applications with magnetic levitation and high-speed-switching technology to realize point to point connections within a large network without intermediate stops. Levitation technologies are indispensably required for operating speeds above 400 km/h as wear of contact-based track-wheel and energy supply systems such as pantographs increases dramatically. Complementary, highly efficient propulsion technology can also be realized magnetically through linear drives incorporated either on the vehicle or in the track.

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8   Discussion & Outlook (HSEL)

While a LPTT CargoTube connection of a LSP to an industrial manufacturing plant can create several qualitative improvements, such as reduction of traffic congestions, better air quality and less noise and light pollution in urban areas, network effects create the potential for improvements with a variety of quantitative benefits in the future. Modelling approaches estimate with very conservative technological assumptions are already at the same level as highly sophisticated electric trucks. This does not consider nowadays congested road capacity and an increasingly tight labor market with a lack of drivers or improved frequencies in the CargoTube system. The innovative transport system is most likely to scale to much higher capacity with increased automation and frequency without overload on the existing networks. While reaching for climate neutrality for Europe, Hyperloop systems can drastically reduce operating energy demand and emissions in the future.

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Surfing the Physical Internet
with Hyperconnected Logistics Networks

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Abstract: *The Physical Internet (PI) presents a transformative vision for logistics systems, where assets are shared openly, and flow consolidation is achieved through standardization, modularization, interfaces, and protocols. Hyperconnected logistics networks have emerged as a promising implementation of the PI, leveraging multi-tier meshed hubs and interconnectivity to achieve greater efficiency, resilience, and sustainability in the transportation of physical goods. However, a lack of clarity in the literature regarding the definition and design of hyperconnected logistics networks presents a significant obstacle to realizing their full potential. To address this gap, we propose a comprehensive definitional framework that integrates key concepts such as tiered network topology, hub interconnectivity, consolidation, and containerization. Moreover, we present a practical design approach for a hyperconnected logistics network in the United States, utilizing a representative demand scenario and accompanying network visualizations to enhance comprehension. Our research aims to unlock the potential of hyperconnected logistics networks as a crucial component of the PI, offering significant benefits to the global logistics industry and society as a whole.*

Keywords: *Physical Internet; Hyperconnected Logistics; Freight Transport; Logistics Network Design; Logistic Hubs; Supply Networks; Network Design; Material Handling; Modularization; Containerization; Omnichannel; E-Commerce Logistics; Modelling; Simulation.*

Conference Topic(s): *networks; interconnected freight transport; logistics and supply networks; material handling; Modularization; omnichannel & e-commerce logistics; manufacturing networks; PI fundamentals and constituents; PI impacts; PI implementation; ports, airports and hubs; vehicles and transshipment technologies.*

***Physical Internet Roadmap** (Link):* ⊠ PI Nodes, ⊠ PI Networks, ⊠ System of Logistics Networks, ⊠ Access and Adoption, ☐ Governance.

1 Introduction

The global logistics market is projected to reach about $13 trillion in 2027 [1], currently contributing to about 12% of the global GDP. However, it deals with serious issues pertaining to sustainability, resilience, and efficiency. The transport and logistics sector contributes to about 24% of global carbon emissions and is projected to go up to 40% if strong and effective actions are not taken [2]. Majority of emissions in the logistics industry arise from low truck fill rate of 40-60%, arising from inefficiencies in network design, routing of physical objects, scheduling of vehicles, etc., coupled with the internal combustion engine technology. Vehicles travel long distances resulting in long working hours and away-from-home journeys, leading to a shortage of truck drivers. Products sit at facilities for a long time leading to a loss of speed

due to poor consolidation and material handling. Supply chain and logistics networks are highly susceptible to uncertainties and disruptions due to lack of resilience considerations.

The Physical Internet was introduced by Montreuil (2011) to tackle these problems, leveraging as a metaphor of the Digital Internet and its multitude of induced innovations. The Physical Internet (PI) is a hyperconnected logistics system that enables open asset sharing and flow consolidation through standardized encapsulation, modularization, protocols, and interfaces, to improve the capability, efficiency, resilience, and sustainability of serving humanity's demand for physical objects [Montreuil (2020)]. A hyperconnected logistics system comprises layers of cluster networks, service networks, resource networks, mobility networks, stakeholder networks, cyber-physical networks, and governance networks [Crainic, Klibi, Montreuil (2023)]. In this paper, we focus on the first three layers.

Traditional network topologies are formed by a mix of hub-and-spoke topology across layers, and a point-to-point topology within the layers. A hub-and-spoke network topology lacks resilience in cases of hub-based disruptions such as strikes, attacks, and demand overloads, or arc-based disruptions such as highway closures. A point-to-point network topology, where hubs can be connected to all other hubs, results in long distances traveled by vehicles resulting in long working hours for drivers, and poor consolidation of goods resulting in low fill rates. A hyperconnected network topology that results from cluster, resource, service, and mobility networks has the potential to improve efficiency, sustainability, resilience, and capability of logistics networks.

This paper provides a comprehensive definitional framework for hyperconnected logistics networks, primarily covering aspects of topology and consolidation. We review the literature on this topic and explain the concept by showing a hyperconnected network for simple examples of uniform and radial demand distributions. We then present an approach for designing a hyperconnected logistics network for a representative demand distribution in the United States. We describe the design approach for multi-tier cluster networks, hub networks, and meshed networks. Our visualizations of the multi-tier networks provide a compelling vision of an essential aspect of the PI. We argue why hyperconnected logistics networks can outperform traditional networks and conclude by highlighting several open research questions involved in their design. Our research aims to contribute to the development of sustainable, resilient, and efficient transportation of physical objects, which has significant implications for the logistics industry and society as a whole.

1.1 Literature Review

Beyond the conceptual Physical Internet pillars (e.g., Montreuil, 2011; Montreuil, Meller, Ballot, 2013), Crainic et al. (2016) introduce the notion of Hyperconnected City Logistics for applying the Physical Internet in urban logistics environments, notably addressing interconnectivity between cities as nodes of the logistics web, and interconnectivity of city logistics shareholders into an open system. Montreuil et al. (2018) leverage hyperconnectivity as a key concept in leveraging PI in parcel logistic network design, introducing notions such as multi-tier pixelization of space and multi-plane parcel logistics web. They propose removing the hub-and-spoke constraint, and instead propose interconnecting hubs with many more flow options through and between plane-specific logistic mesh networks to enable swift and efficient parcel travel and consolidation. Parcels or sets of parcels consolidated in modular containers are proposed to have a dynamically optimized route, which enables to know the next hub in the route, given a current hub. For logistics networks where the origin of the parcel is fixed at order time (such as UPS, FedEx, SF Express, etc.), individual parcels are to be consolidated early in their journey mostly at access hubs and local hubs, and rarely at gateway hubs, inter-regional

hubs, and global hubs. There has been significant research in modeling of two-echelon networks in vehicle routing, facility location, and network design, however multi-echelon logistic networks that are more relevant for solving the problems has been studied by very few [Savelsbergh et al. 2016].

Shaikh et al. (2021) provides a conceptual framework for the transportation of packages in a hyperconnected network, touching concepts of mesh network, dynamic package routing, dynamic containerized consolidation, inter-hub shuttling, and open protocols. In the space of multi-tier mesh networks, there has been some preliminary research on clustering of unit zones to form local cells. Tu et al. (2019) introduces a greedy algorithm, ensuring proximity and demand balance across clusters in the objective function. Hettle et al. (2021) further introduces an optimization-based approach for the clustering task, given locations of local hubs. Muthukrishnan et al. (2021) develops an optimization-based approach for identifying potential locations for access hubs once the unit zones are created. Faugere et al. (2020) provides an example of access hubs in the form of smart locker banks and their design optimization strategies. Several contributions in the literature, such as Campos et al. 2021 and Kaboudvand et al. (2021), focus on hyperconnected logistic network simulator development and simulation-based experimentation, embedding software agents for demand generation, network design, parcel routing and consolidation, service offering, etc.

Since economies of scale play a crucial role in improving efficiency of transportation and logistics systems, PI pushes for open cooperation and collaboration between organizations. Carriers can consolidate their loads and improve their service levels, Hezarkhani et al. (2021) provides an overview of cooperative game theory approaches for designing cost sharing schemes. Several other features of a hyperconnected network that make its implementation successful are real-time monitoring, integration in an information sharing platform, and collaborative decision support systems.

Although there is vast literature on classical network design problems, as described in Crainic, Gendreau, Gendron (2021), stochasticity is generally difficult to deal with in large-scale optimization problems. Literature on hub location seldom considers stochasticity, resilience, or robustness to threats (e.g., Ortiz-Astorquiza et al. (2018)). A hyperconnected framework for pixelization, hub location, and network design, incorporates such considerations in the design. Despite the tremendous progress in research on hyperconnected networks, missing is a framework for defining hyperconnected networks, which this paper intends to provide.

1.2 Hyperconnected Network as Multi-Tier Meshed Network

In framing the applicability of PI-enabled logistics web in the context of city logistics, Montreuil et al. (2018) propose the design of interconnected multi-tier meshed networks and of multi-plane territorial cluster networks. They illustrate the concepts through interconnected six-plane cluster networks and five-tier hub networks. For territorial clustering, customer locations (plane 0) are proposed to be clustered into unit zones (plane 1). Multiple neighboring unit zones get clustered into a local cell (plane 2), multiple local cells into an area (plane 3), multiple areas into a region (plane 4), multiple regions into a block (plane 5), and multiple blocks into our planetary world (plane 6). The facilities in the hub resource network tiers match with the multi-plane spatial cluster network: Tier-1 access hubs are networked in plane 1, then similarly for tier-2 local hubs, tier-3 gateway hubs, tier-4 inter-regional hubs, tier-5 global hubs, and eventually tier-6 earth-planetary hubs. The hubs in each tier are interconnected with neighboring hubs in the same tier, as well as to nearby hubs in the tier directly above and the tier directly below.

The purpose of access hubs is to provide immediate access to neighboring unit zones and are interconnected through streets and roads. They are first/last mile hubs that can for example be smart lockers or mobile trailers. The purpose of local hubs is to consolidate and ease flow in and between neighboring local cells. The purpose of gateway hubs is to connect neighboring areas. The purpose of inter-regional hubs is to connect regions. The purpose of global hubs is to interconnect blocks. They are import and export hubs that have specific processes for customs and security compliance. Flow between hubs leverages transport modes through airways (from drones to airplanes), roadways (from streets to highways), railways, subways, and waterways (from rivers and channels to oceans), including private and public transit systems as pertinent, and depending notably on scale, location, density, and availability.
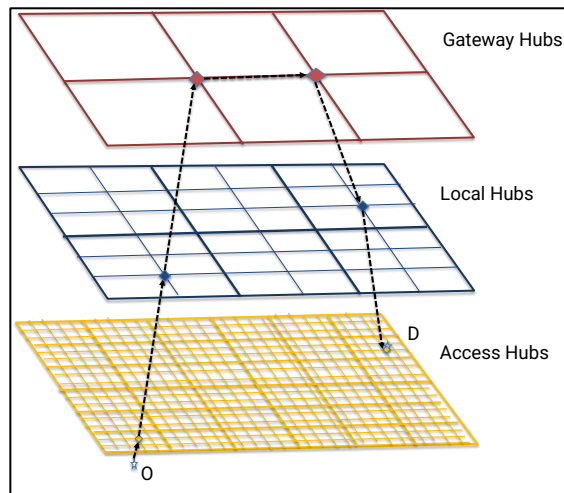

Figure 1: Illustrating flow of goods in hyperconnected networks with uniform demand distribution in a grid space

Figures 1 and 2 illustrate the flow of containerized goods in hyperconnected logistic networks. In a rectangular space, assuming uniformly distributed transport demand, we can structure the space in rectilinear grid fashion as shown for a simple example with three tiers in Figure 1. Each pixel in the bottom, middle, and top tiers respectively denotes a unit zone, a local cell, and an area. At the corners joining pixels in the bottom, middle, and top tiers are respectively located access hubs, local hubs, and gateway hubs. The path of goods depends on the relative location of origin (O) and destination (D), both in specific unit zones at the bottom pixel. Through their path, all goods travel is done consolidated in modular containers (Montreuil et al., 2016). Goods start their journey at O. If O and D are in the same unit zone, goods are shipped directly through some dynamic route. If O and D are in distinct unit zones within the same local cell, then the goods go to an access hub at one of the corners of the origin unit zone (bottom pixel), where they are consolidated towards the access hub most convenient for D, and shipped to D once the goods have reached this access hub. If O and D are in different local cells, they either climb to a local hub at the corner of the local cell or go directly to the D access hub if more convenient when near the origin local cell. At a local hub, if D is in a different area, goods climb to a gateway hub at one of the corners of the area. If D is in the same area, they go to another local hub within the same area. If D is in neighboring local cells, they go down to an access hub in neighboring local cells. Similarly, at a gateway hub, goods either go to another gateway hub within the same region or go down to a local hub in neighboring areas.

Similarly, Figure 2 part (a) illustrates the flow of goods in a hyperconnected network for city logistics with radial pixelization for uniformly distributed demand. Figure 2 part (b) and (c) illustrate ways of pixelization for radially distributed demand in cities, varying inversely with

square of radius. This leads to the next question: how to structure the space and create a hyperconnected network for a general demand distribution? Section 2 addresses this question.

Figure 2: Flow of goods in a hyperconnected network for city logistics with radial pixelization under (a) uniform demand distribution, (b),(c) radial demand distribution varying inversely with square of radius.
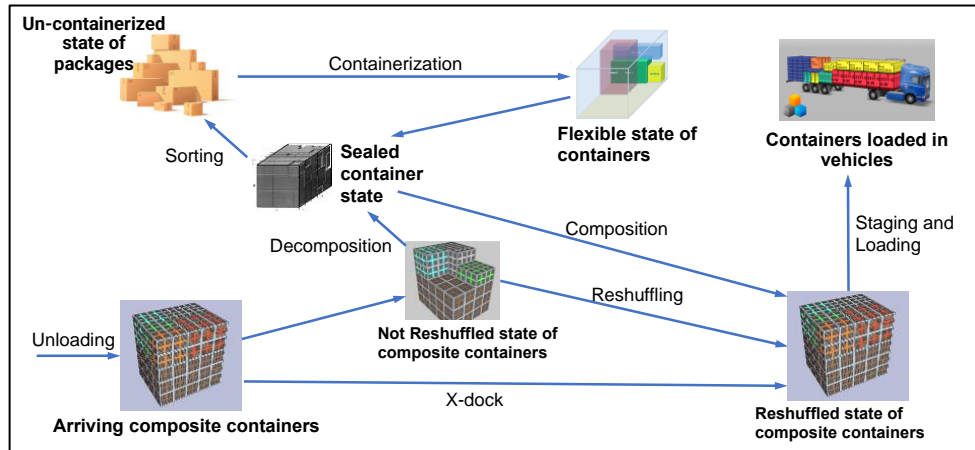

Figure 3: Processes involved in handling of modular containers at a gateway hub

The hubs in a hyperconnected network also differ in material handling and level of consolidation. Access hubs generally deal with individual shipments. Local hubs are usually the first point of consolidation into modular containers, where individual shipments are consolidated by destination local cell. Gateway hubs majorly deal with shipments that are smartly consolidated in modular containers. These hubs primarily perform the operation of re-shuffling smaller handling containers like totes, into larger handling containers like mobile racks, such that containers going towards the same destination gateway hubs are consolidated (Montreuil, McGinnis, Buckley, 2021). Figure 3 illustrates the processes involved in handling modular containers at a gateway hub. They may also cross-dock containers that are consolidated by destination gateway hub. Regional hubs primarily perform the operation of cross-docking containers. They may also act as driver or trailer switching points and charging points for electric trucks. Global hubs deal with the shipments consolidated heavily in shipping containers, that may change from one mode of transport to another.

2 General Hyperconnected Network Design

In this section, we describe the process of building a hyperconnected network for general demand distribution, and we use population data for the U.S.A. to create a representative demand scenario.

2.1 Hyperconnected Multi-Tier Cluster Network for Pixelization

Following are the considerations involved in the logistic space clustering approach used in this paper, along with the reasons.

1. Contiguity: minimizing transportation cost within each pixel, even when there are variations in demand, and making operations easy to manage.
2. Demand balance across pixels: enabling the hubs located to need nearly the same capacity and throughput.
3. Roadways, highways, railroads, and natural boundaries: connecting each pixel well within itself with proper roadways, highways, and railroads to ensure that points inside the pixel can be reached quickly and efficiently; coinciding cluster boundaries with natural boundaries such as rivers and mountains that reduce reachability.
4. Direction and volume of flow: concentrating high-volume nearby flows within the same pixel to minimize flow between pixels and the induced logistic load at inter-pixel hubs.
5. Compactness: minimizing transit times through ease of intra-pixel circulation.
6. Scalability/Adaptability: remaining efficient and/or being readily adaptable and scalable as urban, peri-urban, and industrial areas grow and evolve.
7. Fairness: considering equitably all pixels, whatever their population, logistic flow, and reachability, notably avoiding creating underserved logistic deserts.
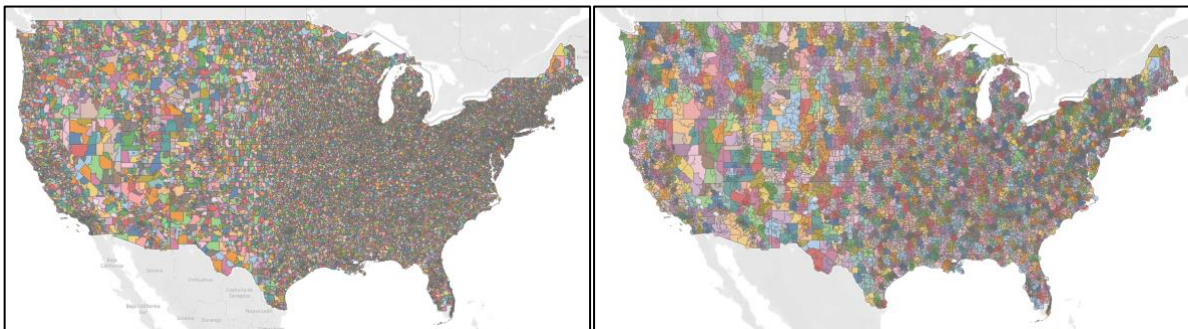

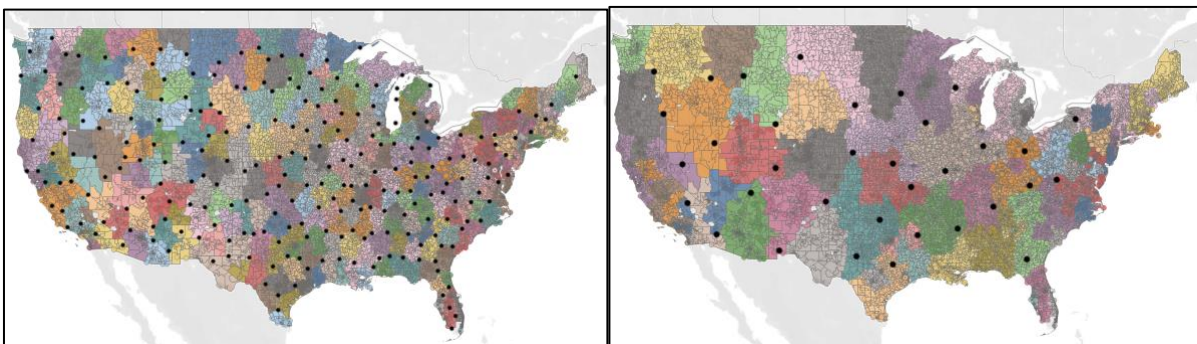*Figure 4: (a) Tier-1 Unit zones and (b) Tier-2 Local cells in a hyperconnected logistics network*

Figure 5: (a) Tier-3 Areas and (b) Tier-4 Regions in a hyperconnected logistics network.

Figures 4 and 5 illustrate the cluster networks in different tiers, with consideration of proximity and demand balance. The maps are not meant to be strictly prescriptive, but rather to facilitate understanding cluster networks and demonstrate their applicability at large scale. From a methodology perspective, proximity-based clustering is done as an initial step to obtain centroids, and an optimization model is used for assignment of pixels to centroids, with a constraint on maximum demand to ensure demand balance across pixels. This is not meant to be a definite prescriptive method, as significant further research is bound to lead to much improved design performance and ease of design.

The plotted cluster networks include 2000 local cells, 300 areas, and 60 regions across the USA. The US 5-digit zip codes have been used for defining unit zones in this illustrative study. This said, we consider that in further studies, the basic definition of unit zones should be challenged, as zip codes were designed for structuring postal services long ago, yet have mostly become fixated, and may not have the most appropriate level of granularity.

2.2 Hyperconnected Multi-Tier Hub Network

The hyperconnected multi-tier hub networks consist of access, local, gateway, inter-regional, and global hubs, which vary by the volume handled, processes involved, and facility designed as described in section 1.2. In a PI paradigm, access to these resources is openly shared as there are multiple cooperating stakeholders from numerous companies.

An interesting location for hubs is the intersection of two or more pixels since it offers efficiency, flexibility, resiliency as lower-tier hubs in the pixel have multiple connectivity options with higher-tier hubs. Black dots in Figure 4, parts (a) and (b), respectively show the potential locations of gateway hubs and regional hubs. These have been obtained from the vertices of a Euclidean distance based Voronoi diagram overlaid on centroids of pixels. A Voronoi diagram is a tessellation pattern in computational geometry, where given a set of finite, distinct, isolated locations in a continuous space, all points in the space are mapped to the closest member of the location set [Boots et al (2009)]. The output is a division of the space into regions, and we use the corners of the regions for locating hubs. We use this because it is a simple method for obtaining approximate intersection points of pixels. We can also have hubs appearing near centers of pixels. This said, real estate access and cost, and traffic, are generally high when very near to high population density, this affects potentially optimal hub locations in practice.

Considerations for creating the tiered hub networks include proximity to higher-tier and lower-tier hubs, and highway intersections for speed of transportation. Megacities have several tiers of hubs within the city. One can have clusters of hubs belonging to the same tier co-located in a proxy location, and some hubs belonging to multiple tiers co-located in the same site. In some networks, locating hubs near ports, and logistics freight corridors also becomes important.

Resilience and robustness to threats are implicitly embedded in the networks of Figures 4 and 5 with the hubs connected as a mesh within a tier and with nearby hubs connected between tiers, as is further described in Section 2.3.

A natural question that arises is how to decide on the number of pixels when there are already facilities that we want to use as hubs in the hyperconnected networks. We use a brownfield analysis for such a scenario and show a simple heuristic approach for Tier-4, inter-regional hubs. When estimating the macro flows through the network, the volume flow across regions can be assumed to be a fraction of the total demand. This fraction would decrease as the size of the region increases. We have assumed this fraction to be concave as a function of the number of regions in the network within a plane. More specifically, we have assumed that this fraction, called average daily inter-regional flow, in terms of percentage of total demand, would be:

$$IRFP = 100 * \left(1 - e^{\frac{1-x}{100}}\right),$$

where, x denotes the number of regions. Shown in Figure 6a, this ensures that the function takes the value zero when there is only one region, is concave, and does not exceed 100%. Since we are locating inter-regional hubs at the intersection of the regions, as we increase the number of regions in the network, the number of tier-4 hubs would also increase. Hence, the average daily volume processed by the hubs would decrease, which we have assumed to be twice the inter-regional flow, divided by the number of inter-regional hubs in the network. We insert the factor

two because some goods may be travelling through more than two inter-regional hubs. This gives us a function of average daily volume processed by hubs, with varying number of regions, shown in Figure 6b. From this, we can decide the number of regions we need to create based on the capacity of the existing facilities in the network. Obtaining such a curve using more precise techniques is an interesting area for further research.
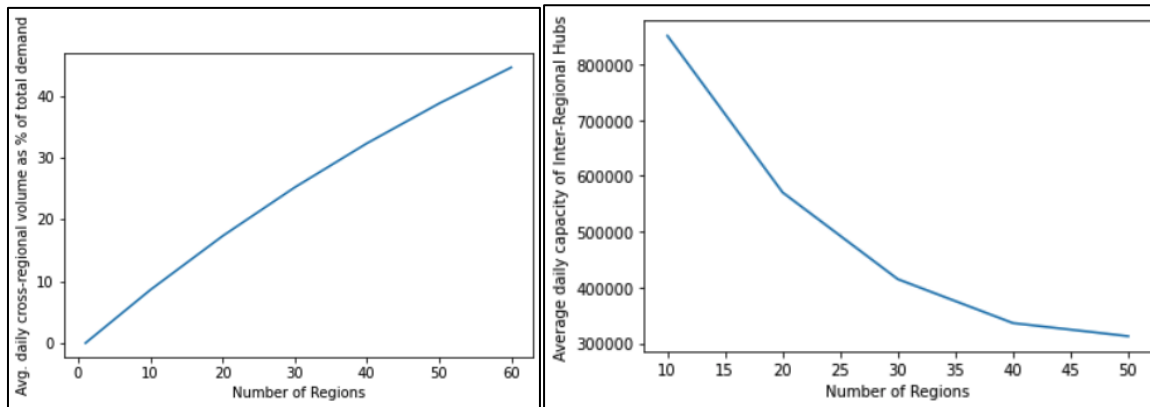

Figure 6: Brownfield analysis for deciding number of regions: (a) Variation of average daily inter-regional volume with increasing number of regions. (b) Capacity required for inter-regional hubs as a function of number of regions.

2.3 Hyperconnected Multi-Tier Meshed Network Design

In a hyperconnected meshed network, there are vertical connections between hubs, i.e., connections between access-local, local-gateway, gateway-inter-regional, inter-regional-global hubs. Hubs in a tier can be connected to hubs in all the neighboring pixels if the connections respect driver regulations. Connections do not skip tiers, for example, access hubs will not directly connect to gateway hubs. Figure 7 illustrates what these connections look like. There are also horizontal connections between hubs in the same tier. Hubs in a tier can be connected to each other if they lie in the same higher-tier pixel as shown in Figure 8, for example, gateway hubs lying in a region, can be connected to each other if the drive time is within regulations. Sometimes, nearby hubs can also be connected across the boundary of the pixel, for example, gateway hubs can be connected to nearby gateway hubs which are in a different region.
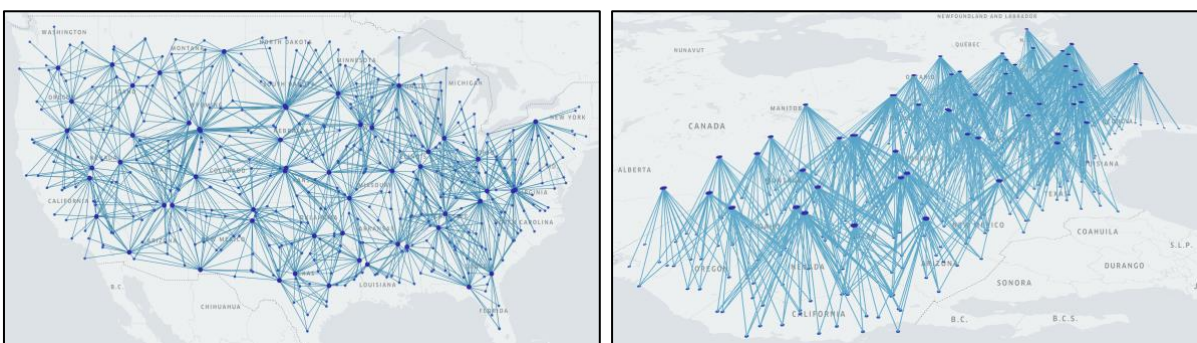

Figure 7: Vertical inter-tier connections between inter-regional hub and gateway hubs shown in (a) 2D, (b) 3D with regional hubs on top tier and gateway hubs at bottom tier, in a hyperconnected network shown for US.

These are all potential connections, and a subset of these connections is to be used for flows associated to any specific shipper. The connections to be used for routing goods on any given day depends on direction and volume of flows, and these potential connections play a role in reducing the size of the network design problem. Once a network is in place, goods are routed dynamically through the network. At each hub in their path, the next hub is decided, notably

such that delivery time constraints are satisfied, vehicle fill rate is optimized, and capacity of the hub is accounted for.
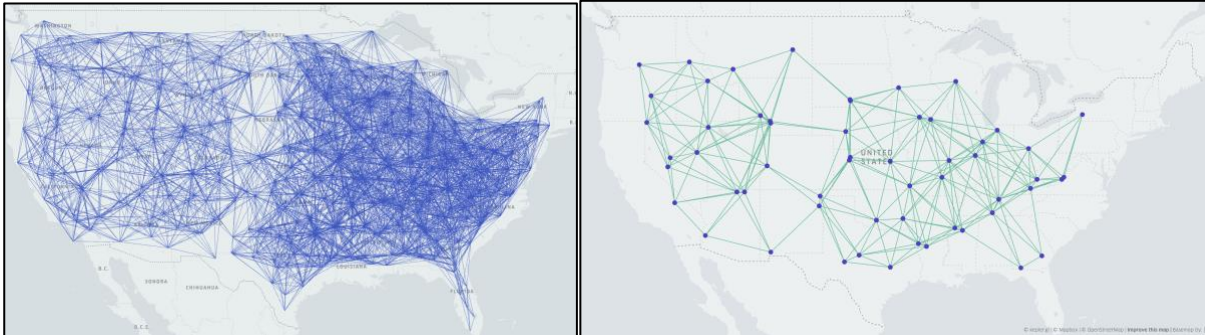

Figure 8: Horizontal same-tier connections between (a) Tier-3 gateway hubs and (b) Tier-4 inter-regional hubs.

3 Conclusion

We have provided a framework for creating hyperconnected logistics networks, starting with a cluster network where we explained considerations for discretizing space. We then described hub networks in specific tiers, and meshed network creation. The hyperconnected networks thus created enable better consolidation when combined with the use of modular containers through the various tiers, as it reduces handling time and efforts at intermediate hubs.

There are several avenues for further research as there are several problems in this framework that can be dealt with using rigorous optimization models. One such example in the cluster network is the problem of defining unit zones as clusters of demand. Beyond zip codes, census blocks can be used for this purpose. Meshed networks can also be defined in further detail by considering flow of goods transferred across regions. Dynamic goods and container routing in a hyperconnected logistics network can be modeled as a sequential decision-making process as at each hub in the journey, goods need to take an action to decide upon next hub from a set of available options, and get a reward depending on level of consolidation. The networks thus created can be tested using simulation with containerized consolidation, to compare against traditional network topologies in important settings. A subject of further research also involves the design and analysis of the network accounting for various types of goods and ownership of hubs. This would involve jointly defining and designing hyperconnected networks for pickup, transportation, and delivery of goods, along with distribution and fulfillment engaged in the deployment of goods.

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Framework for Leveraging Physical Internet Principles for Long-Tail Products in E-Commerce

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Abstract: *The E-Commerce channel has led to the emergence of the long tail phenomenon describing products whose individual sales are low but collectively they contribute significantly to sales. Due to their low, lumpy, and intermittent demand characteristics, they pose extra challenges when retailers are confronted with product assortment, network wide inventory allocation, inventory deployment and order fulfillment with regards to the business goals of profitability, service levels and environmental sustainability. This paper outlines how Physical Internet concepts can help to answer these challenges. By employing the four components of hyperconnected distribution and transportation, inventory sharing and information sharing, we propose a three-level framework that has the potential to promote profitability, customer satisfaction and sustainability for long-tail products.*

Keywords: *E-Commerce, Physical Internet, Long Tail, Sharing, Inventory Management, Order Fulfillment, Service Level, Profitability, Sustainability*

Conference Topic(s): *omnichannel & e-commerce logistics; logistics and supply networks; business models & use cases;*

Physical Internet Roadmap (*Link*): *Select the most relevant area for your paper:* ☐ *PI Nodes,* ☐ *PI Networks,* ☒ *System of Logistics Networks,* ☒ *Access and Adoption,* ☐ *Governance.*

1 Introduction

The E-commerce retail spending market has reached a volume of more than 1 trillion USD in the USA for the first time in history (Essling and Clough, 2023), demonstrating the importance of E-commerce for the consumer's purchasing behavior. While consumers spent most on groceries, apparel, and accessories (Essling and Clough, 2023), a retailer with an e-commerce channel can offer a vast array of products and product categories, because fulfillment centers (FCs) can be placed in comparatively cheap real estate areas and the Internet enables placing orders from everywhere and fulfilling orders from everywhere. As a result, customers discovered niche products, which led to the emergence of the so-called long tail. Long-tail products are defined as goods whose individual sales are low yet collectively contribute significantly to sales (Øverby and Audestad, 2021). The opposite of tail products are head and body products referring to products whose individual sales make up substantial high and medium shares of sales. They respectively correspond in well-known Pareto curves to classes A for head, B for body, and then C and higher for tail. Long-tail products lie at the low end of tail products, in Pareto curves they generally correspond to classes D, E, F and beyond.

For the remainder of this paper, we use the term e-commerce retailer to refer to retailers with only an online platform as well as the e-commerce business of an omnichannel retailer. The e-

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The work does not relate to the authors' affiliation with Amazon.com, Inc.

commerce retailer has three often conflicting, yet crucial goals: service level, long-term profitability, and sustainability, notably in terms of environmental impact. The first goal motivates carrying a large product portfolio to offer a one-stop shopping experience to the customer. Customer satisfaction in e-commerce can also be achieved by tailoring the delivery to the customer's needs in terms of delivery/pickup time, location, and reliability. Hereafter, we use the more general term *service level* to describe customer satisfaction. The second goal is driven by the need to stay in business while the third is driven by customer demand, legal requirements and/or the values of the organization (Heiny, 2022; Pope, 2021; Willsher, 2020). The three goals must be balanced when deciding on product assortment, network inventory level, inventory allocation and order fulfillment. These decisions are already complicated decisions for products with a stable and normally distributed demand (Coelho et al., 2013; Dolgui et al., 2013; Silver, 1981). The characteristics of long-tail products add an additional challenge. Therefore, we look for alternative ways of managing long-tail products for e-commerce retailers to make optimal decisions such that service level, profitability and environmental sustainability are improved. We deem the Physical Internet (PI) with its openly shared resources for storage and transportation as a suitable tool to handle long-tail products efficiently while achieving the intended goals. The PI concepts are particularly interesting for long-tail products because E-commerce retailers can leverage economies of scale resulting from PI for a class of products that by definition do not have economies of scale. We propose a conceptual framework how PI can support E-commerce retailers in efficiently supply and deploy long tail products as well as efficiently fulfill orders with long tail products.

The remainder of this paper is organized as follows: Section 2 reviews literature regarding long tail products and the Physical Internet to position our paper. Section 3 outlines unique challenges of long-tail products and goals for managing them. Based on these insights, Section 4 conceptualizes three scenarios on how the Physical Internet supports the achievements of the goals. Section 5 concludes with summarizing our contribution and proposing research avenues.

2 Literature Review

The literature review focuses on the three main topics: first, research on long tail products; second, findings regarding order fulfillment in e-commerce; and third, current research on PI.

2.1 The Long Tail

Anderson (2006) introduced the term *long tail* to describe the phenomenon that significant total sales can be achieved by selling low volumes of many products. Long-tail products are, therefore, products whose individual sales are very low yet collectively contribute significantly to sales (Øverby and Audestad, 2021). Figure 1 illustrates a classification into head, body, and tail products based on sales ranking, extending into tail and long-tail products. The classification boundaries are often based on the 80/20 rule (Johnston et al., 2003), with the decision where to draw the lines is enterprise specific. Long-tail products are also called very slow-movers because their turning time in a warehouse is much longer than the time spent in warehouse by a head product. Academia describes them as products with lumpy and intermittent demand, referring to the characteristic that demand is not observed in every period as shown in Figure 2 (Boylan and Syntetos, 2021). We use all three terms interchangeably.

The long tail of physical products emerged because warehouses could be located in inexpensive regions and real estate resulting in less space constraints and lower costs compared to a brick-and-mortar store allowing to store more products. Active and passive search tools on an E-commerce retailer's website enable the customer to find the product they want to buy but also to discover other products resulting in increased sales for niche and mainstream products

(Brynjolfsson et al., 2006; Goel et al., 2010). Despite the number of sales for long-tail products being low in absolute and relative terms, e.g. Johnston et al. (2003) report that 75 % of the product portfolio of a retailer have six or less orders per year and Chodak (2020) even describes products that have not been sold once in the year of the analysis, an E-Commerce retailer is motivated to carry a large product portfolio because the "one-stop shopping" experience for the end consumer can increase sales for highly demanded items as well as less popular products (Goel et al., 2010). Moreover, e-commerce allows aggregating niche tastes over entire regions as long as the delivery lead time is acceptable. The resulting aggregated demand of niche products might provide a business argument to carry a niche product (Brynjolfsson et al., 2006).
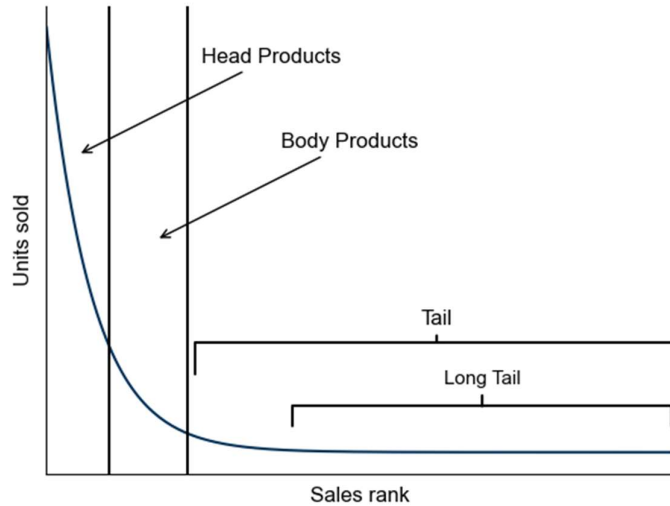

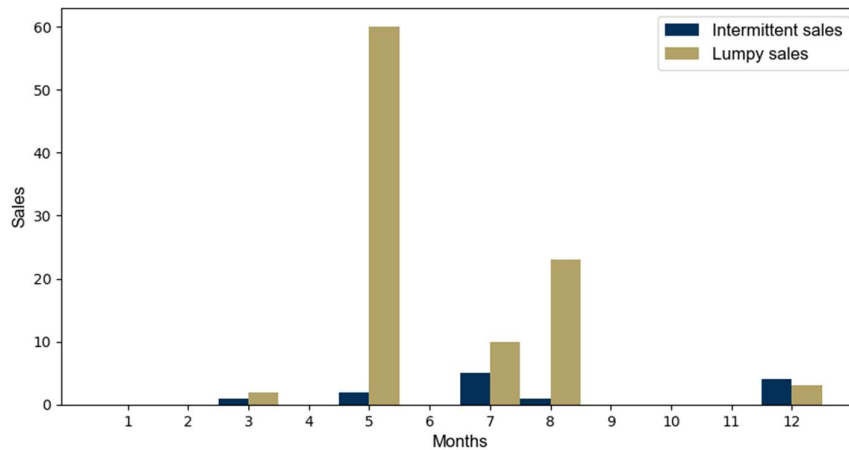*Figure 1: Classification of products based on sales rank*

Figure 2: Intermittent and lumpy sales (sourced from Boylan and Syntetos, 2021)

2.2 Order Fulfillment

Order fulfillment comprises confirming availability of ordered products, then picking, packing, and delivering the order. When ordering a product online, basic information about availability of the product is typically shown to the customer (e.g., is it in stock? What is the promised delivery time?). The information that the product is in the retailer's fulfillment center and does not need to be ordered from an upstream supplier may increase sales by 70% for an average product (Baldauf et al., 2021). Cui et al. (2020) researched how the availability of high-quality

delivery services influences purchasing behavior in online retail where delivery quality encompasses speed, reliability, and pick-up and drop-off flexibility. They showed that the sales of long-tail products depend less on high delivery quality as compared to popular products. A potential explanation is that long-tail products are less likely to be offered by several competitors. This said, delivery speed and reliability are increasingly important factors for the buying decision as shown in a survey by X Delivery (2022). 56% of online shoppers abandoned an online cart because of too long delivery times or fees for delivery. In fact, 36% of shoppers expect free one-day or two-day delivery but only 1% of retailers can accommodate these expectations. Salari et al. (2022) demonstrated that accurate delivery time promise, i.e. neither overpromising nor under promising of the delivery time, can increase sales by up to 6.1%.

2.3 The Physical Internet

Introduced as a new paradigm for moving, deploying, realizing, supplying, designing, and using physical objects, PI aims to enable order-of-magnitude worldwide capability and performance improvements of logistics and supply chains in terms of efficiency, sustainability, and resilience (Montreuil, 2011). PI features include universal interconnectivity; smart modular containers for packaging, handling, and transporting physical objects; protocols, interfaces, and business models for open multi-party, multi-modal flow consolidation and asset sharing; and multi-tier mesh networks of openly accessible logistic hubs for crossdocking and consolidation, and deployment centers (e.g. storage, fulfillment) (Montreuil et al., 2013, 2014; Shaikh et al., 2021).

In the PI, distribution and transportation systems are hyperconnected. Their networks and constituents are connected on multiple layers, such as physical, digital, operational, transactional, and legal, notably through multi-tier meshed networks (Montreuil et al., 2018). Distribution systems leverage a distributed web of openly accessible deployment centers such as long-stay warehouses, distribution centers (DCs), and fulfillment centers (FCs), owned and operated by multiple parties, offering storage and fulfillment services. Transportation systems leverage multiple modes, services, and vehicle types to move goods from their origin to their targeted destination through multi-segment journeys enabling dynamic reconsolidation across multi-tier networks of logistic hubs. Sohrabi et al. (2016) and Kim et al. (2021) have provided optimization and simulation based experimental results documenting cost improvement on the order of 30% solely employing hyperconnected distribution or hyperconnected transportation, and on the order of 40-50% when employing both. Moreover, their studies revealed that providing higher service levels is less expensive with PI than conventional dedicated and hub-and-spoke based systems (Sohrabi et al., 2016).

(Pan et al., 2015) showed the system-wide inventory level and total logistic costs, consisting of inventory holding cost and transportation cost, are reduced for fast-moving consumer goods in PI compared to a classical hierarchical supply chain because of better selection of storage locations as well as flexible and responsive replenishment plans. For example, storage facilities cannot only source from a production site but also from other storage facilities which corresponds to a multiple-sourcing strategy. Additionally, Yang et al. (2017) demonstrated that PI inventory control performs better in the case of demand uncertainty or supply chain disruptions. According to Montreuil (2016), omnichannel business-to-consumers (B2C) logistics in PI can be designed in various degrees of interaction between the business and the PI entities with the two extremes of the business making order fulfillment and inventory deployment and replenishment decisions with internal teams and software all the way to where a fulfillment orchestrator is responsible for inventory and fulfillment decisions for multiple retailers, hence well poised to leverage economies of scale. Naccache (2016) concluded that small and mid-sized e-retailers would benefit the most from PI operations because a small e-commerce retailer aiming to provide one-day delivery windows over a vast territory may rely

on hyperconnected distribution and transportation to dynamically deploy its products over a large distributed yet interconnected set of deployment centers, achieving concurrent high performance in terms of profitability, consumer satisfaction, and greenhouse gas emission reduction, without large investment costs and delays

3 Challenges of Long-Tail Products in E-commerce

E-Commerce retailers are confronted with decisional challenges on four fronts for all types of products: network-wide product assortment, network inventory level, inventory deployment across the network, and customer order fulfillment. Long-tail product management poses additional challenges due to the sheer size of the long tail, the low number of sales of each long-tail product, and the intermittent and lumpy characteristics of long-tail demand. In this section, we present the challenges for all four decisional fronts and explain how they relate to achieving service level, profitability, and environmental sustainability goals.

3.1 Networkwide Product Assortment

E-commerce companies tend to carry millions of products, notably giants such as Amazon and Alibaba. Both e-retailers base their product assortment decisions on their mission. For example, Amazon's mission "to build a place where people can come to find and discover anything they might want to buy online" advocates for its assortment to ultimately include all products made in the world (Hull, 2012). According to Chodak (2020), the long-tail in e-commerce results from the combination of the low marginal cost induced by listing a product on the online marketplace with the ease of finding products using an efficient search engine. This increases potential demand which can lead to higher sales. The more niche products are offered, the more heterogenous customers can be served, which again potentially can lead to higher sales. E-commerce retailers also employ recommendation system to "fatten the long tail", explicitly aiming to increase sales of long tail products as well as fast-moving products (Kumar and Bala, 2017). While customer satisfaction is a key frontside reason why products are offered, another backside reason is that once a product is stored in a fulfillment center, it might not be economical to retrieve remaining unsold units, so it is easier for the e-retailer to keep offering the product on the website until the remaining inventory is completely depleted.

3.2 Network Inventory Level

Decisions on how many units per product to have in the network are subject to forecasting capabilities, the batch sizes imposed by the supplier, potential discounts the supplier offers, and the desired service levels to customers. Despite recent progress, forecasting methods for intermittent demand are more difficult and less accurate than for fast-moving products and adoption of new forecasting methods in commercial software is slow (Boylan and Syntetos, 2021), resulting in imprecise forecasts. Even if true demand was known a-priori, the retailer might only be able to buy a batch with more units than necessary to robustly cover the forecasted demand due to the production process, other economies of scale or discounts (Zhu et al., 2015). For example, a product with a total demand of 10 units per year might have a minimum order quantity of 15 units. This leads to 5 units expected to bind capital beyond a year, incurring holding costs that decrease profitability. For a perishable product, these units must be discarded which is a waste of both financial and environmental resources. In addition, the service level the retailer wants to provide in terms of delivery time might require it to have a higher stock than total demand. If the retailer promises next-day delivery, then at least one unit must be stored within 24-hour reach of each customer. In large geographic markets such as the USA, this could mean that the product must be stored in more than ten FCs depending on available delivery modes to the e-retailer, again requiring more than a year's demand.

In particular, the first product stocking decision can lead to overstocking. The supply recommendation systems are not yet familiar with the product and lack historical data. The supplier, convinced that the product would become popular, pushes to start with high inventory. Lack of data leads to imprecise and/or biased demand forecasts. Hence, sales do not materialize as predicted (Chodak, 2020). In fact, early on, any product is more likely to become a long-tail.

3.3   Inventory Deployment

Inventory deployment decisions answer how many units of each product are to be placed in each FC given the current and projected networkwide inventory level, and where to replenish a specific FC from. In long-tail contexts, such decisions are exacerbated by the huge number of products with low and intermittent demand. Internal decision factors are the targeted service levels, network inventory level, the number, location and capacity of fulfillment centers the e-retailer is using and whether to employ static or dynamic inventory allocation. The market distribution in the serviced region, often highly correlated with population, is the main external factor on the inventory deployment decisions.

Despite lower supply costs because of storage in areas with low real estate prices (Hoskins, 2020), large-scale E-commerce retailers tend to carry millions of products such that even in large FCs, each product unit must justify the space it takes up. Consequently, fast-moving products that free up space quickly are preferred. Another reason why FC capacity is limited are the delivery expectations of customers discussed in section 2.2. To achieve short delivery times, FCs have to be placed close to the customers. As the majority of customers live in metropolitan regions where space is limited and real-estate costs are higher, FCs and the resulting holding costs tend to also be higher. This increases the competition for long-tail products in given FC because it is uncertain whether that unit will ever be demanded in the region the FC is supposed to cover. The solution space is also limited because of the low number of units per long tail product. If the supplier sends the ordered batch to the upstream inbound cross dock, splitting the batch and sending individual units to multiple FCs might not be economical, therefore the batch gets placed in one FC. Even if the retailer splits the batch, the number of units per product might be lower than the number of FCs. For instance, Amazon operates more than 100 FCs in the US (MWPVL International, 2023). Products that have a total expected 99 %-maximum yearly demand of less than 100 units would not allow to store a single unit at each FC, except if multi-year inventory is kept. Thus, the long-tail product units are deployed in a limited number of FCs minimizing expected inbound and outbound transportation, fulfillment, and delivery costs given the capacity constraints. Lastly, deciding on dynamic reallocation of long-tail inventory as the inventory depletes over time can, on the one hand, continually optimize inventory distribution across the market territory. One the other hand, preventive transshipments take away from putting and picking capacity in the involved FCs and induces additional transportation effort that may raise total costs and emissions.

3.4   Order Fulfillment Sourcing

Due to increased automation in FCs, we assume that picking and packaging does not differ between products. Hence, we focus on delivery reliability and velocity. The delivery experience is the only physical touchpoint with the customer underlining its importance. Targeted order fulfillment service levels determine how quickly and reliably each order is promised to be delivered to the customer (e.g. 2-day 99%). Service level performance depends on the decisional triad specifying targeted service levels, inventory level, and inventory deployment. Cui et al. (2020) indicates that customers are willing to accept a longer delivery time for long-tail products, most likely because the product is not offered by competitors. Another reason for accepting a longer delivery time is that customers are probably aware that they are purchasing

a somewhat unique product, so they have contemplated their purchase decision for longer and consequently the additional waiting time for delivery is of less importance. To the best of the author's knowledge though, there has not been scientific studies whether the desired delivery velocity depends on whether it is a head, body, or long-tail product. Moreover, as the desired delivery time generally decreases, the desired delivery time for any item is expected to decrease as well. Going forward we assume that delivery time is one of the decisive factors in the buying decision for long-tail products and contributes to converting a website visitor into a customer.

Table 1: Desired solutions for long-tail decision for retailers' profitability, sustainability, and service level

	Profitability	Environmental Sustainability	Service level
Product Assortment	Profitable long-tail products	Little to no long-tail products	Variety of long-tail products
Network wide inventory level	Network wide inventory level to match demand	Network wide inventory level lower or equal to demand	Network wide inventory level necessary for service level promise
Inventory Allocation	Units stored in low-cost FCs, yet near enough customers	Zero marginal emissions through distribution	Units in potentially high-cost FCs close to customers
Order Fulfillment	Cheapest delivery mode	Delivery mode with lowest emissions	Delivery mode and time in line with customer preference

We summarize the generally desired solution for each of the above long-tail pertinent decisions with regards to our goals of profitability, environmental sustainability, and service level in Table 1 which shows that the three goals are conflicting each other. On the positive side, fast order-to-delivery fulfillment times may lead to higher customer satisfaction, conversion rate, and revenues. On the negative side, it may lead to higher overall customer price, induced costs, and higher carbon footprint. This is exacerbated when delivery transportation is done using modes relying on fossil fuels and generating high emissions. Since long-tail products have a small number of units in the network, their nearest-to-customer unit is, on average, further away from the customer than for head and body products. The question remains therefore what economic and environmental costs justify which service level.

4   Conceptual Framework

This paper contributes to the conceptual research towards PI and to solutions-oriented research by offering a concrete example on how e-commerce can start leveraging PI characteristics for long-tail products. In addition, the long tail theory also becomes more applicable to brick-and-mortar stores (Hoskins, 2020). Moreover, the word E-commerce is typically associated with large companies, like Amazon and Alibaba, but small and local stores, such as 'mom and pop stores', increasingly require and have an online channel. For example, the number of merchants on Shopify more than doubled between 2018 and 2020 (Backlinko, 2022). The framework presented here is of interest for small and mid-sized retailers because they can leverage economies of scale which are currently not available to them. Indeed, the concepts apply to a large portion of long-tail products as well as to a multitude of retailers selling the same long-tail product, enabling increasing cost savings (Kim et al., 2021; Pan et al., 2015).

We show how four components of the PI enable profitable, sustainable, and consumer-oriented long-tail inventory management and order fulfillment. These components are: hyperconnected transportation, hyperconnected distribution and its open space sharing, open inventory sharing,

and open information sharing. The hyperconnected transportation system works best as intended if the other components are in place, and vice-versa. Therefore, we present a three-level framework that increasingly shifts from dedicated to openly shared spaces, inventory, and data, where each level is supported by hyperconnected transportation. For each level, we discuss impacts on sales, storage, transportation, and environmental cost, as well as service levels.

4.1 Level 0: Dedicated Spaces, Dedicated Inventory, Dedicated Data

For completeness, Level 0 describes the current situation that applies to most retailers. Each of them has their own storage facilities, where the inventory is owned and managed by the retailer (or its warehouse 3PL). That means orders are fulfilled only from the warehouse locations operated by the retailer. The retailer potentially loses sales if they run out of inventory, or the desired delivery time cannot be achieved. Even if they provide the desired delivery time, this might come at a high environmental cost, e.g., shipping with planes. Lastly, inventory decisions are made on the demand seen by the retailer only. As pointed out in 3.2, they might be forced to buy more than they will sell, resulting either in units sitting on the shelf and taking up space for faster turning products and/or units that are being disposed of.

4.2 Level 1: Shared Spaces, Dedicated Inventory, Dedicated Data

Level 1 leverages the hyperconnected distribution system and the hyperconnected transportation system. The hyperconnected distribution system provides shared space through a network of interconnected open-access deployment centers. The networked centers are managed and operated by logistics service providers, and each retailer can dynamically use the shared space to locate their products better for desired durations. Level 1 does not require any interactions between e-commerce retailers that offer the same long-tail product.

The concept of sharing warehouse space can already be seen in industry. For example, STORD allows companies to flexibly book warehouse space across the US. While large E-commerce retailers tend to have a fulfillment network across a larger region, this is not the case for small and mid-sized retailers mainly because operating a warehouse far away from the base location is not profitable or operationally not feasible. However, being able to only rent space in a warehouse based on the space a few units of long tail product take up becomes economically more feasible for them. Kim et al. (2021) shows that inventory holding costs and hub usage costs can be twice and three times as high as in the dedicated system, respectively, but still incurring a 10 % overall cost reduction. The consolidation of shipments within PI can result in up to 27 % reduction in delivery time (Venkatadri et al., 2016; Yang et al., 2016; Orenstein & Raviv, 2022) and generate more satisfied customers (Kim et al., 2021). Consolidation reduces environmental cost in form of emissions and transportation costs by up to 50% (Kim et al., 2021). Hence, when assuming the same demand as in the dedicated system, using hyperconnected distribution and transportation for long-tail products will reduce lost sales and induced costs, and therefore increase profits while also providing better service levels.

4.3 Level 2: Shared Spaces, Shared Inventory, Dedicated Data

While Level 1 did not require any interaction between e-retailers, Level 2 expects retailers to share their inventory for order fulfillment. As retailers who sell the same long-tail product can be in different regions, they lower transportation costs and emissions by agreeing that an order is fulfilled by the retailer whose product units are closer to the customer. A potential long-term benefit is the reduction of the inventory level for each retailer while still serving the entire region with the same service levels. The quantification of this benefit depends largely on the

minimum order quantity set by the supplier, targeted service level and the total demand, hence, requiring an extensive simulation study intended for future work. This said, for illustration purposes, consider a two-retailer scenario where the best outcome would be that each retailer only covers one half of the region with inventory, leading to a reduction in inventory costs by approximately 50 %. Legally acceptable protocols and transfer costs ensure achieving the intended benefits. PI literature (Pan et al., 2015; Yang et al., 2016) , as well as general literature (Liu, 2016; Yu & Wei, 2018; Sampath et al., 2022) on inventory sharing concentrates on inventory replenishment from one warehouse to another. Hence, the approach of shipping directly to the customer from a collaborating e-retailer is an extension of current inventory pooling methods tested in the PI context. Location data for product units needs to be made available confidentially by the retailers to a neutral fulfillment decision entity. As fulfillment decisions are completely automated nowadays, the retailers would not be required to disclose their data to the other participating e-retailers. Lastly, it should be noted that shared inventory could also be done without sharing spaces. We believe however that the most benefit is gained by implementing the components in a stepwise manner. For example, retailers may well trust this shared inventory scheme if the stock of each participating retailer is stored and made available in open-access fulfillment centers rather than in each retailer's dedicated fulfillment centers. Therefore, we concentrate on building one level on top of the other.
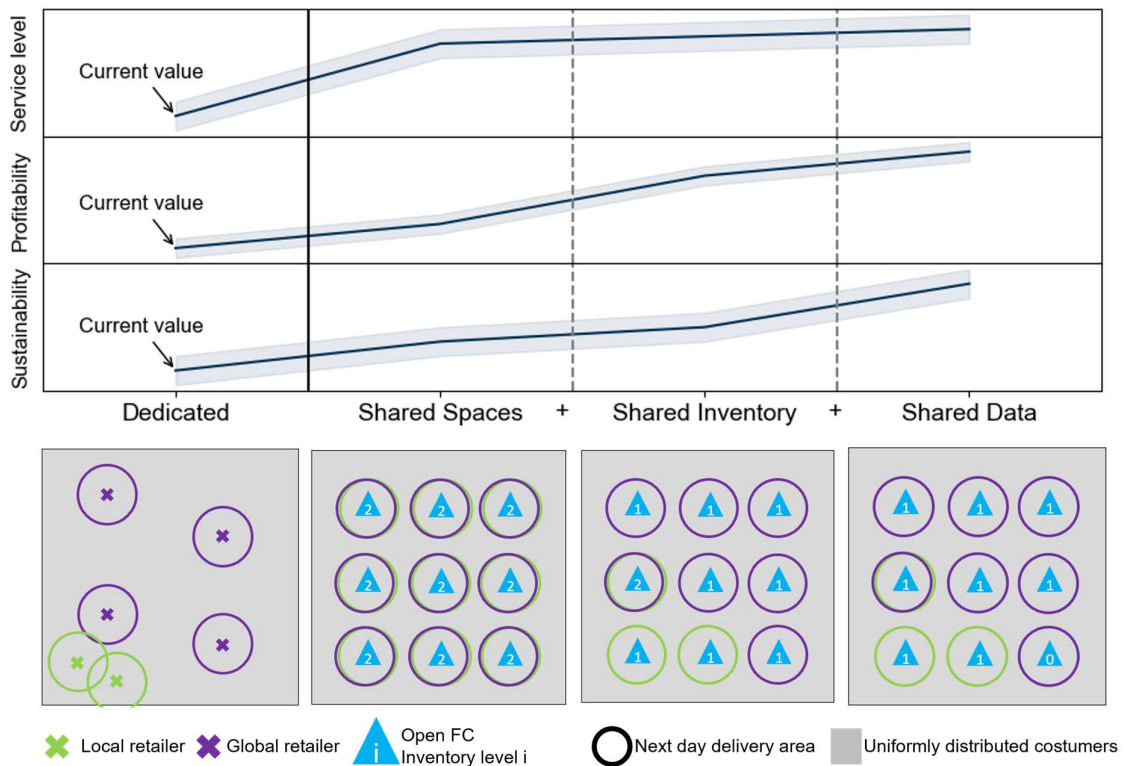

Figure 3: Influence of PI concepts on business goals for e-commerce retailers

4.4 Level 3: Shared Spaces, Shared Inventory, Shared Data

PI relies on digital interconnectivity, interoperability and information sharing to operate its networks efficiently. We apply this idea to our framework of sharing sales/demand data to reduce inventory cost and emissions by requiring less total inventory. If long-tail product demand and sales data for a given period is shared among all participating retailers, they become aware of the true total demand. This is an inventory pooling through information sharing

strategy. Generally, inventory pooling leads to a lower average inventory level which reduces inventory costs. A second effect of sharing demand and sales data is that individual inventory replenishment decisions are made accounting for the entire demand and sales. This leads to further pushing inventory sharing of level 2 (Section 4.3) to avoid ending up with unsold units in the system and the cost for replenishment orders.

Consider a case where the total year-to-date sales of a product was 6 units as of November over all retailers. A retailer who expected to sell 6 units annually and still has one unit in-stock might be more interested in sharing inventory when learning that their forecasting of their market share was an overestimate. Moreover, retailers might consider splitting batch orders from the supplier to the extent allowed by the law. As a result, inventory holding costs are reduced due to inventory pooling while the service levels of Level 1 and 2 are maintained. Environmental emissions are lowered due to the reduction of system-wide inventory level, and potentially more coordinated ordering from suppliers. Similar to Level 2, evaluating such a way of operating depends on multiple cost (e.g fixed ordering cost at supplier, inventory holding cost) and physical parameters (e.g. order batch size; actual sales; demand forecasting model; inventory control method) necessitating a comprehensive simulation study which will be considered for future work. The average per customer order transportation costs is similar to Level 2 as nothing has been changed about order fulfillment. Like Level 2, additional to the well-formulated legal and financial agreement, this concept also necessitates a well-thought-out cybersecurity and data privacy agreement aiming for fair non-colluding treatment of all participating retailers. The sharing of sales/demand data would also be feasible without sharing spaces or inventory, but the intention of this framework is to reap the benefits of all three PI components together.

The lower half of Figure 3 exemplifies how inventory deployment and order fulfillment are affected when two retailers employ the framework. The upper half indicates how sustainability, profitability and service level are expected to develop when leveraging PI concepts for long-tail products. On the left side, next-day delivery for both retailers is limited by their dedicated FCs. By using open FCs, the next-day delivery area is increased for both retailers leading to higher service levels as shown in the upper half. By sharing inventory (middle panel) and data (most-right panel), the system-wide inventory levels are reduced, indicated by the inventory level in open FC icon, notably improving profitability and sustainability in the top graphs.

5 Conclusion

Long tail products are products with low, intermittent sales, making forecasting, inventory management and order fulfillment in E-commerce even harder than frequently purchased products. The PI concepts of open deployment centers, open logistic hubs, cooperation and open data platforms can be leveraged to achieve profitability, environmental sustainability and customer satisfaction. The proposed framework consists of three levels. Level 1 utilizes the hyperconnected distribution and transportation systems to increase service levels and decrease inventory and transportation costs. Level 2 further reduces transportation costs while maintaining service levels by sharing inventory between retailers to fulfill e-commerce orders. Lastly, the sharing of sales data in level 3 can result in inventory cost savings while maintaining service levels and lower environmental emissions. Future research is necessary on the long tail thread as well as the PI thread. The long-tail thread requires a standardized, business-oriented framework for defining long-tail products in a specific organization as well as methods and models to classify a product as long-tail. Moreover, enterprises and academia need to better understand what consumers expect when purchasing unique products. Along the PI thread, a key research avenue lies in developing decision models for levels 2 and 3 and assessing the quantitative benefits of leveraging these hyperconnectivity levels.

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Online Detection of Supply Chain Network Disruptions Using Sequential Change-Point Detection for Hawkes Processes

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***Physical Internet Roadmap** (Link): Select the most relevant area(s) for your paper:* ☐ *PI Nodes,* ☒ *PI Networks,* ☒ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

1. Abstract

In this paper, we attempt to detect an inflection or change-point resulting from the Covid-19 pandemic on supply chain data received from a large furniture company. To accomplish this, we utilize a modified CUSUM (Cumulative Sum) procedure on the company's spatial-temporal order data as well as a GLR (Generalized Likelihood Ratio) based method. We model the order data using the Hawkes Process Network, a multi-dimensional self and mutually exciting point process, by discretizing the spatial data and treating each order as an event that has a corresponding node and time. We apply the methodologies on the company's most ordered item on a national scale and perform a deep dive into a single state. Because the item was ordered infrequently in the state compared to the nation, this approach allows us to show efficacy upon different degrees of data sparsity. Furthermore, it showcases use potential across differing levels of spatial detail.

2. Motivation

Covid-19 caused wide sweeping changes in society and affected all of the elements of our lives from the way we work to the way we socialize. As such, it created new needs, and it is logical to question whether supply chains were affected as people looked for new products to satisfy those needs. Such a question is normally extremely difficult to answer because of the lack of publicly available, up to date, and robust supply chain data. We, however, are in the fortunate position of having access to some of the proprietary data of a large furniture company that operates internationally.

We choose to model the network of orders as a point process because the relative scarcity of the data limits the use of some traditional time series models (e.g. auto-regressive process). Specifically, we use a Hawkes process network, a type of point process which is mutually and self-exciting, where each node represents a territorial region such as a state or county depending on the level of analysis. The rationale behind the use of the Hawkes process is that it has an element that

accounts for a triggering influence of past events on future ones. For example, if a customer buys an item of furniture and likes it, it is possible that she recommends it to a friend.

To detect change-points resulting from Covid-19, we apply two methods: a modified CUSUM (Cumulative Sum) procedure proposed by (Wang et al. 2022) and the window-limited GLR (Generalized Likelihood Ratio) based procedure discussed in (Li et al. 2017). The two methods serve different scenarios. When we have a reasonable estimate of the form of the inflection, CUSUM is computation efficient and has better performance. GLR on the other hand can deal with completely unexpected anomaly types.

To our knowledge, this is the first attempt at using sequential change-point detection algorithms on real supply chain data in a peer-reviewed setting. As such, it serves as a proof of concept and a potential framework for others who wish to try a similar task. We believe the use of the Hawkes process network could be applicable to many other supply chain situations given a similar triggering effect would be present. Additionally, we show that the modified CUSUM method is not only effective in simulation, but in a real life case.

3. Literature Review

The Hawkes process was proposed in (Hawkes 1971) and has since become popular for use in modeling situations where there is a clear triggering effect. For example, it has been used in modeling for seismology in (Ogata 1998) as an earthquake is generally followed by aftershocks. It has also been used to model biological neural networks in (Reynaud-Bouret, Rivoirard, and Tuleau-Malot 2013) as the firing of other neurons has an impact on the firing other neurons in the network. Other applications include stock price (Embrechts, Liniger, and Lin 2011), crime events (Mohler 2013), social media activities (Rizoiu et al. 2017).

However, there has been far less work done on changepoint detection for the Hawkes process. In addition, the majority of the work that has been done has explored offline change-point detection which references the entire time series and do not work in real time. For example, (Rambaldi, Filimonov, and Lillo 2016) develops a procedure for financial data to find the times when bursts in the intensity of the Hawkes process begin. However in our paper, we seek to detect change-points in real time as quickly as possible using an online method. In terms of such work, (Li et al. 2017b) examines the use of the GLR (Generalized Likelihood Ratio) test for Hawkes processes in situations in which the post-change parameters were not known. (Wang et al. 2022) develops a memory efficient modified CUSUM implementation that gives less consideration to events in the far past. This algorithm is further explained in the Background Section. The previously mentioned GLR and modified CUSUM algorithms are two tests we use on our supply chain data.

4. Background and Problem Formulation

In this section we describe the Hawkes process model on networks as well as the change-point detection problem, and how the two detecting procedures are applied to the furniture sales data.

4.1 Hawkes Process

The Hawkes process is one kind of point process, which models the probability of events happening in continuous time. It can be characterized by the intensity function $\lambda : R^+ \to R^+$, where at each time $t \geq 0$ the intensity $\lambda(t)$ is the probability that a new event happens in the infinitesimal near future, $P(\text{new event in } (t,t + dt)) = \lambda(t)dt$.

An example is the Poisson process, where the intensity function is a constant, $\lambda(t) = \mu, \forall t \geq 0$. In the Hawkes process, the intensity $\lambda(t)$ is decided by the history. Let $0 < t1 < t2 < t3 < \ldots$ be the events occurrence times. Let Ht be the set of event occurrence times up to and including time t, and Nt be counting process, i.e. the number of events in Ht. The Hawkes process captures the triggering effect between events by letting

$$\lambda(t) = \mu + \int_0^t \alpha\varphi(t - \tau)dN_\tau, \tag{1}$$

where $\mu > 0$ is the background intensity, φ is a non-negative kernel function describing how the influence of an event is distributed into the future. A common choice is $\varphi(t) = \beta \exp(-\beta t)$ for some β. $\alpha \geq 0$ is the magnitude of the triggering effect. The integral over the counting measure N_t is equivalent to taking the summation over past event times.

4.2 Hawkes process with marks

The Hawkes process can be generalized to fit events data with marks to capture the triggering effect acted through information other than temporal relationship. In our setup, each event i is an order placed online by individual customers, with the occurrence time t_i and the shipping address u_i discretized into states or zip codes. Then the orders can be treated as event data on a network, where each node is one location. For each pair of nodes with index i and j, we consider the triggering effect α_{ij} from i to j when the two geographical locations are adjacent. Then for each node i, the intensity function $\lambda_i(t)$ at this location is

$$\lambda_i(t) = \mu_i + \sum_{j=1}^D \int_0^t \alpha_{ij} \varphi(t - \tau)dN_\tau^j, \tag{2}$$

here D is the size of the network, $\mu_i > 0, N_t^i$ is the background intensity and counting process on node i. The kernel function φ is exponential.

4.3 Change-point Detection

We look to detect an abrupt change in the parameters $(\mu_i)_{i=1}^D, (\alpha_{ij})_{i,j=1}^D$ as quickly as possible. The problem can be formulated as follows:

$$H_0: \lambda_i(t) = \mu_{i,0} + \sum_{j=1}^D \int_0^t \alpha_{ij,0} \varphi(t - \tau)dN_\tau^j, t \geq 0 \tag{3}$$

$$H_1: \lambda_i(t) = \mu_{i,0} + \sum_{j=1}^D \int_0^t \alpha_{ij,0} \varphi(t - \tau)dN_\tau^j, 0 \leq t \leq \kappa \tag{4}$$

$$\lambda_i(t) = \mu_{i,1} + \sum_{j=1}^D \int_\kappa^t \alpha_{ij,1} \varphi(t - \tau)dN_\tau^j, t > \kappa. \tag{5}$$

Here κ is the unknown change-point. Then we carry out a repeated test to decide whether there has been a changepoint. The pre-change model is learnt using historical data, including the decay rate β in the kernel function φ. The post-change parameters $(\mu_{i,1})_{i=1}^D, (\alpha_{ij,1})_{i,j=1}^D$ sometimes represent an unexpected anomaly and thus are treated as unknown. In correspondence to whether or not the post-change parameters are known or can be estimated, we apply the CUSUM and GLR procedure described in the following paragraphs.

4.4 CUSUM

When the post-change parameters can be estimated accurately, CUSUM is a computational and memory efficient detecting procedure which also enjoys asymptotic optimality in performance (Wang et al. 2022). Similar with the traditional i.i.d. case, here the CUSUM statistic over the dynamic Hawkes network is

$$S_t^{\text{CUSUM}} = \sup_{0 \le v \le t} l_{v,t},$$

(6)

where $\ell_{v,t}$ is the log-likelihood ratio up to time t between H_1 and H_0 as if v is the true change-point,

$$l_{v,t} = \sum_{i=1}^{D} \int_v^t \left(\lambda_{i,\infty}(\tau) - \lambda_{i,v}(\tau) \right) \left(dN_\tau^i - d\tau \right),$$

(7)

where $\lambda_{i,v}(t)$ is the intensity at node i as if v is the true change-point, and we use infinity for the case under H_0. The procedure raises an alarm when the statistic S_t^{CUSUM} exceeds some pre-determined threshold (same with GLR). With a proper truncation on the kernel function φ, the CUSUM statistic can be computed recursively with high precision. Also the integral can be replaced with the sum over past events to avoid numerical evaluation because we know the closed form expression of $\int_0^t \varphi(\tau) d$ for every t.

4.5 GLR

When the post-change parameters are unknown, we can compute the generalized likelihood ratio in a sliding window to reflect the difference between the current data and the pre-change model (Li et al. 2017a). For a properly chosen window length w that we believe is long enough to successfully capture the change and yet not too large which results in a large detection delay, the GLR statistic is

$$S_t^{\text{GLR}} = \sup_{\boldsymbol{\mu_1}, \boldsymbol{A_1}} l_{t-w,t,\boldsymbol{\mu_1},\boldsymbol{A_1}},$$

(8)

where $\ell_{t-w,t,\mu 1,A1}$ is the log-likelihood ratio up to time t as if $t-w$ is the true change-point, $\mu_1 = (\mu_i)_{i=1}^{D}$, $A_1 = (\alpha_{ij})_{i,j=1}^{D}$ are the post-change parameters. For each t, $\ell_{t-w,t,\mu 1,A1}$ is convex in μ_1, A_1, and the supremum can be found using the Expectation-Maximization (EM) algorithm. The merit of the GLR procedure is it can detect an unexpected and unknown change, while also giving the estimated post-change parameters when it raises an alarm.

5. Experimental Setup

In each of the experiments, we use the March 2018 to March 2019 data to train the pre-change parameters of the Hawkes network using the likelihood function. To verify the effectiveness of the change-point detection procedures, we would expect the statistics $S_t^{\text{CUSUM}}, S_t^{\text{GLR}}$ to remain small until roughly March 2020 when the WHO declared Covid-19 a global pandemic (Katella 2021) and raise significantly after that. The decay rate $1/\beta = 5$ days in the kernel function φ is found manually since the likelihood ratio is non-convex over β, and the pre-change parameters $\left(\mu_{i,0}\right)_{i=1}^{D}$, $A_0 = \left(\alpha_{ij,0}\right)_{i,j=1}^{D}$ are the maximum likelihood estimates (MLE). For the GLR, we design a window length $w = 100$ days based on life experiences. For the CUSUM, the post-change parameter μ_1 can be set to $2\mu_0$ or $0.5\mu_0$ to detect a change in average demand. If it is desired to detect a local change in the demand correlation, we can design the post-change A_1 to have vanishing edges especially for large states such as California/Texas/Florida/Pennsylvania. We believe more meaningful post-change parameters can be designed with a better understanding of the reasons behind the average demand and spatial correlation.

6. Work Desk – US

We analyze the sales of a specific work desk which is the most commonly ordered item in the company on the national level. We group the addresses into the 50 states and Washington DC for the purpose of creating nodes in the Hawkes process. There is an average of 40 orders per day over the 50 states and Washington DC. You can see from Figure 1, there is a drastic jump in orders between the start and end of March 2020.
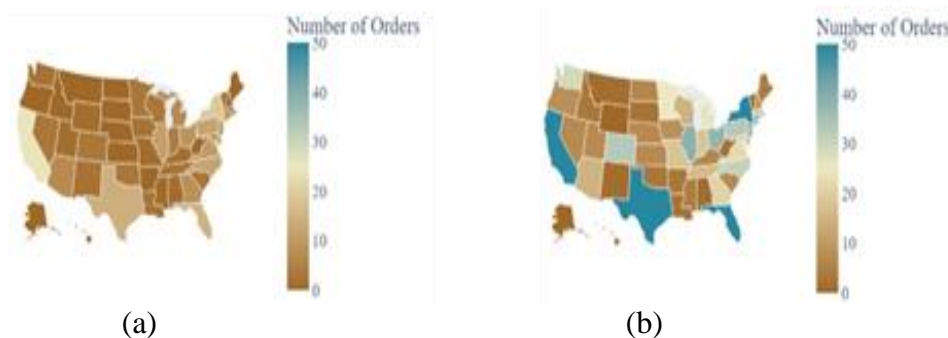

(a)   (b)

Figure 1: A mapping of the number of orders in each state for a week, for the weeks of (a) 2020-02-23, (b) 2020-04-12

6.1 Detection with GLR

As can be seen from Figure 2(a), the GLR score spikes after March of 2020 in a way that it never does between March of 2019 and March of 2020. As shown in Figure 3(a) which displays the fitted pre-change Hawkes process model, there exists a very strong causal effect between states, especially from the more populated states to their neighboring ones. Additionally, we can see in Figure 3(b) which models the fitted post-change Hawkes process that when the detecting procedure raises an alarm at the beginning of Covid, the most salient change in the fitted model is in the magnitude of the background intensities (represented as node sizes), as well as the disappearing influence from California to its neighboring states.

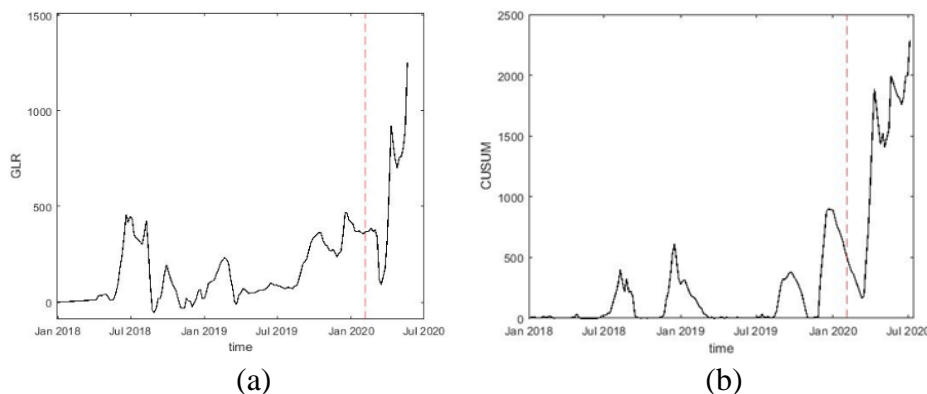(a)   (b)

Figure 2: (a) GLR and (b) CUSUM statistic over time for national orders. The x-axis is in days starting from January 21st, 2018. The vertical line marks March 1st, 2020, when Covid was declared a pandemic.

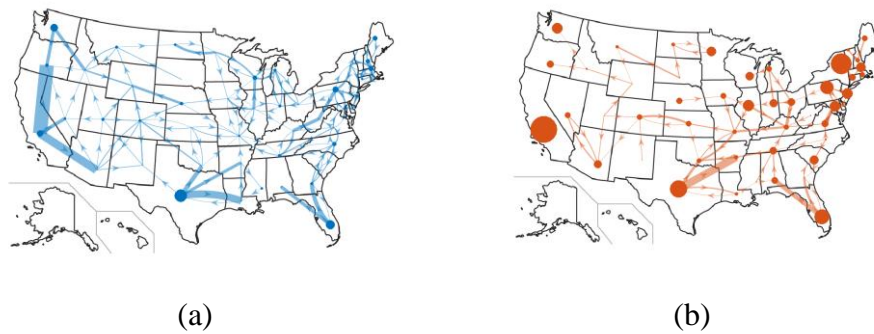(a)   (b)

Figure 3: (a) the fitted pre-change model and (b) post-change model for GLR in USA: Post-change happens at the beginning of Covid when GLR raises an alarm. The width of the directed edges corresponds to the interstate influences, while the size of the node is proportional to the background intensity.

6.2 Detection with CUSUM

We tested both possible post-change parameter for μ_1, $2\mu_0$ and $0.5\mu_0$. As shown in Figure 2 (b), we were able to successfully capture the disruption in the distribution of orders caused by Covid-19 by doubling μ_0. Given the jump in demand in April 2020 that can be observed in Figure 1, it would make sense in hindsight to attempt to detect a surge in demand. The spike in CUSUM after March 2020 is clearly visible and greatly differs in magnitude in comparison to any of the smaller spikes preceding it. CUSUM appears to contain slightly less noise, but both the CUSUM and GLR are very comparable in this situation. For CUSUM, we don't perform an analysis of pre-change vs post-change parameters as post-change parameters are predetermined.

7. Work Desk – California

For experimentation with finer granularity, we isolate the subset of the orders that came from California. We then group the addresses into the 54 counties that exist in the state for which we have data to use for the Hawkes Process nodes. There is an average of 3.5 orders a day, meaning the data is more sparse than the national level orders. The counties with the biggest increase in orders are all in the densely populated Southern part of the state as can be seen from Figure 4.

(a)   (b)

Figure 4: A mapping of the number of orders in each county in California for the weeks of (a) 2020-02-23, (b) 2020-04-12

7.1 Detection with GLR

As can be noted in Figure 5 (a), GLR spikes post March 2020 in a way that exceeds the previous apex of the GLR score. However, this spike is not extreme in magnitude when compared to the spikes that came between March 2019 and March 2020, or to the relative magnitude of the post March 2020 spike that we saw in the GLR score of the national case. There are some interesting patterns in the pre-change fitted Hawkes process displayed in Figure 6(a). Several of the counties in the middle part of California have small populations but still exhibit some influence on surrounding counties possibly because of how close the residents of those counties are in proximity. In the South, we see stronger influences from more populous counties. Moving to Figure 6(b), we see major shifts in inter-county influences in Southern California.
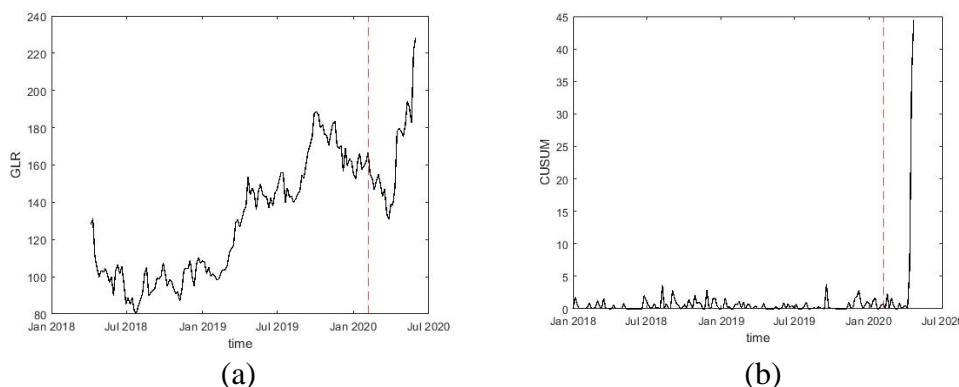

| (a) | (b) |

Figure 5: GLR and CUSUM statistic over time for California orders. The x-axis is in days starting from January 21st, 2018. The vertical line marks March 1st, 2020.
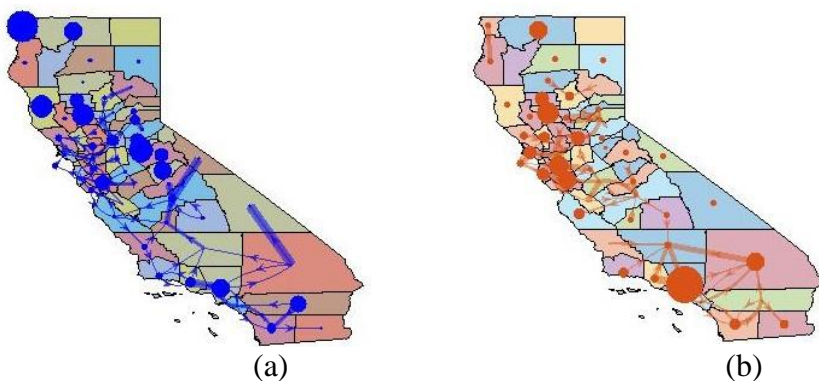

| (a) | (b) |

Figure 6: (a)The fitted pre-change model and (b) post-change model. The width of the directed edges corresponds to the intercounty influences. County color coding is not significant.

7.2 Detection with CUSUM

We again test the possible post-change parameters design and ended up finding success in setting the post-change $\mu_1 = 2\mu_0$. The CUSUM model is then successfully able to detect the surge in demand as can be observed in Figure 5(b). In hindsight, given what we can see in Figure 4, specifically the jump in demand in South California, this formulation makes sense. The model has an extreme spike in CUSUM score after the beginning of Covid while the preceding year is relatively flat. In such a way, the change point is far more clearly defined in the CUSUM model than the GLR model.

8. Discussion

Sequential change-point detection is a valuable tool for monitoring inflections in temporal data. This is the first time it has been applied to real supply chain data in peer reviewed literature. There are several novel features regarding the techniques used. Firstly, we show that the Hawkes Process can successfully be used to model a specific supply chain network. This has evident implications for other situations in which there is a clear triggering effect and data sparsity precludes the use of other traditional methods.

Secondly, we show that the GLR and CUSUM procedure can be successfully applied to online detection of changepoints in the supply chain. Both methodologies were able to successfully detect surges in demand as they were happening. However, CUSUM performed far better than GLR in the case of California and exhibited far less noise. This may have been because the specification of reasonable post change parameters prior to running the CUSUM algorithm.

There are obviously however several limitations to the approach that we used. Firstly, under regular conditions, it is not an easy task to verify the change points that have been detected. The algorithm detects a signal, but it may be difficult to understand what that signal corresponds to. Additionally, a limitation of the CUSUM algorithm is that it requires post-change parameter specification. This presents challenges in situations where post change parameters are difficult to predict. In future work, it would be interesting to apply change-point detection on other tiers of supply chain data. For example, the furniture company also makes sales to downstream sellers such as Amazon and Wayfair. Such orders come in batches and happen less frequently than sales made to individual buyers, which makes the fitting and change-point detection potentially harder.

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InnoPortAR:
Innovative applications for Augmented Reality in inland ports and seaports

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Abstract: The funded R&D project InnoPortAR (IHATEC 19H18008) ran from 2018 until the end of 2021 and focused on the improvement and digitization of workflows in inland ports through the implementation of Augmented Reality (AR) technology. Augmented Reality (AR) solutions enhance the user's perception of the real world by overlaying digital information, such as images, videos, or 3D models, onto the physical environment with the help of a device. The central challenge of InnoPortAR was to develop and test AR solutions for the port environment and give a first indicator on possible use cases and scenarios. Therefore, four use cases were selected to be implemented across the port and terminal environment: maintenance of port equipment, ship loading and unloading, container stuffing, and entrance inspection of trucks and containers at the container terminal. In all use cases, the AR solutions led to shortened process times, error prevention and better documentation. The AR apps were also successfully used to guide and train new dockers.

Keywords: Augmented Reality. Assisted Reality, Mixed Reality, inland ports, seaports, HoloLens 2

Conference Topic(s): ports, airports and hubs; technologies for interconnected logistics (5G, 3D printing, Artificial Intelligence, IoT, machine learning, augmented reality, blockchain, cloud computing, digital twins, collaborative decision making).

Physical Internet Roadmap: ☒ PI Nodes, ☐ PI Networks, ☐ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.

1 Introduction

Ports are important stakeholders in logistics and supply chains. They are central hubs for cargo shipment to other ports or inland transportation via rail, road or waterway; and the significance of seaborne trade will increase further in the future. The European Commission (2013) predicts a 50% growth of cargo, handled in EU ports by 2030. To accommodate for the rising requirements and to stay competitive, ports need to improve their work processes. Digitalization is considered as a major game changer in port development and will help to enhance efficiency, safety, security, and environmental performance (ESPO, 2019).

The funded R&D project InnoPortAR (IHATEC 19H18008) ran from 2018 until the end of 2021 and focused on the improvement and digitalization of workflows in inland ports through the implementation of Augmented Reality (AR) technology.

2 Augmented Reality

According to Cirulis and Ginters (2013), Augmented Reality (AR) describes all applications in which virtual elements such as information or images are projected over the real environment

by means of a device in order to enrich human senses and abilities. In this context, the degree of immersion is low. Unlike virtual reality (VR), AR does not create a new world around the user, but extends the existing real environment.

According to Rauschnabel et al. (2022) AR experiences can be described on a continuum of local presence ranging from Assisted Reality to Mixed Reality. Assisted Reality has low levels of local presence, the user can differentiate between the real world and the additional provided information, e.g., in additional instructions as text overlay or arrows showing directions. Mixed Reality has high levels of local presence, digital objects are projected on top of the real objects, the user perceives a mixed version of the reality, e.g., 3D models are placed over the real objects to show the inner workings.

To implement Assisted or Mixed Reality experiences appropriate hardware is needed. From today, there exist many different AR devices on the market, which can be broadly categorized into four types: head-up-displays (HUDs), holographic displays, smart glasses and handhelds like smartphones or tablets. In head-up displays, information is projected onto a transparent screen located in front of the user. In the past, they were mainly used to support pilots or for weapons systems dashboards. In the meantime, head-up displays are used in a wide variety of applications, especially in vehicles to support the driver. Holographic Displays use light diffraction to display three dimensional virtual objects in the real world. They are still relatively new on the market and mainly used for exhibitions and entertainment purposes. Smart glasses are glasses that display additional information on the lens layered on top of the real world. They can be distinguished in "optical see through" glasses and "video see through" devices. "Optical see through" glasses like the Google Glass allows the users to see their surroundings directly through a transparent display, which enables additional graphical overlays. "Video see through" devices like the HoloLens capture the reality first and show the user a combined image of the real world and computer-generated elements. Smart glasses are used for a variety of AR applications, primarily for the maintenance and servicing of machines. Handheld AR can be seen as a special kind of "Video see through" device. Special software enables handheld tablets or smartphones to be used for AR experiences. (Kore, 2018) Each device offers different advantages and possibilities to implement AR solutions.

Cirulis and Ginters (2013) distinguish six areas of application for Augmented Reality, which can overlap:

- Training scenarios
- Instructions via text, images and/or audio
- Designing via 3D visualizations
- Evaluation of new prototypes
- Information, e.g., additional provided information on television or in museums
- Entertainment like video games

Depending on the application and activities to be supported, there are different requirements and limitations for AR applications. To implement AR applications in a port environment, safety regulations and environmental factors must be considered. Also, the duration of use of the devices as well as, possible data connections are crucial for the choice of suitable technology and the sizing of the AR solution.

3 InnoPortAR use cases

InnoPortAR focused on four use cases which were implemented throughout the whole port and terminal environment. The use cases were specifically selected to apply a broad range of ports and to allow transferability to other ports and branches. The four use cases included the following topics:

- Maintenance of port equipment, using the example of maintaining crane brakes;
- Ship loading and unloading;
- Container Stuffing;
- Entrance inspection of trucks and containers at the container terminal.

Initially, the requirements and constraints were analysed for each use case, the expectations of the end users were recorded, and the AR-assistance was planned. In a second step, the existing data sources, port software and interfaces were evaluated, fitting AR-hardware was chosen and legal conditions and restrictions were assessed. After the implementation the AR-solutions were tested under real and simulated conditions at inland ports. Dockers were consulted at all stages and user surveys were conducted to address their experiences and expectations. A concluding study addressed the assessment of the transferability of the results to seaports and a guide was composed to lead users through the steps, required to conduct AR-projects.

Use case 1 dealt with maintenance and service of the safety catch brake of a gantry crane in the Port of Duisburg. For this use case an AR solution with the HoloLens 2 was developed. During the application, the components to be maintained and the instructions were visualised to provide direct support for the maintenance staff. In addition, sensor data from the brake has been integrated to ensure the correct restart of the catch brake.

In use case 2, the process of loading and unloading inland cargo ships at the Port of Duisburg was considered. An AR solution based on HoloLens 2 was implemented. All process-relevant data that were previously scattered across different media were integrated into the AR application, eliminating media breaks and displaying all the information needed on one source. Container data, stowage plans and possible storing positions were visualised in the HoloLens 2 to give the operator a clear representation of the process.

In use case 3, the stuffing process for the transportation of steel-coils in containers in the logistics company Haeger&Schmidt was supported. To provide a lightweight, mobile AR solution, the Google Glass was used, showing instructions that guide the employee step-by-step through the coil securing process. Using Bluetooth beacon-based localization, the Glass app can automatically detect which container a docker is in front of.

Use case 4 dealt with supporting dockers at the trimodal terminal in Dortmund with entrance control of trucks and containers. An AR-solution based on iPads was developed to assist dockers with OCR-based container recognition, provide all necessary safety checklists, and enable the documentation of damaged containers.

In all use cases, the AR solutions led to shortened process times, error prevention and better documentation. The AR apps were also successfully used to guide and train new dockers.

In the following chapters, use case 1 and 4 will be elaborated more detailed.

3.1   Maintenance and service of cargo handling equipment

This use case focussed on maintenance and service of cargo handling equipment in the port of Duisburg, specifically the maintenance process of the safety catch brake of a gantry crane. Without the AR solution, the maintenance of the crane parts is largely carried out using paper-based maintenance manuals and most of the time experienced personnel from the manufacturer has to perform the inspection. The goal of this use case was the development of an AR-solution to help with the maintenance of the brake units in the gantry crane and to provide a step-by-step guidance through the process. The AR solution is expected to simplify the maintenance process, enable less trained personal to perform it and accelerate the whole process.

In the first step, the process chain was recorded, and a requirement analysis was conducted. The requirement analysis focussed on port-specific requirements and challenges and provided an initial overview of the preconditions for the AR solution.

Parameter	Value		
Mobility	mobile use		stationary use
AR type	Mixed Reality		Assisted Reality
Hardware	smart glasses	display	handheld
Added value	additional information	remote access	visualisation of 3D objects
Surroundings	weather conditions	light	noise
Safety	helmet mandatory		hands-free usage
Work duration	< 2 hours	< 4 hours	> 4 hours

Table 1: Requirements checklist for the maintenance use case (Maas et al, 2022)

Table 1 lists the requirements and conditions for the maintenance use case. Instead of a display or tablet, smart glasses were chosen that can be used hands-free and display the information directly in the employee's field of vision. To assist the maintenance worker additional information regarding the process steps as well as a 3D model of the brake parts shall be displayed. If further assistance is required, an expert can be called via remote access. In the case of the maintenance activity, AR use takes place in an enclosed space with constant light and noise conditions and no helmet requirement.

Due to the port-specific criteria such as mobile usability, the insertion of 3D objects, and hands-free use, the HoloLens 2 was selected as the hardware component.

In a second step, the maintenance process was recorded as a clear sequence of actions. For this purpose, the maintenance manual and the staff of the Port of Duisburg as well as the brake manufacturer were consulted. Based on the given data, an exemplary maintenance process was developed and tested. The system design includes the implementation of an abstract AR project for the HoloLens that can be easily adapted for other maintenance tasks, as well as the connection of live data provided by sensors. To transmit the sensor data in real time, a Raspberry Pi was connected to the Programmable Logic Controller (PLC) as shown in Figure 1: System design for the maintenance use case (Maas et al, 2022)Figure 1. The Raspberry Pi processes the data and makes it available to the HoloLens 2 via Wi-Fi.
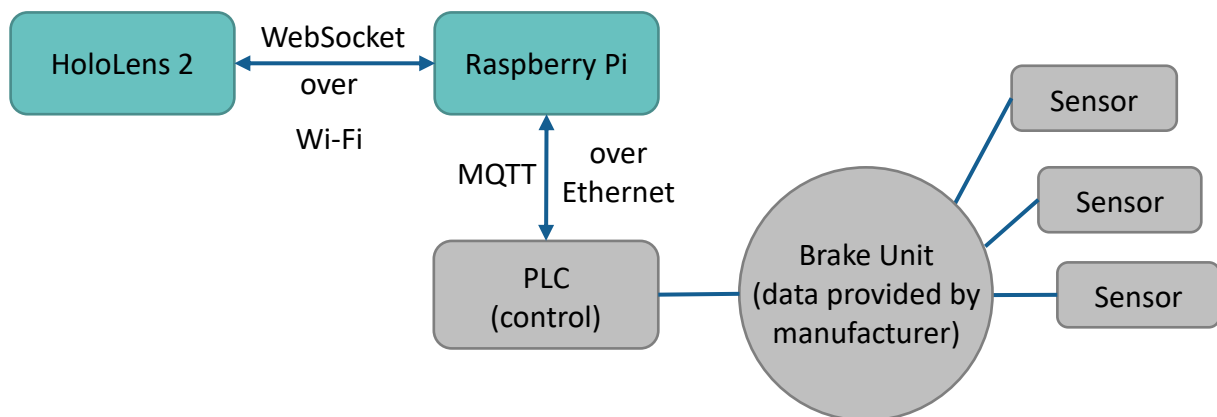

Figure 1: System design for the maintenance use case (Maas et al, 2022)

The application displays text instructions and the components to be serviced to directly assist maintenance staff. The sensor data ensures the correct restart of the catch brake and can be used for predictive maintenance in the future. In detail, the HoloLens 2 application provided the following components:

- Automatic recognition of the brake unit
- Visualisation of step-by-step guide through maintenance process
- Visualisation of relevant sensor data
- Monitoring of the maintenance steps by the crane operator
- Documentation of the maintenance process

The Mixed Reality app for the HoloLens 2 was created in Unity3D. Various approaches were discussed for the object recognition of the brake unit. Training a recognition algorithm with a set of brake images was considered as well as an approach based on 3D data. Since image-based learning would have required a lot of training data, recognition based on the 3D model data was preferred. VisionLib was chosen as the object recognition software because this library provides edge-based recognition of the real objects from 3D CAD models and can be used offline. The maintenance process was implemented as a BehaviourTree, a tree of hierarchical nodes that controls the process flow for the application.
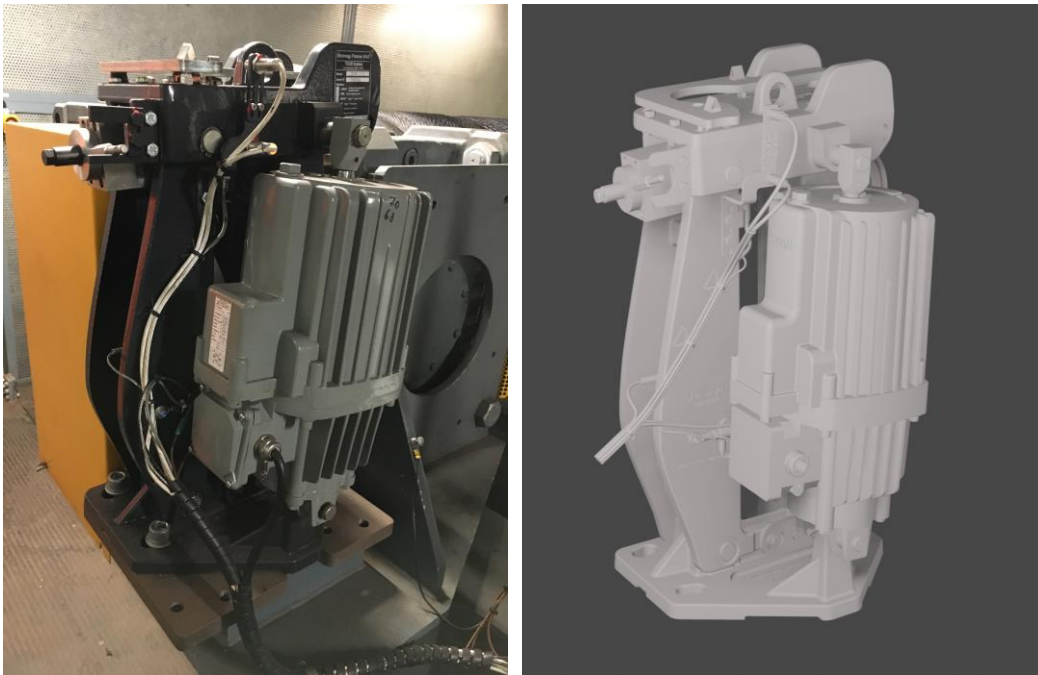

Figure 2: Visualization of the brake unit (Maas et al., 2022)

The system developed within the project was tested in the port. The realisation of the maintenance process in a BehaviourTree and the guidance of the maintenance employee via the HoloLens 2 worked very well. Since the HoloLens 2 has limited memory, an attempt was made to reload the instructions for individual process steps from the Raspberry Pi during the maintenance process. This resulted in delays due to the reloading and rendering of the data, which severely limited the user experience. Therefore, it was decided to preload the complete process for the planned maintenance procedure on the HoloLens 2 and only reload the live sensor data as required. This approach resulted in good guidance for the maintenance employee.

The object recognition of the brake unit, on the other hand, proved to be difficult. Smaller components were easily recognizable via the edges. For the entire brake unit, the system was

unable to detect the object due to overpainted edges and cables that were not included in the 3D model. For further technical tests, it was planned to develop several less complex 3D models of the brake, according to the LOD (level-of-detail) principle or, alternatively, to separate 3D models of individual components of the brake to ensure object recognition in this way. This approach could not be successfully tested during the project period.

Overall, the maintenance time could be reduced, and the documentation of the maintenance was significantly simplified for the employees, since it was automated by the program. Furthermore, the ability to call in experts remotely in the event of problems was rated very positively.

3.2 Entrance inspection of trucks and containers at the container terminal

In this use case, the support of the employees in the Container Terminal Dortmund (CTD) at the interface in the trimodal terminal was considered. The incoming inspection of containers on trucks in the terminal must be carried out according to predefined steps. In particular, the documentation of damage and the post-processing of this are time-consuming and not optimised. The AR solution developed in the project implemented image recognition for the container number in order to avoid input errors. In addition, the checking app in the CTD was further developed and the damage management was simplified. The goal of the AR application was the simplification of the checking process as well as the creation of a user-friendly checking software. For transferability reasons, the interface development was based on the DIN SPEC 91073. (DIN e.V., 2018)

For the systematic identification and presentation of the individual process steps, an actual process chain and a target process chain were created for the entrance inspection. Based on the process description, the requirements for the use case were analysed.

Parameter	Value		
Mobility	mobile use		stationary use
AR type	Mixed Reality		Assisted Reality
Hardware	smart glasses	display	handheld
Added value	additional information	remote access	visualisation of 3D objects
Surroundings	weather conditions	light	noise
Safety	helmet mandatory		hands-free usage
Work duration	<2 hours	<4 hours	>4 hours

Table 2: Requirements checklist for the entrance inspection use case (Maas et al, 2022)

Table 2 lists the requirements and conditions for the entrance inspection use case. When inspecting the trucks, the employees need to move around them, so the mobile use of the AR solution is required. Since the CTD was already working with tablets, it was decided to develop an app that guides the checker and adds Assisted Reality and image recognition elements. The environmental conditions at the container terminal are characterised by constantly changing weather, light and noise conditions, which must be considered when developing the solution. In terms of safety, it is not possible to implement a solution with data glasses, as the trucks are very close together and the employees are restricted in their field of vision by the data glasses. The tablet solution also makes it possible for employees to use the end device during the entire shift.
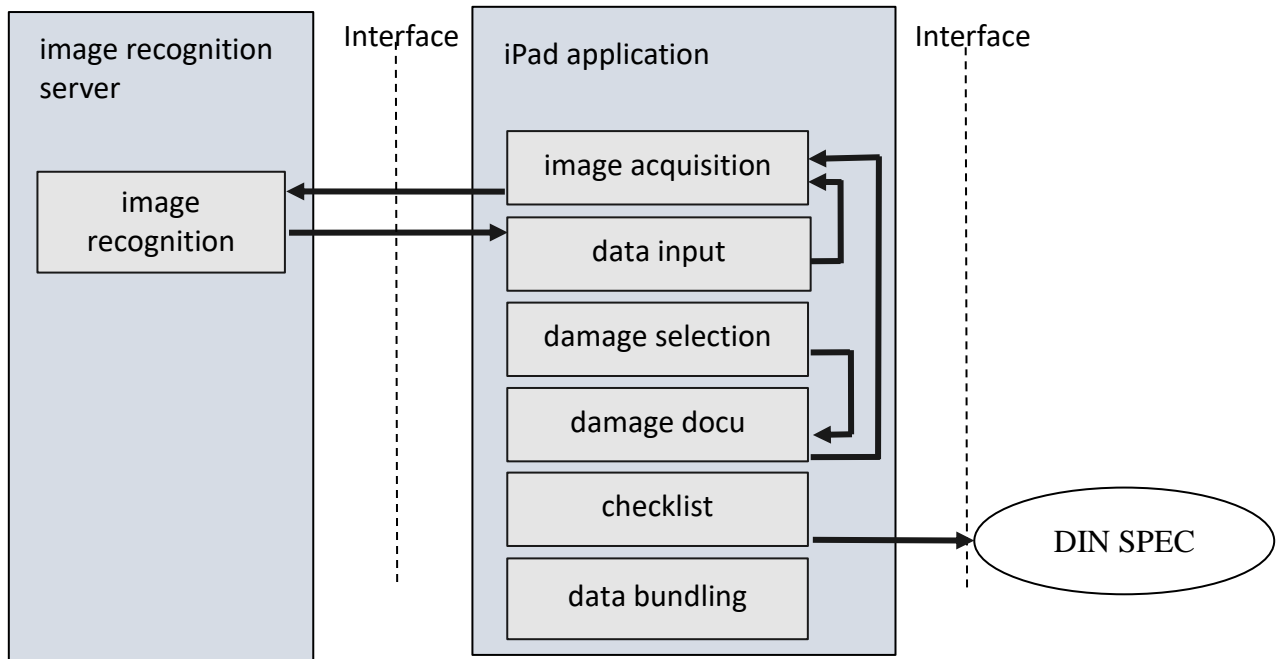
Figure 3: System architecture for the entrance inspection use case (Maas et al., 2022)

As shown in Figure 3, the process for the entrance inspection was realised by an iPad application. To identify the container data, photos are sent to a server, running an image recognition application developed specifically for this use case. After the evaluation, the image recognition sends the results back to the iPad application, where they are further processed. Afterwards, the checker can enter all other required information in a checklist as well as document damage to the container. The iPad integrated camera is used for the damage documentation, by assigning the damage data including photos directly to the corresponding container data. Finally, all data will be bundled and transferred for storage via an interface that complies with DIN SPEC 91073.

The image recognition application consists of a pipeline of several steps:

- text detection (recognition of the regions where text can be found),
- data pre-processing,
- text recognition (recognition of the characters),
- data correction.

In the iPad application, a frame is displayed in the camera image that the user positions around the corresponding text area in the image, as shown on the left in Figure 4. The image and the text frame are transmitted to the server for text recognition. Text detection first searches for the relevant text elements in the image, indicated by the green frames in the centre in Figure 4. The text segments found are pre-processed, and the characters are recognised and verified. The image recognition returns the recognised text segments character by character with a probability of correctness. In this way, the application can point out any uncertainties and the user can check them and correct them himself if it is necessary.
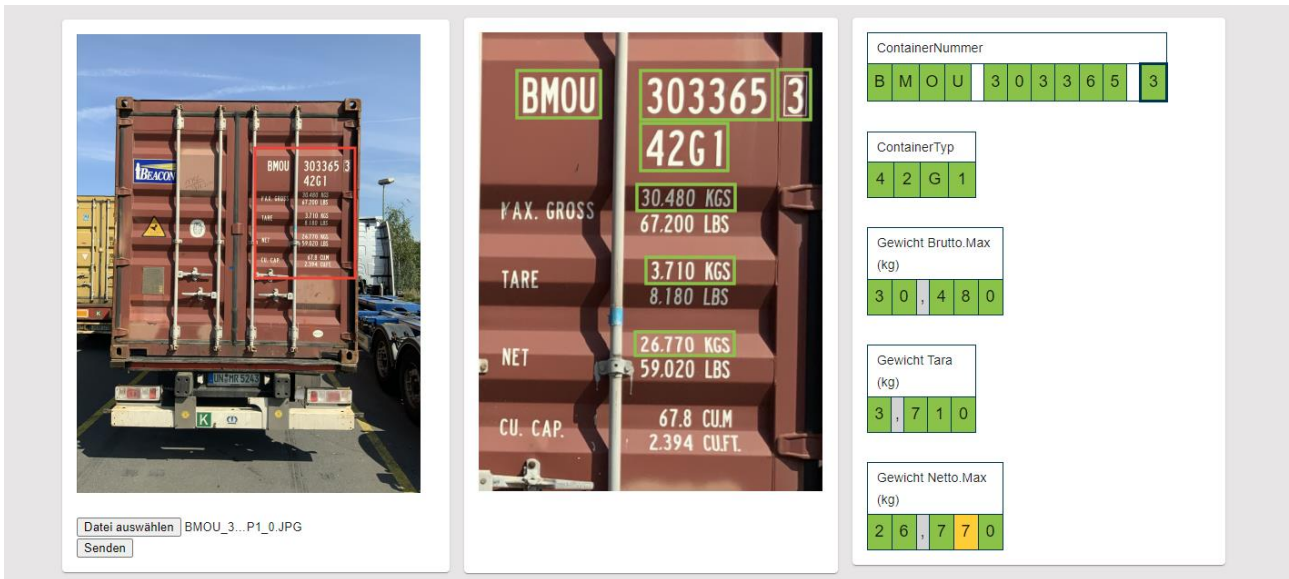
Figure 4: Image recognition for the entrance inspection (Maas et al., 2022)

The AR application was tested at the terminal by terminal-employees. The test showed that the optimised presentation of information on the tablet and the user-friendly display representation created an easier checking process for the employees. Avoiding media discontinuities, for example by using a digital camera to record damage, simplifies the process, makes it more reliable and reduces process times. Overall, the implementation of the AR solution improved the postprocessing of damages and reduced process times through the image recognition.

4 Lessons Learned

InnoPortAR gave a first insight into the possibilities of AR solutions for ports and showed some possible applications in the port environment. Overall, the AR solutions developed led to lower error rates, time savings, avoidance of media discontinuities, better documentation, and a reduction in the mental and physical strain on employees. In addition, the effectiveness of AR solutions for training and instructing new or inexperienced employees was demonstrated.

Since AR hardware is still under development and needs to be further adapted to volatile environments, AR solutions can only be used in the port to a limited extent. In particular, the use of certain AR devices is difficult due to external environmental conditions, lack of space, and safety regulations.

Comparing Assisted Reality and Mixed Reality solutions, it can be said that Mixed Reality solutions have limited applicability in an operational environment, as ergonomics, safety and battery life have to be considered. Often, the head-mounted displays required for Mixed Reality solutions can only be used for a limited time due to their weight or battery life. Restrictions on the field of vision or helmet requirements can lead to further problems in the implementation of AR solutions with head-mounted displays.

Assisted Reality solutions, on the other hand, are easier to implement in the port environment. The required hardware is often less expensive, and the head-mounted devices that enable Assisted Reality experiences are often lighter and can therefore be used for longer periods without ergonomic restrictions.

With regard to software solutions, object recognition of complex components still proved difficult at the time of the project due to algorithms that still need to be optimized and the limited computing power of AR devices.

In summary, software development is easier for standardised use cases with existing process chains and documents. To create cost-effective AR solutions, AR applications must be deployed to a large number of users. An application for a single use case is very costly. However, as AR software development and artificial intelligence evolve, development costs may decrease in the coming years. Based on the positive results for supporting employees, AR solutions are an interesting option for specific use cases in ports in the future.

5   Future perspectives

Ports will have to continue to work on optimizing their work processes and increasing their productivity. In the future, digitalization will be a driving factor in staying productive, user friendly, efficient and competitive. Agatic and Kolanovic (2020) conclude their study about port service quality in respect to the process of digitalization by saying "It is expected that in the future, seaport service quality will be determined by digitalization and more digitalized services will be implemented". Augmented Reality is one way to improve the quality of service and to educate and train employees. Studies suggest that the use of Augmented Reality will increase in the future with improved hardware and software. (Yadav and Arun, 2022)

In the AR hardware sector, improvements can be expected especially in head-mounted displays, as these are very widely used. (Tan et al., 2022) Smart glasses will become more lightweight and offer more computing power, but the development cycles are rather long. E.g., as of now, there is no release date for the HoloLens 3, the earliest release date mentioned is 2024. With the improved hardware it may become possible, to use the head-mounted displays for whole work shifts and to reload and render data dynamically.

The sensor technology is also constantly being improved. Of particular interest here are LiDAR sensors, which measure distances and help with orientation and detection of obstacles and complex environments. LiDAR sensors are already built into some mobile devices, such as the Apple iPad Pro. (Makarov, 2022)

Development is also progressing in the software sector. New methods for object recognition and tracking are being developed and existing ones improved. The AR libraries for mobile devices, ARKit from Apple and ARCore from Android, are constantly being expanded and more and more devices support them. (Makarov, 2022) The aforementioned use case for entrance inspection is currently being extended with the help of ARKit, so that damage to the container can be recorded in the future by clicking on a virtual grid placed over the container side.

The further distribution of 5G connectivity also offers interesting opportunities for AR solutions. For example, 5G could solve the problem of patchy network coverage in large areas such as ports. On the other hand, 5G can also help improve localisation accuracy - both on outdoor terrain and indoors. Given the high efficiency of communications and the high density of base stations, the emerging 5G has the potential to circumvent the limitations of existing localisation technologies in their accuracy and usefulness. (Tan et al., 2022)

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Policy Approaches for Placing Parcel Lockers in Public Space

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Abstract: This paper explores policy approaches for parcel lockers in public space. While last-mile delivery service providers primarily focus on the economic and customer service benefits of parcel lockers, securing approval from local governments to place lockers in public spaces requires justification of their public value. Our study identifies six factors that decisionmakers can consider when evaluating requests for parcel locker placement: carbon emissions, nuisances of the delivery vehicle, nuisances at a locker location, customer preferences, innovation, and the pull effect of parcel lockers. Through a series of semi-structured interviews and a workshop with public decisionmakers in cities across the Netherlands and Europe, we find that delivery vehicle nuisances and potential new nuisances at the locker location are important factors for decisionmakers at local government. Our study reveals two distinct approaches taken by local governments when facing requests for parcel locker placement in public spaces: reactive and proactive. Overall, this study contributes to the understanding of the policy perspective on parcel lockers in public spaces and provides insights for sustainable urban logistics planning.

Keywords: Parcel lockers, public policy, last-mile logistics

Conference Topic(s): Omnichannel & e-commerce logistics; PI implementation.

Physical Internet Roadmap ([Link]):

☐ *PI Nodes,* ☐ *PI Networks,* ☐ *System of Logistics Networks,* ☐ *Access and Adoption,* ☒ *Governance.*

1 Introduction

Last-mile delivery services are turning to collection and delivery points to manage costs, improve customer service, and reduce their carbon footprint. Collection and delivery points can either be staffed, such as in gas stations and supermarkets, or unmanned parcel lockers. They can be situated on private property, like in apartment buildings or parking garages, or in public spaces. This study specifically focuses on the placement of parcel lockers in public spaces. Public space is limited, particularly in densely populated urban areas, and is subject to the competing demands of various stakeholders. Local governments play a vital role in managing public spaces; consequently, their approval is frequently necessary before parcel lockers can be installed in such locations.

Delivery companies are primarily concerned with the economic and customer service benefits of parcel lockers, which is why most research on the subject concentrates on network and delivery route optimization (e.g., Deutsch & Golany, 2018; Orenstein et al., 2019; Sitek et al., 2021). However, securing approval from local governments to place parcel lockers in public

spaces requires justification of their public value. The latter is not as well understood as its economic value and there is a lack of understanding of how local governments make decisions on parcel locker placement in public spaces. Hence, our research question is: *How does local government evaluate placement requests for parcel lockers in public spaces?*

2 Evaluation framework

Parcel lockers are one form of collection and delivery points, where a customer can retrieve or return their parcel. Other forms include shop-in-shop locations and neighborhood hubs. Because parcel lockers are an unmanned solution—a customer uses a one-time password, barcode, or QR code to access the locker—they are always accessible and can be placed in public space. No previous studies examined parcel lockers mainly from a policy perspective (Olsson et al., 2019). Instead, most studies take the perspective of the last-mile delivery service provider. Nonetheless, those studies provide insights that can be relevant for public decisionmakers in evaluating placement requests for parcel lockers in public spaces. Below, we discuss those factors that may play a role in this decision making.

There is ongoing debate about the ability of parcel lockers to reduce harmful **emissions**. From the perspective of the last-mile delivery service provider, including parcel lockers in delivery networks enable more efficient delivery routes (Enthoven et al., 2020) and could thus reduce emissions from delivery vehicles. Parcel lockers can also reduce the rate of failed deliveries (Mangiaracina et al., 2019) and vehicle idle time—significant drivers of harmful emissions in urban delivery routes (Figliozzi et al., 2020). Looking at the last-mile delivery system more generally, it is likely that the emission reduction of the delivery vehicle is offset by the mode choice of customers traveling to the parcel locker (Niemeijer & Buijs, 2023). Their study of over 50,000 customer trips show that the mode choice is influenced strongly by distance—if the length of the trip to a parcel locker is more than 400 meters, more than 10% of customers take the car and may thereby collectively emit more carbon than the delivery vehicle saved.

Last-mile delivery vehicles have been subject to criticism. They congest narrow streets, are noisy, park on sidewalks, and are involved in accidents and unsafe driving behavior. Christie & Ward (2019) explored road safety of parcel delivery drivers and found they perceive strong pressure to drive fast due to piece-rate payment schemes, use distracting work apps in their delivery vehicle, are exhausted due to grueling work schedules, and speed to meet delivery targets. These factors have a direct relationship with vehicle use. Shorter route length, fewer failed deliveries, and shorter stop times may decrease delivery **vehicle nuisances**.

Parcel locker may also create new **nuisances** themselves. For instance, they will likely lead to increased vehicle movements and parking near the locker—both of delivery vehicles and of customers using their car to travel to the parcel locker. This may be undesirable if driving space and parking opportunities are limited. Customers may feel unsafe using lockers, as they worry about potential criminal activity (Lachapelle et al., 2018). Therefore, the location decision should include consideration for perceived safety, for example, by locating parcel lockers in open areas behind shopping centers, lockers facing away from the street obscuring potential assailants, lockers with only a single exit opportunity, and so on.

Another reason to consider parcel locker placement is that it may meet **customer preferences**. Compared to unattended home deliveries—which may lead to negative feelings about security—some customers favor parcel locker delivery (Merkert et al., 2022). Generally, most customers still prefer home delivery though, but this may shift towards self-collection if there is a monetary incentive to do so compared to home delivery (Buldeo Rai et al., 2019).

Parcel lockers are often perceived as innovative, or as a driver for further **innovation** towards sustainable last-mile delivery. A parcel locker design with a fixed locker bank is implemented most widely, but there is no standard design yet. Faugère & Montreuil (2020) explore the option of modular locker towers within a locker bank while others contemplate mobile parcel lockers (Schwerdfeger & Boysen, 2020). Instead of requiring a permanent position in public spaces, mobile parcel lockers would require multiple locations where they can park for a certain period. They could be combined with cargobike logistics or play a role in optimizing crowd shipping (Gatta et al., 2019). These developments also explain why parcel lockers are a potential driver for innovation.

Lastly, parcel lockers could pull economic activity toward nearby stores. Early research on parcel lockers found that a quarter of consumers using a parcel locker also purchase something at a nearby store whilst retrieving or returning a parcel (Weltevreden, 2008). Not much research has been performed on this **pull effect** since.

A review of the academic literature on parcel lockers—and collection and delivery points more broadly—reveals a list of six factors that public decisionmakers may consider when they evaluate placement requests for parcel lockers in public spaces: emissions, nuisances of the delivery vehicle, nuisances at a locker location, customer preferences, innovation, and the pull effect of parcel lockers.

3 Methodology

Our methodology consists of two different stages, namely a series of semi-structured interviews at Dutch local governments followed by a workshop and multiple case study.

3.1 Semi-structured interviews

We first conducted semi-structured interviews with decisionmakers in local government. We aimed to capture a variety of policy approaches used in evaluating requests for parcel locker placement by selecting cities with different characteristics. For example, we expected different results across cities because some have no parcel lockers in public space yet, whilst others have over fifteen. We also expected different results because some cities have more public space available than others due to different spatial development. Specifically, older cities often have less public space available as streets were not designed with cars and trucks in mind.

In total, we conducted 12 interviews across different cities in the Netherlands (see Figure 1 for the geographical spread of the cities). The interviews lasted 45 minutes on average, ranging from 37 to 68 minutes. During these interviews, we spoke to 14 public decisionmakers knowledgeable about parcel locker location issues—two interviews included two interviewees from the same city. The decisionmakers were mostly policy advisors with a focus on mobility, freight transport, public space, air quality, retail and leisure, or sustainability. Before the interview, all participants consented to be recorded. Afterward, they were informed how their data would be used (Turner, 2010). Alongside a transcript, interview data was categorized using structured meeting notes. These meeting notes aid construct validity (Karlsson, 2016; Yin, 1994) in the same way a coding scheme would whilst also allowing straightforward post-interview verification by the interviewee. In fact, several interviewees reached out to develop the meeting notes with data that had not come up in the initial interview.

Interview questions were designed to be neutral, clear, and open-ended, aiding reliability (Yin, 1994). In general, the interview consisted of introductory questions, an open discussion about parcel locker placement requests, focused questions aimed at weighing the six factors that public decisionmakers may consider when they evaluate placement requests, and some

concluding questions. For weighing the six factors, we adopted a point allocation method from multi-criteria decision making (MCDM) research, specifically by letting interviewees divide 100 points across the six factors (Bottomley et al., 2000; Mukhametzyanov, 2021). MCDM methods have been used previously in transport policy research as reviewed by Gohari et al. (2022). Our point allocation method is easy to understand for interviewees and forces them to consider trade-offs in the relative importance across all six factors (Zardari et al., 2015). The other elements of the interview were aimed at elaborating on how the points were allocated and how the city deals with requests for parcel locker placement generally.

Figure 1: Geographical dispersion of local governments in this study

Our analysis of the interview data began by identifying similarities in the results of the point allocation method. We then employed an iterative process to uncover different policy approaches by examining the point allocation results, meeting notes, and quote comparisons from interview transcripts. During the interviews, some participants shared internal guidelines for evaluating requests to place objects in public space, allowing us to compare their statements with their written guidelines. Additionally, we reviewed long-term spatial planning visions published by some cities, which confirmed our understanding of their commitment to reducing vehicle movements. To further support our findings, we utilized maps of last-mile delivery service providers to verify the presence of parcel lockers in public space, and to gauge potential issues related to their location. Through this approach, we obtained preliminary insights into the policy approaches governing the placement of parcel lockers in public spaces.

3.2 Workshop and multiple case study

After completing the semi-structured interviews, we presented the results at a workshop for cities participating in the EU Horizon 2020 project ULaaDS. This workshop was attended by public decisionmakers from cities across Europe. The workshop provided a valuable platform to examine the different policy approaches and their implications.

4 Ranking of factors

First, we present the results of the semi-structured interviews. Specifically, Table 1 shows the outcomes of the point allocation method. These illustrate in broad strokes that delivery vehicle nuisances are an important factor for local decisionmakers when considering parcel locker placement. Table 1 suggests that anticipated reductions in delivery vehicle nuisances are weighed against any new nuisances that may be created at the locker location—another factor with a generally high importance. Generally, innovation and the pull effect receive little attention. Emissions and customer preferences receive mixed scores, suggesting they are important factors in some cities, but not in others.

Table 1: Results of the point allocation

City	Emissions	Nuisances by vehicle	Nuisances at locker	Customer preferences	Innovation	Pull effect
City A	25	10	25	25	10	5
City B	10	40	30	10	0	10
City C	20	25	10	15	10	20
City D	35	35	15	15	0	0
City E	21	30	21	11	6	11
City F	25	30	10	20	5	10
City G	0	20	30	20	15	15
City H_1	30	30	30	0	10	0
City H_2	20	20	20	20	20	0
City J	0	60	25	5	5	5
City K	33	34	33	0	0	0
City L_1	10	40	10	30	5	5
City L_2	30	20	20	30	0	0
City M	0	0	100	0	0	0

Prior research suggests that parcel locker networks can reduce the number of failed deliveries (Deutsch & Golany, 2018), reduce distance driven by delivery vehicles (Enthoven et al., 2020; Iwan et al., 2016), and thereby reduce the number of delivery vehicles (Deutsch & Golany, 2018). By contrast, several local decisionmakers see parcel lockers as a useful solution when they would ban delivery vehicles in specific streets: *"There should be no vehicles at all in the public space of City H. They are tacky. At this point, we feel City H should no longer be gray, but green and livable instead. [...] With parcel lockers we will not remove delivery vehicles from the municipality fully, but we can get them out of the capillaries of neighborhoods. They no longer need to go through every street of a neighborhood"* (City H_1). Similarly, City A is developing a new neighborhood where no cars may enter at all. This is a novel insight on how parcel lockers fit into policy approaches of local governments.

All interviewees deem nuisances at the locker location as a primary constraint for placement in public spaces. For some interviewees, it is clear that they will almost always prohibit placement of parcel lockers in public spaces as they perceive too high of an impact of parcel lockers on public spaces. *"The chance of a parcel locker passing our decision framework is very small. This is a guiding principle, as there is so much demand for use of public space"* (City B). Also: *"We have a vision on spatial structure in City H. Therein we named the content for all public space. ... Other than functional street furniture such as a bike rack or a bench we do not want to offer any objects in public space. ... We do not want parcel lockers in public space at all"* (City H_1). Other interviewees pose that reduced vehicle movements may not be achieved if parcel locker placement is obstructed significantly: *"Not wanting to work with them [parcel*

lockers]. I would like to flip it. Everything. Why would you not want to work with them? This is a fundamentally different vision, right? A different point of reference" (City M). The degree of restrictiveness for placing parcel lockers in public spaces is offset against the perceived effectiveness of parcel lockers in reducing vehicle movements—and we observed fundamental differences between decisionmakers in that regard during our interviews.

5   Policy approaches

Our study also identified two distinct approaches that decisionmakers in local governments take when facing requests for parcel locker placement in public spaces. The first approach is a *reactive* one, where requests for parcel lockers are addressed on a case-by-case basis. Delivery companies request a location that is optimal for their business, and local government either approves or denies the request. The second approach is *proactive*, where the local government actively participates in location decisions for parcel locker placement in public spaces.

5.1   Reactive policy approach

Many cities adopt a reactive policy approach. The common denominator in this policy approach is that requests for parcel locker placement in public spaces are generally considered case by case. Differences emerge depending on the attitude of the local government towards parcel locker placement in public spaces, which could be more negative—resulting in a de facto restrictive policy—or more positive, leading to a generally permissive policy.

5.1.1   De facto restrictive

The de facto restrictive policy was identified most saliently in City J. Their approach is based mainly on a fear of many locker providers conglomerating at the same location: *"Our urban planner would already be worried about a single locker. Say that a locker is placed in the city center at the central station, a place where everyone comes. Suddenly, four more parcel companies want to have their parcel locker there. [...] Maybe we should not do it, if the alternative is getting four parcel lockers.* (City J)*"*. City J perceives very little opportunities for parcel lockers to be placed in the city center: *"Especially in the inner city, parcel locker placement would not result from their ideal location based on science but on the very few locations where they would even fit. [...] It's a consistent point of attention, how can you fit things nicely."*. Finally, City J believes that postal companies have plentiful opportunities in private space, and hence sees little need for parcel lockers in public spaces: *"Why should a delivery company get public space? Currently, postal companies manage inside specific third-party stores. ... It will always be a question, should we even consider parcel lockers in public space?"*.

Following the initial interview, City J developed a decision-making framework based on the de facto restrictive approach. This framework helps guides the response to placement requests by parcel companies. Furthermore, the framework allows any locker provider to easily familiarize themselves with the municipality stance on parcel lockers in public space. The framework of City J is based on two guiding principles. First, the distance to existing parcel points, as this guides the mode of transport used by consumers (c.f., Niemeijer & Buijs, 2023). Second, the use of public space should only be considered if no private space is available. Any building destined for commercial use—excluding restaurants and pubs—is classified as available private space is. Residential buildings such as flats or apartment blocks are not considered as the commercial exploitation by locker providers is currently too limited.

5.1.2 Generally permissive

The generally permissive policy was found most strongly in the semi-structured interview with City M, which was approached by a major Dutch parcel delivery company with a request for parcel lockers in public spaces. The local government created a decision framework to assess placement requests. Within this framework, City L assumes that parcel lockers generally have a positive effect and that parcel delivery companies are best suited to determine optimal parcel locker locations. To reduce decision making time, the municipality now considers itself solely an auditor of placement requests.

In our semi-structured interviews, policy advisors often noted a concern of many parcel lockers suddenly appearing next to each other in public spaces if they adopt a permissive approach. From City M, we learn that this concern is not necessarily valid: *"They used those arguments: Well, you will get 25 kinds of parcel lockers next to each other. It will look horrible. Guys, I don't see that happening yet. If the problem were to arise, we would do something about it. However, it is not something we will regulate beforehand as it will kill the entire concept as well"* (City M).

Another lesson learned is that by simply starting to permit parcel lockers in public spaces local government will learn how to fill in a decision framework along its own wants and needs: *"Then they placed the lockers. This caused quite a stir. Suddenly everyone felt they needed an official permit. So, we started that trajectory. Then, the environmental committee voiced their opinion. The locker was too big, there was too much advertising. I said, do you not want the lockers? This was not the case, they just had certain requests. All parts of the municipality had to have their say. You simply have to endure that and make some changes to the existing parcel lockers. […] We added all of that into a procedure. What does the municipality find important? We had done this previously, but now we made it official."* (City M).

5.2 Pro-active evaluation

At the time of the semi-structured interviews, none of the cities we studied had a pro-active policy approach, where the evaluation of parcel locker placement requests in public spaces is an integral part of a broader sustainable urban logistics plan. During the workshop, the city of Mechelen and last-mile delivery service provider bpost discussed their Ecozone approach, now rolled out to six cities across Flanders, Belgium. The city of Mechelen took a pro-active stance and published a public tender for parcel lockers in public spaces in 2018, and again in 2021.

After awarding the contract to bpost, the city of Mechelen and bpost together determined the ideal number and location of parcel lockers in public spaces. This involved coordination among different departments within local government and with bpost. The coordination efforts resulted in a network with 57 collection and delivery points within the inner city of Mechelen, including eight manned pick-up points and 49 parcel locker locations. The Ecozone not only involves developing the network of collection and delivery points, but also the greening of the fleet of delivery vehicles and a microhub to complete the network. The parcel lockers and home addresses in the inner city of Mechelen are supplied by cargo bikes. Due to the dense network of parcel lockers, 81% of customers traveled less than 500 meter to collect their parcel—resulting in a minimal use of car travel. 85% of customers picked up their parcel by bike or on foot. Overall, the Ecozone reduced total carbon emissions by 97%: 122.4 ton was avoided because of bpost using zero-emission vehicles and another 0.6 ton was avoided by changing customer travel behavior when going from and to a collection and delivery point (VUB Mobi, 2021).

6   Conclusions and discussion

In this paper, we discuss policy approaches for parcel lockers in public space. If last-mile delivery service providers want to locate parcel lockers in public spaces, they require the approval from local government. When faced with a request for parcel locker placement in public spaces, decisionmakers at local government will consider the public value parcel lockers may bring. Our study shows that carbon emissions, locker location nuisances, delivery vehicle nuisances, customer preferences, innovation, and the potential pull effect on nearby commercial establishments are elements that can be considered. The results of 12 semi-structured interviews and a workshop with public decisionmakers in cities across the Netherlands and Europe provide a clear picture of how decisionmakers weigh these elements when considering a request for parcel locker placement in public space. Interestingly, the study reveals decisionmakers at local governments mostly see parcel lockers as a solution to address delivery vehicle nuisances, whereas the academic literature primarily views parcel lockers as a means to reduce carbon emissions and improve customer service through improved consolidation and reduced failed deliveries.

Local governments either adopt a reactive or proactive approach when facing requests for parcel locker placement in public spaces. Many cities take a reactive approach, mostly addressing requests for parcel locker placement on a case-by-case basis. Under this approach, delivery companies consider what would be a suitable location for their operations—considering the economic and customer service benefits of parcel locker—and file a request for placement at the local government. If the location is not suitable from the perspective of the local government, for example because it would attract unwanted vehicle movements, the request is denied, and the delivery company could file a request for another location. This back and forth commonly results in few—if any—parcel lockers in public spaces. Even in these cities, though, parcel lockers tend to pop up on private property, but only where they make economic sense for the delivery companies. This means that the negative externalities associated with these locations, such as nuisances at the locker location or increased emissions from customers picking up their parcels by car, are beyond the control of the local government.

A few cities around Europe have taken a more proactive approach, for example, by publishing a public tender for operating a network of parcel locker locations in the city. While a proactive approach requires extensive coordination across different departments within local government and communication with potential delivery companies, such an approach can result in more positive outcomes of parcel locker placement in public spaces.

Acknowledgements

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5G-enabled innovation in ports' logistics: expectations from the 5G-LOGINNOV Project and relevance for the Physical Internet

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Abstract: The EU funded 5G-LOGINNOV Project will support the generation of new 5G-enabled technologies for logistics operations in three Living Labs (LLs): Athens, Hamburg, and Koper. Athens mainly deals with technologies for real-time tracking and enhanced visibility of 5G yard-trucks for service optimization, job allocation and predictive maintenance; Hamburg addresses the usage of 5G to improve port operations, specifically for connecting the Hinterland to the port's facilities; Koper focuses on 5G enabled technologies to improve the automation of logistics processes in ports and to support mission critical services in the port area. Therefore, the Project will ensure relevant advancements for Physical Internet, pushing for supply chain synchronization and "5G-intelligent" approaches for the management, routing, and optimization of operations in ports areas. This study presented in the paper aims to present the methodology to assess stakeholders' expectations on the potential benefits of 5G-enabled technologies on business models and operation. While preliminary results of the assessment have been presented, the analysis will continue until the end of the demonstration period by assessing if stakeholders' expectations have been met.

Keywords: 5G, logistics innovation, stakeholders' expectations.

Conference Topic(s): business models & use cases; logistics and supply networks; PI impacts; PI implementation; ports, airports and hubs.

Physical Internet Roadmap (Link): Select the most relevant area(s) for your paper:☐ PI Nodes, ☐ PI Networks, ☒ System of Logistics Networks, ☒ Access and Adoption, ☐ Governance.

1   Introduction

The relevance of 5G as a support element for the implementation of the Physical Internet (PI) is one of the aspects that are being developed within the framework of the 5G-LOGINNOV Project[1]. This project is a Horizon 2020 Innovation Action, which started in September 2020 with a 36-month duration and involves 15 partners belonging to a vast range of stakeholders' categories, including logistics providers, infrastructure and communication operators, automotive industries start-ups and SMEs, and research institutions.

The aim of the project is to support the creation of a European market supply that serves as a flywheel to the development and diffusion of 5G core technologies and IoT devices. Therefore, 5G-LOGINNOV is aimed at fostering the emergence of new market players,

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[1] https://5g-loginnov.eu/

capable of developing new products and services applying 5G technologies within logistics processes and contribute to the development of globally harmonized standards for the implementation of 5G devices in the field of logistics and transport processes. To this end, the 5G-LOGINNOV project will contribute to the development and implementation of different Use Cases (UCs) in three port cities, namely the Living Labs (LLs) of Athens, Hamburg, and Koper, with the aim of supporting the future usage of 5G-enabled innovations in logistics processes.

2 Linked works and motivations for the study

With the massive increase of flows of people and goods, various limitations related to traditional logistics solutions have been brought into light. In this regard, Montreuil et al. (2011) underline the unsustainability of logistics, highlighting various aspects that limit the efficient use of resources and the optimization of processes. The first of these disadvantages is that containers travel empty or not fully loaded in most cases, constituting a waste of resources and time, and affecting the efficiency of the logistics chains. In many other cases, the goods are unnecessarily moved through logistic chains that extend for several kilometers, without there being a clear and smart planning of the chain capable of optimizing the logistics processes. Logistics networks are developed in a disorderly way and do not communicate effectively with each other, using different operating standards and with infrastructures that are often inadequate to interact in a multimodal system. Another fundamental aspect is linked to the safety of drivers, who are forced to make long journeys and encounter various health problems due to a lifestyle that keeps them away from their families and loved ones. Finally, a system thus developed constitutes damage to the environment, causing a strong increase in CO_2 emissions and compromising the air quality in inhabited areas.

The PI paradigm has been designed to overcome these limits, representing an open and interconnected logistics system, in which goods can travel through multimodal logistics chains on standardized containers (Montreuil et al., 2012). In the definition of Ban et al. (2021), the Physical Internet "*enables hyperconnected logistics which is capable of transforming the freight transport fragmentation, logistics and distribution industries into a single manufacturing. Goods would be encapsulated and designed in standard for logistics that are modular, smart and reusable PI-containers…. (that) can be routed from end to end through open hubs by developing real-time identification, tracking, and communication systems. Also, PI containers can store data or information required during different operations in terms of handling and transportation*". In this view, Physical Internet is a concept that conceives logistics networks as an interconnected system which, similarly to the Internet, uses standardized languages and models to allow its parts to communicate effectively by exchanging information. Unlike current logistic processes, this data is exchanged between one logistic node and another using common protocols, such as to allow the exchanged units, i.e., containers, to be transported more efficiently. These units must necessarily have common standards in order to function effectively. In particular, the containers must have standardized dimensions to make transport more efficient, and at the same time they must be equipped with devices capable of providing information on the external and internal environment, in order to guarantee the monitoring of the transported content. Furthermore, it is necessary that they are recognizable, i.e., that they have unique identifiers according to a common standard in order to guarantee tracking, management and storage. At the same time, the means used for handling containers, i.e., all the devices and tools used to move the latter from one point to another, must be designed to interact with the units being transported. This implies the adoption of technologies such as IoT systems that

allow a continuous exchange of information on logistics processes and increase the flow of data aimed at supporting decision-making processes. Finally, logistics nodes and protocols are two building blocks of the Physical Internet. The logistics nodes are represented by all those infrastructures used for the management of flows, or rather the starting and arrival point of the latter. Together with protocols, they are a fundamental part of transport network management, and have the key role of facilitating the inbound and outbound flow of containers. Inside the logistics nodes, the information flows are processed by means of sets of rules and standardized procedures, or rather the protocols, which serve to implement the ability of the logistics network to communicate in all its parts.

The application of a system designed in this way implies the need to implement technologies capable of effectively connecting all the components of the logistics chain. To this end, IoT devices, such as wireless sensors, AI, GPS devices that exploit the 5G internet network can be used to optimize logistics processes, being able to be integrated with the components of the production cycle, increasing efficiency. Tran-Dang et al. (2020) summarize these technologies into four basic groups:

1) Data acquisition technologies. This set identifies all IoT systems and devices aimed at acquiring information on logistics processes. They include systems aimed at identifying cargo and containers, such as QR codes and bar codes, those used to collect information about the surrounding environment, such as sensors, and those aimed at tracing the different components, such as GPS and GRPS systems.

2) Connectivity technologies. This vast group includes all the technologies that serve to speed up and make more efficient communications between the various components of the logistics chain. They apply to all activities of the production cycle and include the mobile communication networks that allow the functioning of the Physical Internet. This set also includes 5G technologies, which exploit cellular technology to implement all the other components, such as sensors, tracking technologies, warning systems, etc.… Connectivity technologies are therefore applied to other technologies and increase their operating capacity, acting on factors such as the speed and amount of data exchange, thus supporting decision-making processes and the management of the logistics system.

3) Data processing technologies. This set identifies all the technologies used for data processing and storage. The growth in data volumes generated by logistics flows has contributed to the diffusion of cloud-based platforms to which data is transferred and managed in a centralized way. In this sense, big data travels on the internet and is processed by these platforms to then be stored in the servers. Data processing technologies concern not only cloud services for the management and processing of information, but also the development of analysis algorithms that allow these processes to be optimized, thus supporting decision-making processes.

4) Middleware. This group of technologies identifies all the components and applications that serve to effectively coordinate data flows between IoT components. This whole is vast and heterogeneous and accompanies other technologies, facilitating communication between its parts.

Within this conceptual framework, 5G-enabled technologies constitute a fundamental element of the logistics chain. They have the function of supporting the operations of data acquisition systems, implementing the transmission of information from one component of the logistics system to another, and supporting decision-making processes.

3 Objectives of the study and methodological approach

The main objective of the study is assessing the current market scenario in the context of the 5G-LOGINNOV LLs by collecting information on the products and services used for the UCs implementation. Moreover, the study aims to analyze, for each product or service:

- the "5G operational" relevance, to assess to which extent the uptake may benefit 5G-enabled logistics operations of the area.
- the "Business Model" relevance, to define to which extent the uptake may benefit the business models of the LLs.

For this purpose, a bottom-up approach was adopted aimed at collecting data on the products and services developed in the three different LLs. Therefore, in Phase 1, a data-set was built aimed at classifying the information on the technologies developed, their functions within the logistics processes and the expectations of stakeholders on the future impact of the products and services developed on logistics and business models. In Phase 2, the aggregation of data led to the creation of a taxonomy, aiming at clustering the products and services and allowing for an easier comparison. A conceptual framework for the analysis has been developed, aiming to guide the definition of preliminary results. In Phase 3, preliminary results have been provided; however, as this is an ongoing study, continuous updates and feedback rounds with LLs stakeholders are implemented, by continuously feeding the data-set of information on products and services. The final results will be made available at the end of the project, when expectations will be matched with real outcomes of the LLs trials.

3.1 Phase 1: Data-sets building and data clustering

The information collected by LLs actors was clustered into two data-sets. The first data-set regarded the characteristics of the products and services and their functions, the second concerned the expectations of stakeholders on the future use of products and services in LLs.

More specifically, the first data-set has grouped the following information:

- General information about the product/service. This set of information included the description of the functionalities of the products and services, or their ways of functioning. Within these data it is possible to distinguish: the name of the product/service; the supplier of the product/service; the description of the features and the purpose(s) of the product/service.
- Application areas. This set of information defined the areas in which the product/service have been planned to be applied in the single LL. For this purpose, a set of application areas was selected, following what was indicated by the stakeholders operating in the three Living Labs. This process has led to the identification of the following application areas: Network slicing; MEC; NFV-MANO; Precise Positioning; Traffic Management Applications; High-performance CCTV Surveillance Applications; Real-Time Tracking & Enhanced Visibility; Maintenance Support.

The second data-set concerned the expectations of stakeholders on the future use of products and services in LLs. This set is in turn divided into two groups, which respectively define:

- The use of technologies in the different phases of the 5G-LOGINNOV project. For each LL, the use of 5G technologies and IoT devices was studied before, during and after the implementation of 5G-LOGINNOV.

- Stakeholders' expectations about the future impact of products and services. In particular, the expectations of the stakeholders have been analyzed with specific regard to the impact of the technologies developed on the processes and services and on the business models, i.e., on how they are expected to improve the operations of the ports in the different Living Labs.

3.2 Phase 2: Taxonomy creation and establishment of a Conceptual Framework for the comparison

The second phase of the analysis focused on the creation of a taxonomy of products and services, aiming to enable a more reliable comparison between each LL. For this purpose, the information collected in data-sets for each LL have been classified according to five levels of aggregation.

- The first level ("Technology Type") defined the specific type and goals of technology adopted
- The second level ("Area of Application") related to the area of application in the logistics process.
- The third level ("Role in the Logistic Chain") referred to the role assumed by the product or service in the logistics process and to the ways in which the technology developed affected the production cycle.
- The fourth level ("Role in the LLs activities") consisted in the role played by the products and services in all those actions supporting logistics operations, such as decision-making processes and data collection activities.
- The fifth level of aggregation referred to the expected key contribution made by the developed technology on LLs ("Expected Impact").

The first three levels of aggregation represent all the information related to the technical features of the products and services; the latter two levels, instead, are linked to the ways such technologies are used by stakeholders.

The resulting Conceptual Framework, depicted in Figure 1, has been useful to guide the assessment of products and services used in 5G-LOGINNOV LLs and to provide preliminary results.
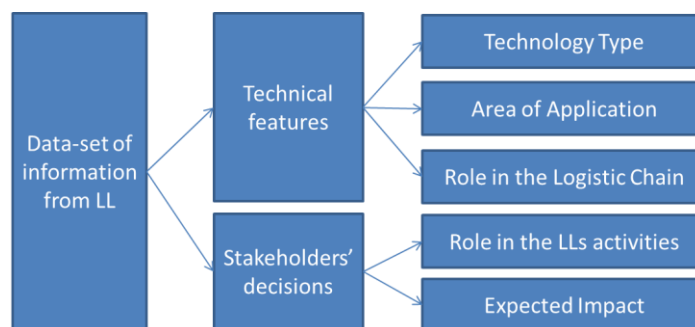

Figure 1 Conceptual Framework guiding the analysis of potential impact and benefits of 5G enabled technologies in the 5G-LOGINNOV LLs

3.3 Phase 3: Definition of preliminary results and continuous monitoring

Within the Conceptual Framework defined above, the products and services used in LLs for the UCs implementations have been assessed: for each level of aggregation, LLs features have been compared and analyzed. Specifically, such comparison has addressed the different expectations of stakeholders for what regards the impact of products and on logistics

operations and business models. Moreover, it was possible to discover the relevance of 5G for what concerns PI-friendly logistics technologies.

In line with PI principles, the 5G-LOGINNOV Project highlights the importance of stakeholders' collaboration for enabling logistics efficiency and economic improvements; therefore, the Project's LLs are open to the entrance of new actors in UCs. For instance, during the 5G-LOGINNOV Project, an Open Call for Start-ups[2] has allowed each LL to welcome in UCs implementations new companies: the analysis of products and services is still ongoing and constantly collecting new data to feed the data-sets of information. The final results of the analysis will be therefore available only at the end of the 5G-LOGINNOV project, when the final assessment will address if stakeholders' expectations have been met.

4 Preliminary results of the assessment

4.1 Preliminary analysis conducted in the Athens LL

The products and services developed in the Athens LL consist in 5G and AI technologies, with focus mainly on two application areas:

1. Improvement of human safety and optimization of the operation times linked to the loading and unloading procedures;
2. Increase of maintenance capacity by means of the collection of real-time information on vehicle status, with the scope of making forecasts on required maintenance.

The role in the supply chain of these products and services is related to the detection of the human presence in high-risk areas, aiming to minimize the risk of vehicle collisions, and to the detection of elements linked to drivers' health status and to container seals in vessel loading/unloading processes.

Stakeholders in Athens LL use these products and services for improving data collection, analysis and information forecast, since the specific expectation from such products relate primarily to the acquisition of information about vehicles status and the prediction of possible breakdowns. Also, the data collection and forecast systems are expected to provide real-time information on logistics corridor flows, such as exact positioning, optimal speed, arrival and departure times and waiting times.

The potential impacts on the Business Models are mainly associated to cost minimization and reduction of risks linked to human health, by means of the optimization of loading-unloading processes. The logistics processes optimization may lead to better use of resources, and improved security by the utilization of tools that can substitute or accompany human work in risk areas. Moreover, the potential benefits on Business Models are given by the improvement of data collection and analysis tools regarding the maintenance status of vehicles and relevant supply chain data such as location, travel time, fuel consumption, etc.…

4.2 Preliminary analysis conducted in the Hamburg LL

In the Hamburg LL, the assessed products and services are 5G enabled technologies applied in the port and in the hinterland areas for:

1. Pollutants control

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[2] https://5g-loginnov.eu/open-call/

2. Human safety
3. Traffic flow management.

The role of these products and services in the logistics chains are heterogeneous, as they are primarily related to the collection, analysis and forecasting of information in a wide area.

The implementation of these products and services for the LLs scopes is related to the ability to collect information on air quality, fuel consumption and traffic flows inside and outside of the port area. Specifically, the improvement of the accuracy of data regarding precise positioning, vehicle, and flow mapping, and the collection of parameters regarding road characteristics is the main scope of the UCs.

Furthermore, the technologies developed in the Hamburg LL are expected to optimize the traffic flows by means of the integration of the data detecting information such as the quality of the environment, the characteristics of the infrastructure's road traffic and information from vehicles (optimum speed, journey times, fuel consumption, etc.). In this sense, they are expected to minimize the resources' consumption, the waiting times in the parking slots, and will provide innovative tools for supporting decision-making processes on the logistics chain, improving individual behavior by means of an increased amount on real-time data on the micro-dynamics connections between individual vehicles and port infrastructures.

Regarding the expectations on Business Models, the products and the services introduced in Hamburg will be useful to improve the management capacity of the logistics processes, the trucks flow and truck platooning, and the connections among the logistics chain, thus contributing to minimizing the costs of these operations.

4.3 Preliminary analysis conducted in the Koper LL

Products and services used in Koper LL represent 5G technologies related mainly to obtaining high-resolution graphic data, images, and videos, capable of providing a greater amount of information on the logistic chain and assuring a more efficient monitoring of the activities carried out within the port's activities.

The data available thanks to these products and services will serve to implement a more capillary monitoring system of the different parts of the logistic chain, providing real-time visual data on the transport flows with greater frequency, and detecting other parameters linked to human safety in the port's area. Furthermore, the novel data collection system improves the communication network by means of the integration of the existing communication technologies with the 5G technologies for mobile services.

These functionalities are expected to support the collection of an even-greater amount of data, for the improvement of the resolution of the visual information, and for the increase of communication speed. These elements, taken as a whole, have the scope to foster the greatest number of collected data and their resolution, increasing the ability to analyze information, optimize the resources, and improve the security by means of mobile systems designed on cloud-native principles supporting Network Functions Virtualization Management and Orchestration.

The Business Models' expectations in Koper concern the creation of a more flexible and interconnected infrastructure, by developing or improving systems with 5G technologies that can be used to implement different solutions according to the different Use Cases. The products and services will support greater automation and digitalization, fostering the resilience and adaptability of the port infrastructure and the optimization of resources spent in the logistics processes.

5   Conclusive remarks

The technologies developed in the Athens LL are aimed at three types of purposes, which respectively concern the improvement of human safety in the workplace, the optimization of the logistics processes through 5G&AI automated services, and the improvement of the information forecast and data collection capacity. In the Living Lab in Hamburg, 5G technologies have been developed with the dual purpose of increasing the ability to collect, analyze and predict information and improving the data exchange and transferability of the information among the different components of the logistics chain. These scopes can also be found in the Koper Living Lab, focused on the improvement of the data collection and analysis systems in industry 4.0 environments and on the connectivity of the communication networks among the various sectors of the logistics system

The three 5G-LOGINNOV LLs constitute examples of good practices, allowing the stakeholders to adopt innovative 5G-enabled products and services supporting the PI principle of more integrated infrastructures and logistics chains. The new technologies introduced will improve the data management capacity, thus fostering the implementation of safety systems, reducing the risks in the workplace, optimizing resource consumption, reducing the pollutants, supporting the decision-making processes the flows' management, and the connection networks within the ports' areas. These tools are expected to have a positive impact also beyond the project boundaries, supporting the uptake of PI concepts, implementing collaborative Business Models, and improving the relationships between the actors of the ports' environment, offering the opportunity to test them in a small scale before the exploitation in the markets.

The approach to the analysis shown in this paper is functional to the scopes of the 5G-LOGINNOV project, that aims to evaluate the impact of 5G-enabled technologies on operations and economy. In facts, this study represent a preliminary assessment that needs to be matched with the final outcomes of the trials and with the results of the quantitative assessment of the UCs. However, the overall approach presented in the paper may be re-used and adapted to analyze the products and services used in other Innovation projects, as it provides a clear and simple methodology to assess products and services implementations.

Acknowledgment

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Stochastic Service Network Design with Different Operational Patterns for Hyperconnected Relay Transportation

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Abstract: *Hyperconnected relay transportation enables using a relay system of short-haul drivers to deliver long-haul shipments collectively, which helps address root causes of trucker shortage issues by transforming working conditions with potentials of daily returning home, accessing consistent schedules, and facilitating load matching. This paper investigates hyperconnected relay transportation as a sustainable solution to trucker shortage issues through a logistics platform. We propose a two-stage programming model to optimize consistent working schedules for short-haul drivers while minimizing transportation costs. The first stage involves opening services and contracting truckers under demand uncertainty, where each service has a service route and approximate service schedules adhering to USA federal short-haul hour-of-service regulations. The second stage assigns hauling capacities to open services and manages commodity shipping or outsourcing given the demand realization. We extend the model formulation to account for various operational patterns (e.g., freight loading and unloading or hauler swapping) and schedule consistency requirements (e.g., weekly or daily consistency). A scenario-based approach is employed to solve the model for a case study of automotive delivery in the Southeast USA region. The experimental results validate the proposed approach, and further explore the impact of stochastic demands, operational patterns, consistent schedules, and hauling capacities on hyperconnected service network design. This research aims to offer practical guidance to practitioners in the trucking industry.*

Keywords: *Hyperconnected Relay Transportation; Logistics Platform; Stochastic Service Network Design; Short-Haul Truckers; Hour-of-Service Regulations; Demand Uncertainty; Operational Patterns; Consistent Schedules; Hauling Capacities; Physical Internet*

Conference Topic(s): *Interconnected Freight Transport*

Physical Internet Roadmap *(Link): Select the most relevant area for your paper:* ☐ *PI Nodes,* ☒ *PI Networks,* ☐ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

1 Introduction

Transportation is crucial in moving people and goods across the world, and over the years, various transportation systems have emerged to meet the diverse needs of society. Currently, the prevalent system combines point-to-point and hub-and-spoke transport. The former involves direct movement from one location to another, whereas the latter utilizes a series of spokes to connect hubs that function as transfer points. Hyperconnected relay transport is a recent concept stemming from the Physical Internet (PI) vision (Montreuil, 2011). Inspired by the Digital Internet, where data packets independently traveling through routers and cables form a complete message upon arrival, it relies on a meshed network of interconnected relay nodes for multi-segment and intermodal transport. Unlike hub-and-spoke transport, hyperconnected relay transport enables each hub to act as a transfer point, achieving flexible consolidation opportunities and delivery options. Additionally, it enables a relay system of short-haul drivers

to collectively transport long-haul freight, addressing the core issues of trucker shortages by transforming working conditions with benefits such as daily home returns, consistent schedules, and improved driver-freight matching. In this paper, we want to provide a sustainable solution to trucker shortage from the perspective of hyperconnected relay transport.

In recent years, the global logistics industry has witnessed a rise in the number of logistics platforms driven by the growth of e-commerce and the demand for fast, reliable, and cost-effective logistics solutions. These platforms offer numerous advantages, including streamlined market access, efficient load matching, enhanced shipment visibility, and increased delivery efficiency. This paper explores the application of a logistics platform to facilitate the implementation of hyperconnected relay transport. Specifically, it considers a scenario where a logistics platform manages services over a network of relay hubs. The platform receives long-haul loads from shippers and offers short-haul contracts to carriers and owner-operator truckers. The primary goals are to deliver the loads efficiently and reliably within shippers' requested time windows and to improve truckers' working conditions by getting them back home daily. The platform offers compelling value propositions to its three main stakeholders. Firstly, shippers benefit from the ability to express their transportation needs for the foreseeable future, with consistent access to the required transport capacity at lower costs and a wider range of delivery options. Secondly, carriers attain opportunities to secure contracts, revenues, and shipments for their truckers well in advance. Lastly, the platform ensures both company-employed and owner-operator truckers the ability to return home each day through shorter-haul routes, increased visibility into upcoming tasks, and more consistent and predictable schedules.

In this paper, we propose a methodology for optimizing the platform's tactical decisions to persistently achieving its goals and value propositions. We focus on designing a truck-based hyperconnected service network by solving a two-stage stochastic programming model. The objective is to create optimal consistent working schedules for contracted short-haul truckers considering stochastic demands, while minimizing the total transportation cost for the platform. In the first stage, we make decisions regarding which services to open and determine the number of truckers to contract for each open service, taking into account uncertain demands. Each service has a defined route and approximate schedules, complying with USA federal short-haul hour-of-service regulations. In the second stage, after the realization of the demand scenario, the decisions are to determine whether to ship or outsource commodities, how to ship them through open services, and how to assign hauling capacities to each open service. Additionally, we extend the model to incorporate different operational patterns, such as freight loading and unloading or hauler swapping, as well as schedule consistency requirements (e.g., weekly or daily consistency). We solve the model using a scenario-based approach for an automotive delivery case in the Southeast USA region as a testbed. The transportation involves carriers and truckers responsible for delivering vehicles from multiple Original Equipment Manufacturers (OEMs), railheads, and ports to dealers through a relay hub network. The results demonstrate that our proposed approaches can significantly improve the drivers' work-life balance by allowing short-haul drivers to return home daily and maintaining steady working schedules, while considering short-haul hour-of-service regulations and delivery timeliness. We also conduct comparisons of the service network design under various operational patterns, schedule consistency requirements and hauling capacity options to analyze their impact on the network structure and capability.

The full paper is organized as follows. Section 2 discusses the related literature. Section 3 proposes the two-stage stochastic model formulation of hyperconnected service network design and explores its variants. Section 4 analyzes the computational results. Section 5 summarizes the contributions, limitations, and future work directions.

2 Related Literature

In the context of hyperconnected relay transportation, researchers have conducted comprehensive assessments of its performance from economic, environmental, and societal perspectives through simulation-based experiments (Hakimi et al., 2012; Sarraj et al., 2014; Hakimi et al., 2015). By employing case studies with large-scale industrial data, they have demonstrated the substantial improvements on efficiency and sustainability by implementing hyperconnected relay transportation. These improvements encompass a range of factors, including reduced CO_2 emissions, cost savings, decreased lead time, improved delivery travel time and so forth. In addition to the aforementioned assessment research, which implements and operates hyperconnected relay transport through heuristic protocols, researchers have also delved into solution design research to address key planning and operational decisions induced by the concept of the Physical Internet in hyperconnected relay transport (Pan et al., 2017). Orenstein et al. (2022) developed a mathematical heuristic for routing and scheduling vehicles involved in parcel transfer, as well as a parcel routing mechanism within the hyperconnected service network. Their simulation study demonstrated the effectiveness and advantages of the proposed approach compared to a tree-like service. Li et al. (2022) designed an operating system based on a multi-agent architecture to tackle daily large-scale operational decision-making related to generating shipments, coordinating shipments, tractors, and trailers, as well as assigning and scheduling truckers. Their simulation results outperformed conventional end-to-end transportation in terms of delivery timeliness, driver at-home time, and total operational cost. Qiao et al. (2016) investigated a dynamic pricing model based on an auction mechanism to optimize carrier bid prices. They considered PI-hubs as spot freight markets where less-than-truckload requests arrive over time for short durations. These studies focus on optimizing routing, scheduling, and pricing decisions with the knowledge of demands in hyperconnected relay transport. In this paper, we address a significant difference by considering how to plan logistics services and make contracts with carriers before the knowledge of demands, given the novel business context of a logistics platform. Additionally, we explicitly address factors such as hub operations patterns, schedule consistency, and hauling capacities, which have not been extensively explored in previous literature. We present model variants and experimental results to analyze their impacts on hyperconnected service network design.

Another related literature topic is called service network design, which involves planning routing and scheduling of services and shipments through a network of terminals. Many researchers have approached the modeling of the service network design problem by utilizing the time-space network formulation and incorporating customized rules for various settings, including the network infrastructure, transportation operations, and fleet composition (Scherr et al., 2019; Medina et al., 2019). A recent focus in service network design is addressing uncertainty to enhance robustness and stability, known as stochastic service network design. Two common sources of uncertainty are demands and traffic time, where the former typically arise prior to transportation activities and the latter occurs during and after these activities. Bai et al. (2014) introduced rerouting as a flexible approach for freighters to adapt to demand uncertainty, in addition to outsourcing. Wang et al. (2016) considered variable service capacities and ad-hoc handling to tackle stochastic demands. Lanza et al. (2021) compared travel time uncertainty to demand uncertainty and proposed a model that explicitly incorporates travel time uncertainty and quality targets. In our study, we focus on demand uncertainty in developing consistent approximate schedules, referred to as services, for contracted short-haul truckers. We represent this uncertainty through cyclic scenarios of demand patterns and formulate a two-stage model. Such "inherently two-stage problem" focuses on the first stage of designing a network and creates a correct understanding of how the network will be operated through the second stage. It actually simplifies the multi-stage nature of the real problem such

that we can bypass intricate details that are more pertinent to the dynamic operational phase. We also list refining approximate schedules by accounting for stochastic traffic time as one of our future works. Such idea of approximation-then-refining is inspired by Boland et al. (2017), who introduced a systematic computational method known as dynamic discretization discovery for the continuous service network design in a general context.

3 Methodology

We focus on the case where a platform manages the logistics service over a provided relay hub network. The physical network is denoted by $\mathcal{G}^P = (\mathcal{N}^P, \mathcal{A}^P)$ with node set $\mathcal{N}^P$ representing hub nodes and arc set $\mathcal{A}^P$ representing connected arcs between hub nodes. A planning horizon is considered and discretized into $T + 1$ evenly distributed time instants, which is denoted as $\mathcal{T} = \{0,1,2,\ldots,T\}$. We then construct a time-space network $\mathcal{G} = (\mathcal{N}, \mathcal{A})$ based on the physical network $\mathcal{G}^P = (\mathcal{N}^P, \mathcal{A}^P)$ and the discretized planning horizon $\mathcal{T}$. The node set $\mathcal{N}$ is attained by replicating each node in $\mathcal{N}^P$ for $T + 1$ times, where $\mathcal{N} = \{(n,t)|n \in \mathcal{N}^P, t \in \mathcal{T}\}$. The arc set $\mathcal{A}$ consists of a moving arc set $\mathcal{A}^M$ and a holding arc set $\mathcal{A}^H$. The former includes the arcs between time replicates of two different hub nodes to model the movements of freight or truckers, while the latter incorporates the arcs between two replicates of the same hub node at two consecutive time instants, used for modeling idle time or processing time of freight or truckers. Each arc $a \in \mathcal{A}$ has the form $a = \left((n_a^1, t_a^1), (n_a^2, t_a^2)\right)$ where $(n_a^1, t_a^1), (n_a^2, t_a^2) \in \mathcal{N}$. Specifically, if a is a moving arc, we will have $n_a^1 \neq n_a^2$ and $t_a^2 - t_a^1$ representing the travel time plus buffer time for the movement from hub node n_a^1 to hub node n_a^2; if a is a holding arc, we will have $n_a^1 = n_a^2$ and $t_a^2 = t_a^1 + 1$.

The platform makes contracts over a set of potential services $\mathcal{S}$ to transport freight. Each service $s \in \mathcal{S}$ has a fixed service route and approximate service schedules, represented by $s = \{a_s^1, \ldots, a_s^{r_s}\}$, where $a_s^i \in \mathcal{A}^M$ indicates the i-th movement of service s for $i \in \{1, \ldots, r_s\}$. For example, a service $s = \{((n_1, t_1), (n_2, t_2)), ((n_2, t_3), (n_1, t_4))\}$ represents a service planned to start from hub node n_1 at time instant t_1, arrive at hub node n_2 at time instant t_2, then leave hub node n_2 at time instant t_3, and return to hub node n_1 at time instant t_4. The platform needs to decide which service to open and how many truckers to contract over each open service before the knowledge of demands. Once truckers are contracted, the contract fees are paid and cannot be cancelled. Each service $s \in \mathcal{S}$ has a contacted trucker capacity q_s. Once the truckers are contracted to services, the platform can then add a hauling capacity $u \in \mathcal{U}$ (or zero capacity in case of excess capacity) to each contracted trucker based on the actual demand scenario.

The platform receives the transportation requests for multiple commodities. Each commodity $k \in \mathcal{K}$ has an origin hub o_k, a destination hub d_k, an entry time t_k^e, a due time t_k^d, and volume v_k. For each commodity, the platform has the option of transporting it by contracted services or outsourcing it to third-party logistics. All commodities are expected to be delivered on time.

We assume that the hyperconnected service network of the logistics platform adheres to a distinct hub operations pattern and maintains certain schedule consistency. Two operational patterns are taken into consideration for hub operations: freight loading and unloading (FLU) and hauler swapping (HS). For FLU, drivers stay with their trucks (including tractors and haulers), and freight can be loaded and unloaded at each hub for crossdocking. On the other hand, for HS, haulers can be separated from drivers and tractors. Once freight is loaded into a hauler, it remains inside the hauler until reaching its destination, without any additional loading or unloading during the delivery process. Furthermore, for FLU, we consider a condition whether freight of the same commodity will travel along a unique commodity path from origin to destination. Such consideration is due to the facts that customers may prefer to receive the

products as a whole pack and keep better track of the shipments. Consequently, we have three operational patterns to consider: *(i-1)* freight loading and unloading with multiple commodity paths (FLU - MCP), *(i-2)* freight loading and unloading with single commodity path (FLU - SCP), and hauler swapping (HS). Schedule consistency is also taken into account due to drivers' preference for consistent schedules, such as weekly or daily schedules. We denote the planning horizon as $\mathcal{T}$, which is composed of multiple schedule cycles, i.e., $\mathcal{T} = \mathcal{T}^1 \cup \dots \cup \mathcal{T}^C$, where C represents the total number of cycles. Each service s has its start time determined by the service cycle c_s and the specific start time t_s^c within that cycle.

3.1   Two-Stage Stochastic Programming Formulation

We develop a two-stage stochastic programming model for the platform to design the hyperconnected logistics service network. We first provide the formulation with operational pattern as FLU - MCP and schedule consistency with total number of cycles $C = 1$. For FLU - MCP, a trucker refers to a driver, to whom we can assign trucks with different hauling capacities. The objective is to minimize total transportation cost consisting of trucker contract cost and hauler rental cost, while building optimal consistent service schedules for short-haul relay truckers. The first-stage decision variable is X_s, an integer variable representing the number of drivers to contract to short-haul service $s \in \mathcal{S}$. The second-stage variables consist of $Z_k(w)$, $F_{ka}(w)$ and $Y_{su}(w)$. $Z_k(w)$ is a binary variable to indicate whether to outsource commodity k in demand scenario w. $F_{ka}(w)$ is a nonnegative continuous variable meaning the volume of commodity k that will traverse arc a in demand scenario w. $Y_{su}(w)$ is a nonnegative integer variable representing the number of trucks with capacity size u that will be assigned to service s in demand scenario w.

The mathematical formulation is shown through equation (1) – (5). The objective function (1) is to minimize the sum of total contracted cost of drivers as well as the total expected costs of truck rentals and commodity outsourcing with regards to demand uncertainty. Constraint (2) ensures the contracted number of drivers does not exceed the maximal contracted trucker capacity for each service. Constraint (3) assigns trucks of different capacity sizes to contracted drivers. Constraint (4) guarantees the total truck volume capacity is no smaller than the total commodity volume on each arc. Constraint (5) is the commodity flow balance constraint, which also ensures the timely delivery.

$$\min \sum_{s\in\mathcal{S}} c_s^f X_s + E_{w\in\mathcal{W}}\left[\sum_{s\in\mathcal{S},u\in\mathcal{U}} c_{su}^v Y_{su}(w) + \sum_{k\in\mathcal{K}} c_k^o Z_k(w)\right] \tag{1}$$

$$s.t.$$

$$0 \le X_s \le q_s \qquad\qquad\qquad\qquad \forall\, s \in \mathcal{S} \tag{2}$$

$$\sum_{u\in\mathcal{U}} Y_{su}(w) \le X_s \qquad\qquad\qquad \forall\, s \in \mathcal{S}, w \in \mathcal{W} \tag{3}$$

$$\sum_{s\in\mathcal{S}_a, u\in\mathcal{U}} u Y_{su}(w) \ge \sum_{k\in\mathcal{K}} F_{ka}(w) \qquad\qquad \forall\, a \in \mathcal{A}^M, w \in \mathcal{W} \tag{4}$$

$$\sum_{a\in A:n_a^2=n} F_{ka}(w) - \sum_{a\in A:n_a^1=n} F_{ka}(w) = \begin{cases} v_k(w)(Z_k(w)-1), & \text{if } n = (o_k, t_k^e) \\ v_k(w)(1 - Z_k(w)), & \text{if } n = (d_k, t_k^d) \\ 0, & \text{otherwise} \end{cases}$$

$$\forall k \in \mathcal{K}, n \in \mathcal{N}, w \in \mathcal{W} \tag{5}$$

3.2   Model variants

Based on the model formulation in the Section 3.1, we then provide model variants that account for different operational patterns. For FLU – SCP, given the fact that each commodity stays on a unique shipment path, we maintain decision variables $X_s, Y_{su}(w)$ as nonnegative integer

variables and $Z_k(w) \in \{0,1\}$ but change $F_{ka}(w)$ to a binary variable meaning whether shipment of commodity k will traverse arc a in demand scenario w. The formulation is updated to (1) – (3) plus (4') and (5'), where constraint (4') and (5') adjust the truck capacity constraint and commodity flow balance constraint respectively by considering a unique shipment path for each commodity.

$$\sum_{s \in S_a, u \in U} u Y_{su}(w) \geq \sum_{k \in K} v_k(w) F_{ka}(w) \qquad \forall a \in \mathcal{A}^M, w \in \mathcal{W} \qquad (4')$$

$$\sum_{a \in A: n_a^2 = n} F_{ka}(w) - \sum_{a \in A: n_a^1 = n} F_{ka}(w) = \begin{cases} Z_k(w) - 1, & if \ n = (o_k, t_k^e) \\ 1 - Z_k(w), & if \ n = (d_k, t_k^d) \\ 0, & otherwise \end{cases}$$

$$\forall k \in \mathcal{K}, n \in \mathcal{N}, w \in \mathcal{W} \qquad (5')$$

For HS, we refer a trucker to a driver-tractor pair, to which we can assign the haulers with different hauling sizes. The three decision variables $X_s, Y_{ku}(w)$ and $F_{ku}(w)$ become nonnegative variables now. X_s represents number of driver-tractor pairs contracted to service s. $Y_{ku}(w)$ represents number of haulers with size u used for commodity k in scenario w. Note that one of the subscripts of Y variables are updated from service index s to commodity index k, since haulers now stay with freight instead of drivers and tractors. $F_{ku}(w)$ indicates number of haulers with commodity k traversing arc a in scenario w. We keep $Z_k(w)$ as the same.

The updated model formulation is given by (1'') – (5''). The objective function (1'') is to minimize the sum of total contracted cost of driver-tractor pairs as well as the total expected cost of hauler rentals and commodity outsourcing with regards to uncertain demands. Constraint (2'') ensures the contracted number of driver-tractor pairs does not exceed the maximal contracted trucker capacity for each service. Constraint (3'') assigns haulers of different capacity sizes to contracted truckers. Constraint (4'') guarantees each commodity is accommodated into haulers with enough volume capacity. Constraint (5'') is the commodity flow balance constraint, which also ensures the timely delivery.

$$\min \sum_{s \in S} c_s^f X_s + E_{w \in \mathcal{W}} \left[\sum_{k \in K, u \in U} c_{ku}^v Y_{ku}(w) + \sum_{k \in K} c_k^o Z_k(w) \right] \qquad (1'')$$

$s.t.$

$$0 \leq X_s \leq x_s^{max} \qquad \forall s \in \mathcal{S} \qquad (2'')$$

$$\sum_{k \in K} F_{ka}(w) \leq \sum_{s \in S_a} X_s \qquad \forall a \in \mathcal{A}^M, w \in \mathcal{W} \qquad (3'')$$

$$\sum_{u \in U} u Y_{ku}(w) \geq v_k(w)(1 - Z_k(w)) \qquad \forall s \in \mathcal{S}, w \in \mathcal{W} \qquad (4'')$$

$$\sum_{a \in A: n_a^2 = n} F_{ka}(w) - \sum_{a \in A: n_a^1 = n} F_{ka}(w) = \begin{cases} -\sum_{u \in \mathcal{K}} Y_{ku}(w), & if \ n = (o_k, t_k^e) \\ \sum_{u \in \mathcal{K}} Y_{ku}(w), & if \ n = (d_k, t_k^d) \\ 0, & otherwise \end{cases}$$

$$\forall k \in \mathcal{K}, n \in \mathcal{N}, w \in \mathcal{W} \qquad (5'')$$

We also consider model variants accounting for different schedule consistency requirements. A strong version of consistency constraint is to have $X_s = X_{s'}$ if service s and s' have the identical route path and cycle time but just belong to different cycles within the planning horizon. A soft version is to put a penalty on the cycle inconsistency and add it into the objective function, which can be measured by the sum of differences in contracted number of service truckers across cycles. In this paper, we consider the strong version. Given the weekly and daily rates of driver payment and fleet rental are different in reality, we aim to examine the impact of consistency on the network structure and cost calculation.

4   Results and Discussion

In this section, we present the computational results using the data derived from a real-life automotive delivery case in the Southeastern USA. A hyperconnected relay hub network is used for transportation with 19 hubs and 95 arcs, as illustrated in Figure 1. Most of hubs are interconnected to multiple adjacent hubs, and each arc is designed to accommodate traffic uncertainty with a robust arc travel time of approximate 5.5 hours. This ensures that every short-haul trucker can complete a round trip on each arc and return to domicile within the daily maximal driving window of 11hours, as mandated by the USA federal hour-of-service regulations. The demand sample considered in this analysis spans from January 1, 2020, to January 14, 2020, and consists of a total of 13,903 ordered vehicles. Notably, 94.9% of commodity flow is observed to move from west to east, while the remaining 5.1% moves from east to west, as depicted in Figure 1. This indicates an inherent imbalance in the commodity flows between the two directions, with the hyperconnected service network design predominately catering to the higher volume of commodities moving towards the east.
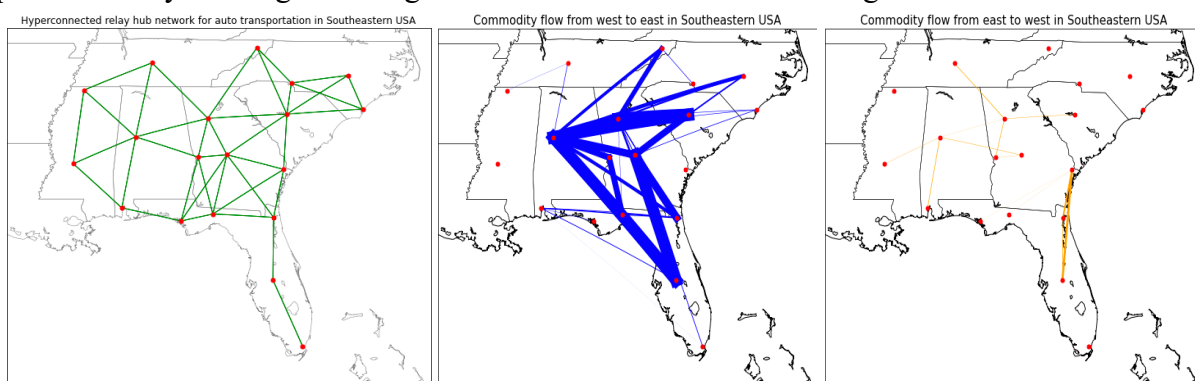

Figure 1: Hyperconnected hub network, commodity flows towards east (in blue) and west (in orange)

We utilize a scenario-based approach to solve the hyperconnected service network design model. In our experiments, the planning horizon spans five days, discretized into six-hour time intervals. We generate a total of 30 demand scenarios, encompassing 196 potential commodities between every pair of hubs for the initial four planning days. The delivery time window for these commodities is set as two days. We consider all possible short-haul services with service routes between any two adjacent hubs, while ensuring that service approximate on-duty durations do not exceed the daily maximum on-duty duration of 14 hours imposed by the USA federal hour-of-service regulations. The other parameters for experiments are provided in Table 1. Notably, we employ a consistency cost discount factor of 0.8, which reflects the cost advantages associated with maintaining consistent daily schedules as opposed to weekly consistency.

Table 1: The other key parameters used for the experiments

Hourly driver contract fee ($)	29	Hourly size-8 hauler rental fee ($)	10
Hourly tractor rental fee ($)	18	Hourly size-4 hauler rental fee ($)	5
Outsourcing cost per vehicle per mile ($)	0.93	Average mile per hour	50
Contracted trucker capacity per service	10	Consistency cost discount factor	0.8

We first conduct two model runs to calculate the Value of the Stochastic Solution (VSS), which is used to measure the importance of incorporating stochasticity. In the first model run, we employ a stochastic model with demand scenarios. In contrast, the second model run involves fixing the first-stage decisions as the deterministic solutions obtained from the deterministic version of the proposed model with demand input as the sample average of demand scenarios,

and tests the fixed first-stage decisions in the second stage using demand scenarios. The second model run commonly called "deterministic design in the stochastic model" (Xin et al., 2016). The comparison results of two model runs are shown in Table 2. The deterministic design has less contracted hours of drivers and fewer average rental hours of tractor-hauler pairs than the stochastic one, resulting in 10.3% more average outsourcing rate of commodities. In addition, the VSS is 556,464 – 422,985 = 133,509 in dollars, which shows that the stochastic design can save about 24% of the total expected transportation cost, compared to the deterministic one.

Table 2: Comparison results of deterministic design vs. stochastic design in a stochastic environment

KPIs \ Demand patterns	Deterministic	Stochastic
Total contracted hours of drivers (hrs)	9,408	12,444
Average rental hours of tractors (hrs)	8,023	9,285
Average rental hours of haulers (hrs)	8,023	9,285
Average outsourcing rate of commodities	10.3%	0%
Total expected transportation cost ($)	556,494	422,985

To explore the impact of different operational patterns on the hyperconnected service network design, we then perform three model runs with operational patterns as FLU – MCP, FLU – SCP, and HS respectively. In all three model runs, we with consistency requirement set as weekly and fixed hauler size as 8 vehicles per trucker. The comparison results are summarized in Table 3. From FLU-MCP to FLU-SCP, the contracted hours of drivers and rental hours of tractor-hauler pairs increase by 3.4% and 2.9% respectively. All commodities are shipped through the platform logistics, with a 2.1% rise in total expected transportation cost. The reason is that compared with FLU-MCP, FLU-SCP restricts the delivery of each commodity along a single path to ensure freight integrity. Consequently, consolidation opportunities decrease, resulting in a higher number of trucks operating at increased costs. From FLU-SCP to HS, we can observe a 2.6% decrease in total contracted driver hours. This decrease can be attributed to the fact that drivers now remain with their tractors, resulting in higher costs for opening services and contracting truckers. Additionally, the implementation of HS also led to a discernible increase in the outsourcing rate of commodities, accompanied by an overall elevation in the total expected cost. This outcome arises from the absence of crossdocking in the HS setting, necessitating the outsourcing of several commodities as a favorable alternative. However, it is essential to note that HS offers enhanced freight protection by securely maintaining the goods inside the haulers throughout the entire delivery process. Furthermore, it reduces operational efforts by facilitating the efficient swapping of haulers, as opposed to the time-consuming process of loading and unloading freight. While not explicitly modeled in this paper, these aspects present valuable avenues for future research.

Table 3: Comparison results of stochastic solutions with three different operational patterns

KPIs \ Operational patterns	FLU-MCP	FLU-SCP	HS
Total contracted hours of drivers (hrs)	12,444	12,864	12,528
Average rental hours of tractors (hrs)	9,285	9,312	12,528
Average rental hours of haulers (hrs)	9,285	9,312	955.2
Average outsourcing rate of commodities	0%	0%	1.3%
Total expected transportation cost ($)	422,985	431,880	492,742

The subsequent experiment aims to examine the influence of different consistency requirements and hauling capacities on the hyperconnected service network design, with the operational pattern set as FLU – MCP. Two consistency requirements are considered: weekly consistency and daily consistency. The corresponding results are presented in Table 4. Comparing weekly consistency to daily consistency, we observe that daily consistency results in increased contracted hours for drivers and rental hours for trucks, while yields a lower total expected cost.

This outcome can be attributed to the fact that daily-consistent contracts have, on average, lower driver contracted fees and truck rental costs per hour compared to weekly-consistent contracts. Figure 2 visualizes the open services of a weekly-consistent vs. daily-consistent designs. An interesting observation is that, between hub 0 and hub 1, weekly-consistent design has open services on both routes of hub 0 – hub 1- hub 0 and hub 1 – hub 0 – hub 1 on certain days, while daily-consistent design only has open services on the route of hub 1 – hub 0 - hub 1 repeating every day. Furthermore, based on the results in Table 4 and Figure 3, we can observe that various hauling capacities leads to more contracted hours of drivers and rental hours of tractor-hauler pairs, yet contributes to less total expected transportation cost. The reason is that various hauling capacities offer better flexibilities in fleet selection, particularly during periods of low demands, thus the commodities can be shipped in a more cost-effective manner. Additionally, when considering the total expected cost, we find that daily consistency contributes more to cost savings compared to the various hauling capacities. This is because driver contracted fees carry a higher weight in the total expected cost than truck (tractor/hauler) rental costs.

Table 4: Comparison results of weekly vs. daily consistency requirements in stochastic environment

| Consistent patterns	Weekly		Daily	
KPIs \ Hauling capacity	Fixed	Various	Fixed	Various
Total contracted hours of drivers (hrs)	12,444	12,348	13,500	13,620
Average rental hours of tractors (hrs)	9,286	10,562	9,456	11,045
Average rental hours of haulers (hrs)	9,286	10,562	9,456	110,45
Average outsourcing rate of commodities	0%	0%	0%	0%
Total expected transportation cost ($)	422,985	418,253	357,840	355,152
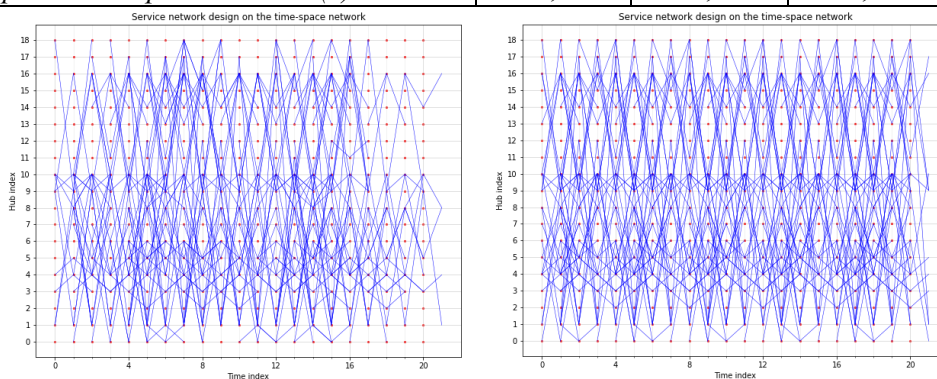
Figure 2: open services of model designs with weekly consistency (left) vs. daily consistency (right)
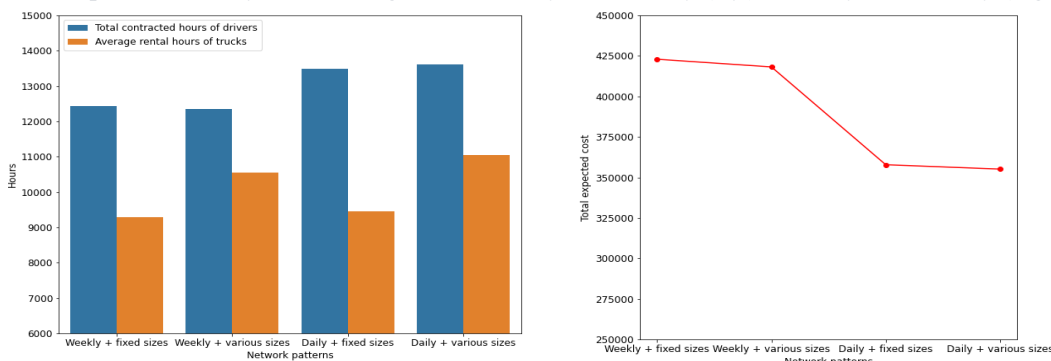

Figure 3: Total driver contracted hours and truck rental hours (left) and total expected cost (right)

5   Conclusion

The contributions of this paper are threefold. First, it proposes applying hyperconnected relay transportation as a sustainable solution to truck driver shortage issues through a logistics

platform as a novel business context. Second, it provides a two-stage stochastic model for hyperconnected service network design of the platform. The formulation supports different operational patterns and schedule consistency requirements. Third, the paper runs the experimental results on an automotive delivery test case in Southeastern USA and discusses the impacts of demand uncertainty, operational patterns, consistent schedules, and various hauling capacities on the service network design, providing guidance to practitioners in industry.

There are several avenues for the future work. The first direction is to develop more advanced computational methods such as bender decomposition or sample average approximation for optimizing larger scale instances. The second is to perform sensitivity analysis upon experimental parameters such as delivery time window and maximal driving time window. The third is to model more route patterns for both short-haul and long-haul, contracted services tailored to trucker preferences, and on-market carrier capacity. The fourth is to refine the approximate service schedules accounting for traffic time stochasticity.

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Enhancing Circular Logistics of Unit Loads by Leveraging Physical Internet Modularization and Consolidation Principles

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Abstract: *Returnable Transportation Items (RTI) such as pallets are crucial for any supply chain, however this remains an understudied area in comparison to other subjects in logistics. As part of a case study, this paper intends to demonstrate the operational benefits that can be achieved by introducing PI concepts of modularization and cargo consolidation into the core process of reparation at an RTI service provider. Different maturity levels of a process were developed based on PI concepts and compared with a baseline to highlight their adaptability to unexpected changes in demand. The results indicate that the implementation of PI concepts could result in significant cost savings and increased supply chain efficiencies.*

Keywords: *Physical Internet, Reverse Logistics, Consolidation, Modularization, Repair, Recycling, Modular Workstations, Simulation, Sustainability, Pallets.*

Conference Topic(s): *PI impacts; PI modelling and simulation.*

Physical Internet Roadmap (*Link*): *Select the most relevant area for your paper:* ☒ *PI Nodes,* ☐ *PI Networks,* ☐ *System of Logistics Networks,* ☒ *Access and Adoption,* ☐ *Governance.*

1. Introduction

The logistics industry faces new challenges every day as they operate in a dynamic environment and are forced to develop flexible and adaptive responses to customer demand. Customers expect rapid delivery of high-quality products, along with the option of unrestrictive returns, while companies strive to maintain a profitable and sustainable supply chain. In response to these challenges, researchers are exploring the potential of the Physical Internet (PI) framework as it can transform modern logistics and supply chain management.

This paper will focus on two fundamental concepts of PI: modularization and cargo consolidation. The implementation of these concepts typically involves changes in the supply chain and the node network. However, this study aims to explore how the application of modularization and cargo consolidation can reshape the core processes of companies. Specifically, the study will analyze the impact and changes on the dynamics of a repair pallet company, that from now we will refer to as Returnable Transportation Item (RTI) service provider, and how the adoption of such principles makes the company more flexible to attend unexpected changes on the demand.

The paper's structure will be as follows: Section 2 provides background information about the RTI's service provider studied, its operational context, and major challenges. In Section 3, we present the proposed methodology for studying the case and its scope. Section 4 delves into the simulation implementation and how the PI inherent concepts of modularization and cargo

consolidation are considered, along with results and insights obtained. Finally, Section 5 summarizes the key insights obtained and evidence-based conclusions will be stated.

2. Industry Context

The Physical Internet (PI) proposes to revolutionize current logistics by incorporating a set of standardized, modular, reusable, and ecofriendly transport containers designed for hyperconnected logistics (Montreuil, 2011; Montreuil et al., 2015); however, in the meantime logistics still heavily rely on the consolidation of bulk cargo that is placed on pallets and totes.

Although pallets and totes as we know are not the ideal transport containers from a PI perspective, we can still study the current dynamics of these items and learn how to improve the operational efficiency of its transportation, reparation, and distribution to obtain valuable insights that we can then apply to the new generation of containers. In this paper, we will analyze specifically the case of pallets.

The flow of pallets is necessarily aligned with the flow of products across the supply chain, for that reason it inherits the complexity of the network which involves multiple tiers and different stakeholders. It is possible to map the relationship between the transportation containers and the supply chain networks, which relevant literature (Gnoni et al., 2015) classified into: Closed Loop Supply Chains (CLSC) or Circular Logistics, and Open Loop Supply Chains (OLSC). In the OLSC, pallets are seen as disposable items, thus the cost of bringing back the items can be saved and provide flexibility to the companies so they can freely decide and change the quality and material.

In the other hand, we have the circular case, under this setting pallets and totes are returnable and can be categorized as Returnable Transportation Items (RTIs). To avoid the additional complexity and costs that will imply that each actor of the supply chain need to move the transportation items to the previous stage or the fact that some of these pallets may be damaged and require a reparation before being returned; the common practice is to include a third-party company that will consolidate the pallets, review the items that require a reparation and perform it, then allocate the optimal number of pallets to each actor (see Figure 1).
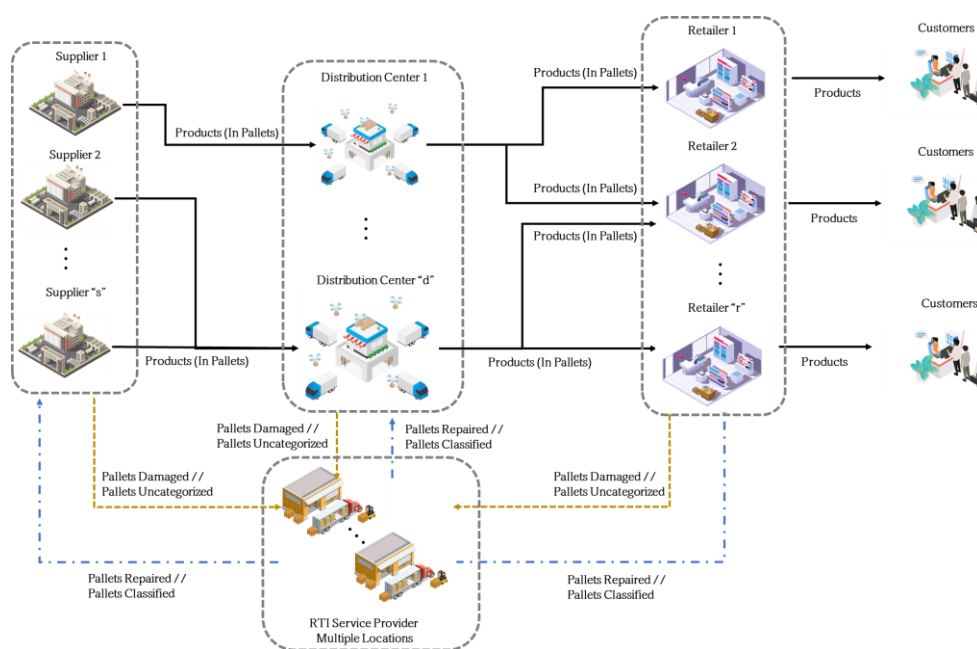

Figure 1. Flow of resources in Circular Supply Chains with outsourced Reparation Facilities.

2.1 RTI's Workflow inside Reparation Facilities

The commencement of the company's operational workflow is conditioned upon the arrival of pallets, which typically ensues through 35 ft trucks. The unloading process of a truck can either be manually done by removing the pallets one by one and placing them in a buffer zone, or by unloading pallets in groups of ten using forklifts. Once the pallets are stacked in the buffer zone, workers move them to the workstations, where they undergo inspection to identify the type and level of damage. Pallets are classified into three categories: Class A (high quality pallets), B (medium quality pallets), or C (low quality pallets). If the pallet is a Class C, it is taken to the recycling buffer, otherwise, the pallet goes through preparation where broken boards and debris are removed. After preparation, the pallet is repaired and sent to the buffer of final products. If a request for pallets is received during this process, they are loaded onto a truck and dispatched to the clients. Figure 2 summarizes the process:
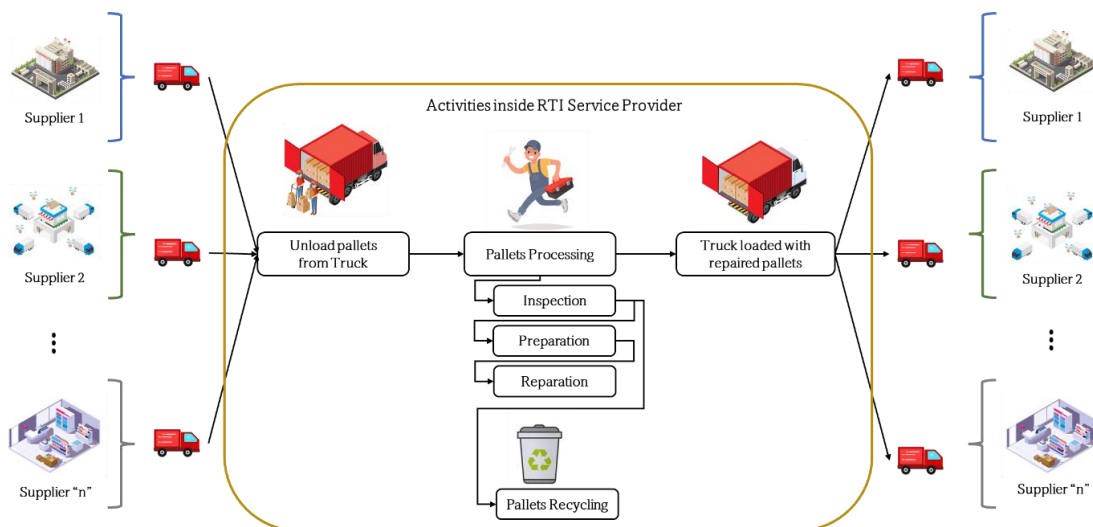

Figure 2. Operational workflow within Reparation RTI Facilities.

2.2 Challenges faced by RTIs Service Providers in Circular Logistics

When a third-party company is engaged to handle the reparation, transportation, and allocation of RTI's, it automatically inherits the complexity of the entire supply chain as it necessitates the optimal allocation of these RTI's among each actor involved. This represents a multitude of significant challenges, including:

2.2.1 Demand Fluctuation of RTIs

The number of RTI's demanded to a service provider is constituted by the number of pallets and totes that are requested from each player of the supply chain: Suppliers, Distribution Centers (DCs) and Retailers. As expected, this amount is not fixed and varies according to the seasonality of some products, special occasions, and holidays, or by shortcomings in the production. Additionally, it must be considered that RTI service provider's ability to satisfy the demand imposes a capacity constraint.

Notice as well that in some cases is not desired to process all the pallets received in a short period of time; for example, consider the case of transitioning from a high period demand to a low period demand, then is expected to receive a high number of pallets in the facilities, but is not required to repair all these items as this may imply overtime, more workers and other additional costs.

2.2.2 Lack of standardization in the unloading process

Typically, RTI service providers attend multiple circular supply chains to achieve the benefits of economies of scale, however this also implies that pallets from different actors of the Supply

Chain may be contained in the same ship. To maintain the traceability and ownership of such items, as these RTIs may have different standard sizes, quality, weight capacity, and useful life, is possible to use lean manufacturing methods, for example color coding to differentiate the pallets from each supplier.

Another layer of complexity to consider is the type of work that an RTI will require inside the facility; for example, pallets may require repairs, simple sorting or may be marked for recycling. If pallets go through for the entire process, then workstations will concentrate all the work and become bottlenecks, in the other hand if the process for identifying which is the next step for each pallet takes too much time, then the risk is underutilization of the workstations. This trade-off is one key aspect of the simulations that will be shown in the following section.

2.2.3 Variability in time processes

The reparation process is the combination of three separate activities: Inspection, where the pallets are analyzed and the decision to repair or not a pallet is made, if the pallet is not going to be repaired then is sent for disposal; the Preparation, where the debris of pallets that are going to be repaired is cleaned; finally, the Reparation, where the broken boards of the pallet are replaced. Although the process is standard and relatively simple in practice it exhibit variability, a major part of the variability come from the time that workers employ to transport pallets, this is, workstations are not designed to minimize the walking distance; the other source of variability is that workstations do not have a standard set of tools to perform a reparation so if a specific tool is required a worker need to walk to another station to grab the missing instrument.

3. Methodology

The research presented herein adopts a case study methodology aimed at comprehending the dynamics of a pallet reparation company in the United States, which is part of a CLSC. The study focuses on the repair process of pallets obtained exclusively from distribution centers and begins with the pallets being unloaded from trailers sourced from various distribution centers within a specific state and concludes with the allocation plan of the pallets to a designated group of retailers within the same state. The study's main objective is to show the feasibility of leveraging the fundamental principles of the PI operations, particularly modularity and consolidation, to see operational improvements in a process.

Figure 3 illustrates a four-layer framework. The first layer involves system requirements which has three main sub requirements namely: functional requirements (demand, system capacity, and resource utilization), PI operational requirements (modularity and cargo consolidation concepts) and resource requirements (labor force and pallet inventory). The second layer consists of two subsections: the design parameters subsection, which provides design parameters and high-level assumptions for the system, such as facility used for the case, demand behavior over time, scheduled workforce; the second presents the proposed system architecture, comprising five types of agents:

- Job agents: representing pertinent information for processing the RTIs (product ID, job type, supplier, batch quantity)
- Worker agents: show the relationship between workstations and worker over time.
- Resource agents: reflect available resources in the system such as material availability, process cycle time, forklifts, and tools per workstation.
- Layout agents: take decision of the simulation layout that will be used.
- Operation agents: enable the operational aspect that will be used in each maturity level scenario (Considering modularity and cargo consolidation pertinently).

The third layer represents the simulation model which includes three maturity levels: Maturity Level 1 lacks the central elements of our study: modularization and consolidation. In Maturity Level 2, modular workstations are implemented, but cargo consolidation remains omitted. The inclusion of adaptable, flexible, ergonomic, and efficient modular workstations allows the system to effectively respond to changing demands (Babalou et al., 2021). This setting also provides insights into the adaptability of modular workstations in different RTI facility layouts. In Maturity Level 3, cargo consolidation is integrated into the operation of RTI facilities with modular workstations. This configuration ensures that only pallets requiring full processing undergo the consolidation process, accelerating the progress of pallets that do not require repairs for dispatch (Sallez et al., 2016). Finally, the fourth layer presents key performance indicators (KPIs) for comparing the models.

To ensure the accuracy of the findings, this study utilized a combination of data collection methods, including observation, document analysis, and expert consultations with industry professionals. To compare the effectiveness of the model, key metrics were obtained through the simulator.
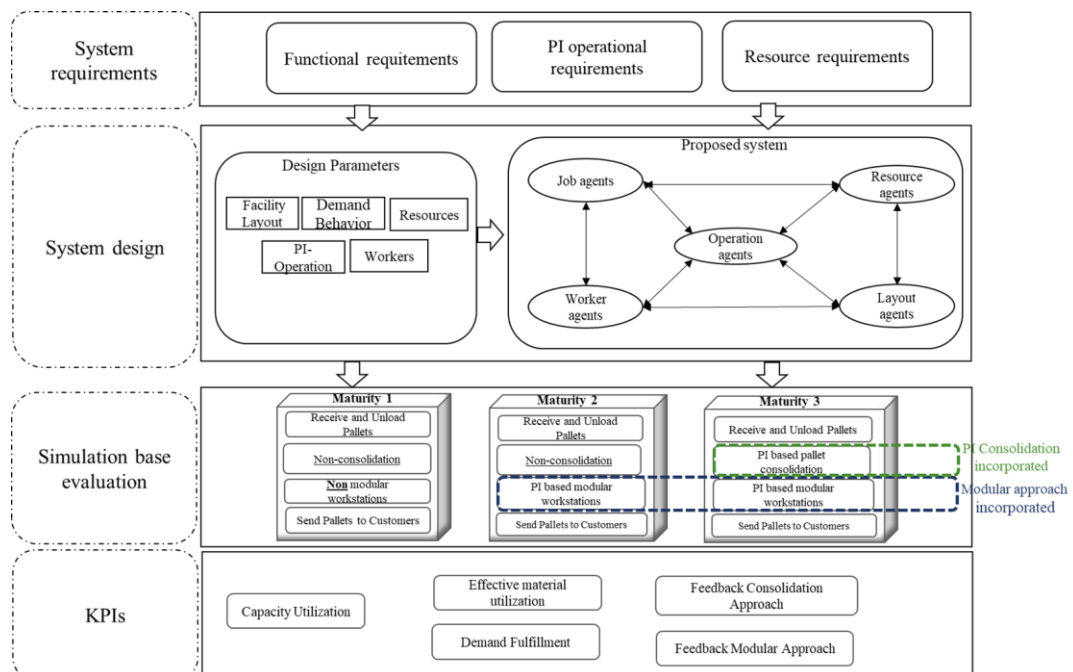

Figure 3. Designed framework to implement PI based operational process.

4. Simulation Implementation

As described in the preceding section, the object's study is to simulate three distinct maturity levels to different layouts of two RTIs facilities. Regarding the architecture of the simulation, for this study it is considered that the interarrival times for the trucks to each facility will follow a Poisson Process with mean: 31 and 59 trucks per week, the pallet loads of these trucks will be random and follow an Uniform Distribution with parameters [250, 310], the forecast demand of pallets associated for each of these RTI's service providers will be obtain via exponential smoothing based on the historical behavior of the previous year. The times considered for non-value generated activities will be automatically computed based on the distances using an event base simulation software called FlexSim. Lastly, when pallets reach a workstation, the work time will be generated with the assumptions pertinent for the case and that will be explained in more detail in the following section.

The simulations will follow general business rules (apply for all cases) and specific assumptions for each case modeled.

4.1. General assumptions

- Use of historical real data as the source of information that provides the number of pallets received per day and the number of trucks unloaded per day.
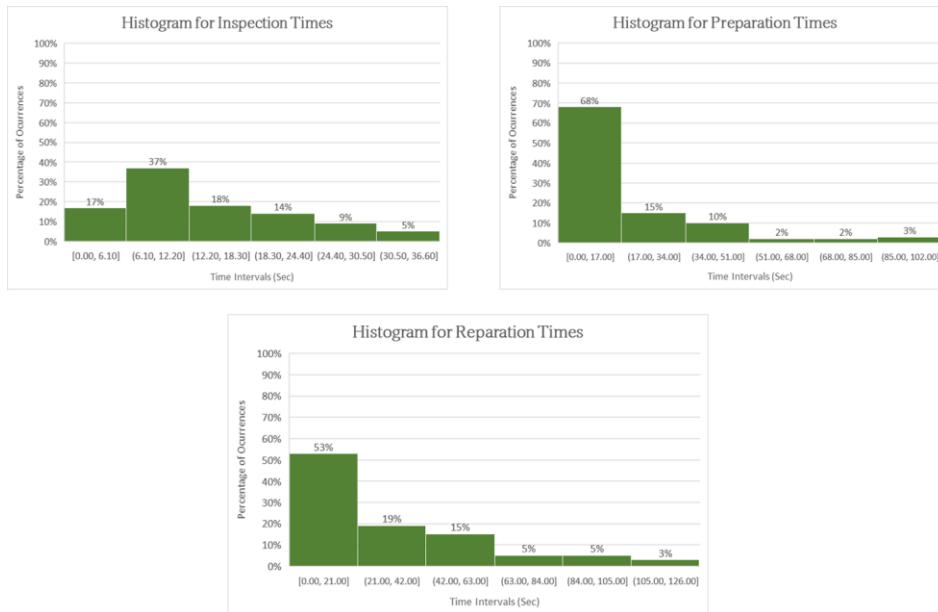

Figure 4. Empirical Distribution for different processing times (base case) plotted using a Histogram.

- For all the maturity levels, they will start with two operative workstations in the small RTI layout and four operative workstations for the larger facility.
- The study will consider that daily, the proportion of pallets received for reparation is 65%, 30% for pallets to be sorted and 5% for pallets to be recycled.
- The simulation will start assuming that on the system there already exist an amount of pallets equivalent to the capacity of one 35 ft truck. The next days will start with the number of pallets that were not processed the previous day.
- Pallets can be stacked, and each stack of pallets cannot contain more than ten pallets.
- The height of an operator will be 5 feet and 8 inches, and the speed of a worker will be 3 mph.

4.2 Maturity Level 1 (ML1): Non-modular workstations and non-consolidation process
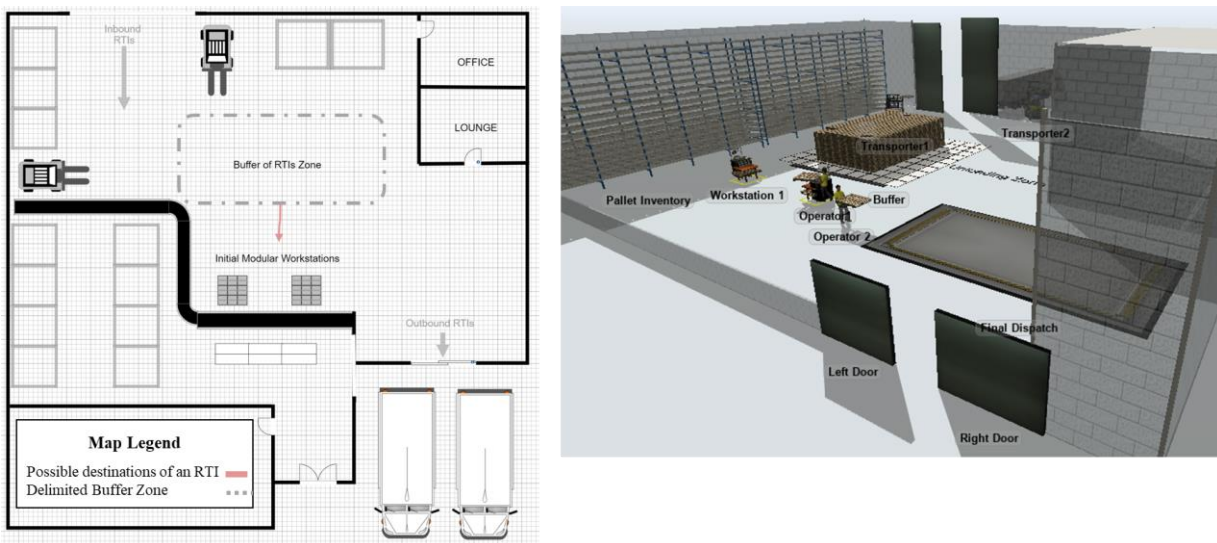

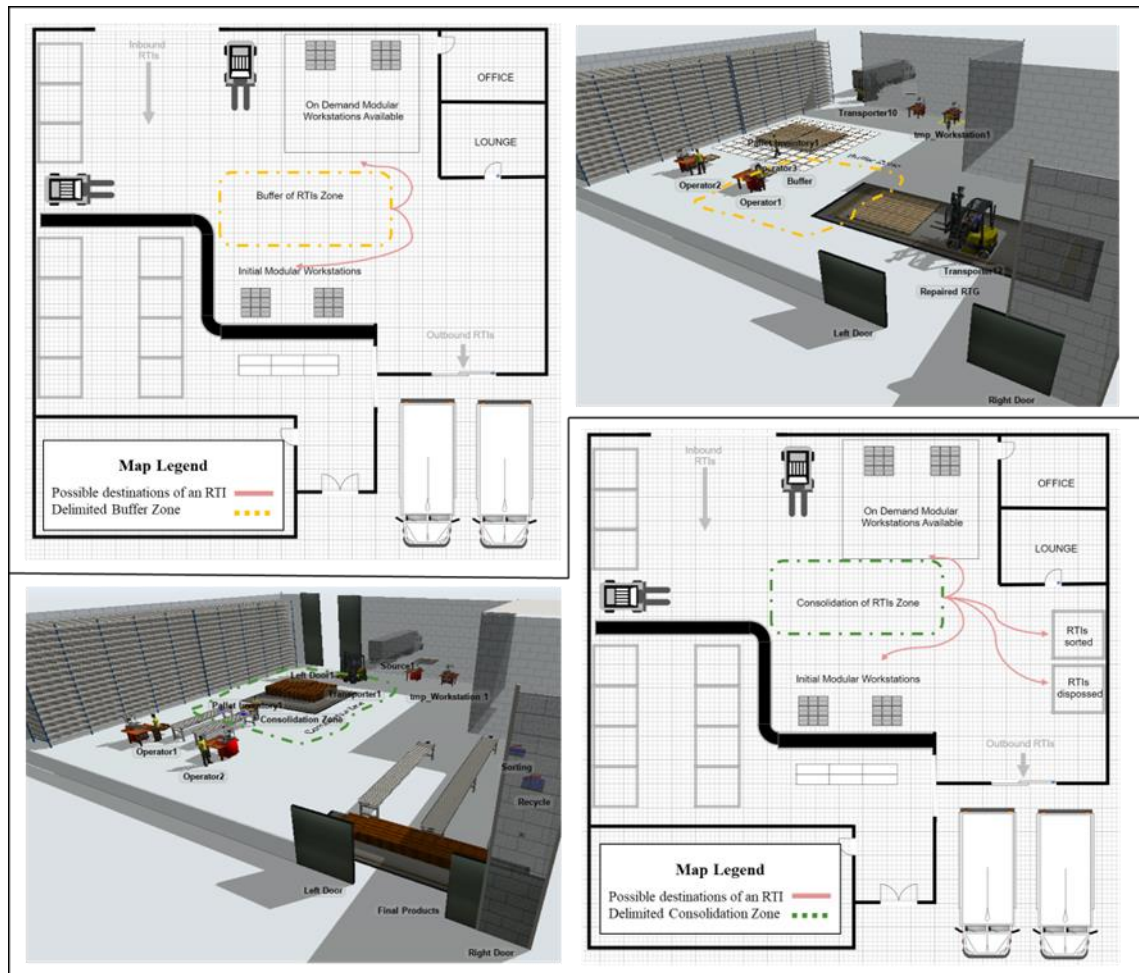*Figure 5. Non-modular and non-consolidation scenario (ML1).*

Figure 6. Layout proposed for ML2 (top) and ML3 (bottom)

- Assume a fixed capacity through the whole simulation (the assumption of two/four workstations is fixed).
- As we are working with no cargo consolidation all pallets will feed the system.
- Under this setting, the study case will use real data for the **inspection, preparation,** and **reparation** times (before any change), such times will vary between 0.00 and 36.60 sec, 0.00 and 102.00 sec and 0.00 and 126.00, respectively. Also, the times will be chosen randomly based on the histograms plotted for the real data (see Figure 4).
- The time spend in non-value activities like walking to other stations to retrieve a tool, the time to grab a pallet, the time from workstation to final buffer will be the ones that FlexSim calculate based on the average speed of the worker and the average height.

4.3 Maturity Level 2 (ML2): Modular workstations and non-consolidation process

- With the inclusion of modular workstations, we now assume that it is feasible to adapt the capacity of the plant according to the demand and the required changes can be made in less than an hour (the assumption of fix capacity will no longer hold). Modular workstations also imply that it is possible to rotate, move and adjust such terminals inside any facility.
- The modularity of the workstations also includes that all terminals have a standard set of tools to perform the operations and therefore the intervals of time are also reduced.
- The process times are now under statistical control with a 95% confidence interval and the mean times are 15 sec, 45 sec and 60 sec for the **inspection**, **preparation**, and **reparation,** respectively.
- As the no cargo consolidation assumption remains, all pallets will feed the system.

4.4 Maturity Level 3 (ML3): Modular workstations and cargo consolidation process

- Cargo consolidation now imply that the pallets received are going to be divided into groups: Pallets for disposal, Pallets that just require to be classified (sorted) and Pallets to be repaired, these last group will be the only items that feed the entire system. As sorted pallets will not require reparation is possible to consolidate them as soon as they are unloaded and send them as a package to the desired location, the same logic applies for pallets to be disposed.
- The assumption that it is possible to adapt the capacity of the plant on demand holds because of the modular terminals. Similarly, the process times from the previous point will also apply to this case.

Table 1. Summary of the assumptions used for the different maturity levels.

Assumptions for the Proposed Models	Simulated Maturity Level 1	Simulated Maturity Level 2	Simulated Maturity Level 3
Demand Behavior	Historical data Forecast	Historical data Forecast	Historical data Forecast
Capacity of the Facility	Fix	Flexible	Flexible
Workstation adaptability to a layout	Not feasible	Feasible	Feasible
Inspection Times	Empirical Distribution [0.00-36.60]	Normal (15,1) 95% CI	Normal (15,1) 95% CI
Preparation Times	Empirical Distribution [0.00-95.00]	Normal (45,2) 95% CI	Normal (45,2) 95% CI
Reparation Times	Empirical Distribution [0.00-120.00]	Normal (60,5) 95% CI	Normal (60,5) 95% CI
Pallet Organization	Pallets are not categorized	Pallets are not categorized	Pallets are categorized
Pallets in repair system	All pallets unloaded	All pallets unloaded	Pallets identified for reparation

5. Simulation Results

The information presented below is based on the results of the simulation of 65 weeks (to cover an entire year and the seasonality effect during that time). In all the cases the study does not consider a warm-up period and the results are obtained as an average after 1000 replicas.

Table 2. Key Performance Indicators measured for different maturity levels (MLs).

KPI's	MLs	Max. Value	Average Value	Min Value
1. Number of pallets repaired per week (Smaller Layout)	Level 1	8,120	7,710	7,281
	Level 2	11,388	9,051	6,215
	Level 3	12,294	9,051	6,215
2. Number of pallets repaired per week (Larger Layout)	Level 1	16,010	14,298	13,440
	Level 2	22,472	18,154	10,353
	Level 3	24,638	18,154	10,353
3. Inventory on Hand Utilization (Smaller Layout)	Level 1	95.21%	63.06%	52.79%
	Level 2	97.68%	92.93%	88.83%
	Level 3	99.63%	99.38%	99.17%
4. Inventory on Hand Utilization (Larger Layout)	Level 1	92.01%	59.66%	49.31%
	Level 2	96.14%	91.88%	85.59%
	Level 3	98.77%	98.57%	98.25%

5. Cycle Time of Repair Process in Small Layout (Min/Pallet)	Level 1	0.46	0.43	0.41
	Level 2	0.54	0.37	0.29
	Level 3	0.54	0.37	0.27
5. Cycle Time of Repair Process in Large Layout (Min/Pallet)	Level 1	0.50	0.47	0.42
	Level 2	0.65	0.39	0.31
	Level 3	0.65	0.39	0.28

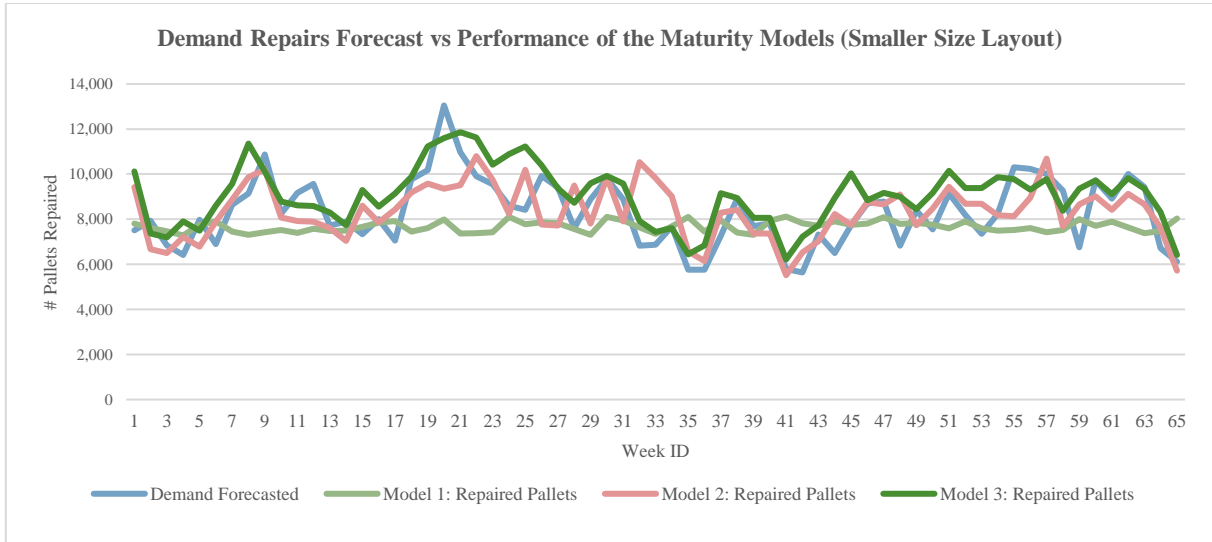To show the robustness and flexibility of the models it is possible to plot the following figures:

Figure 7. Demand of pallets to repair vs the results of the three generated models (small size).
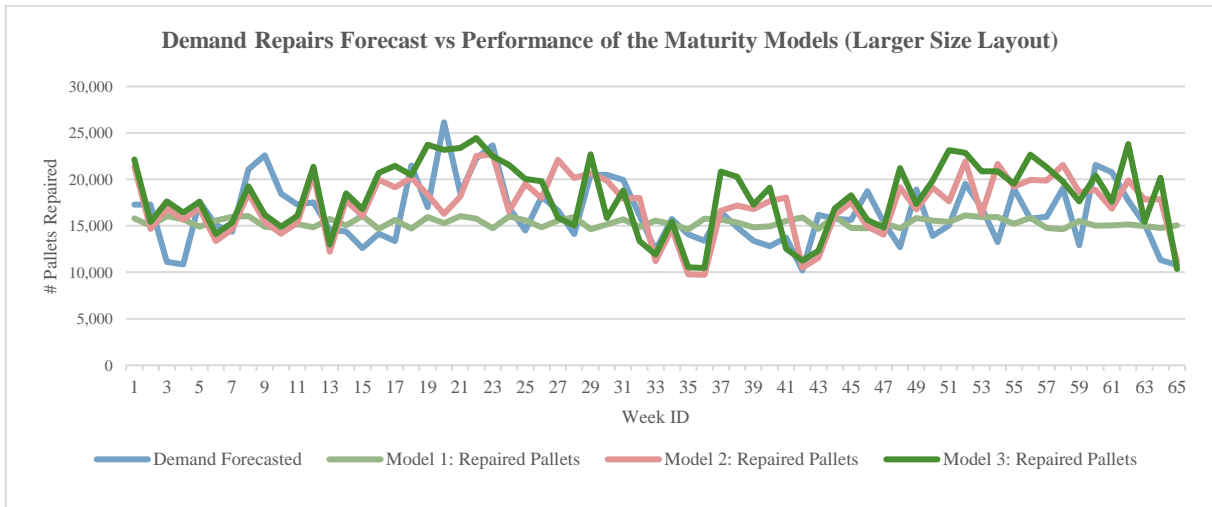

Figure 8. Demand of pallets to repair vs the results of the three generated models (large size).

The first point to discuss is the adaptability to random demand behavior. Maturity Level 1 exhibits a relatively stable and consistent flow of pallet repair, which is why the weekly throughput falls short in meeting demand during spikes, therefore, to avoid shortages it will necessitate high inventory levels, larger storage areas, and increasing holding costs. With Maturity Level 2, the addition of modular workstations upon request enables a more flexible throughput pattern, attempting to mimic demand behavior. Nonetheless, this improvement is constrained by the unresolved operational flow issues. With Maturity Level 3, considering cargo consolidation, the throughput behavior not only closely aligns with forecasted demand but also allows for anticipation of future demand, preventing strain on the production line during periods of heavy demand.

The second aspect to explore pertains to the effectiveness in processing received pallets and allocating them to their final destinations. In the case of Level 1, it becomes evident that even when operating at maximum capacity each week, the system fails to meet the forecasted demand. In the Level 2 scenario, an increase in capacity is observed, although it is not optimal. Nevertheless, it consistently meets the demand in each period. However, during periods of high demand, the system continues to heavily rely on inventory accumulated from previous periods of low demand. Lastly, within Level 3 it is evident that the system's capacity enables it to produce a surplus of pallets compared to the forecasted demand. Moreover, the primary constraint within the system shifts from capacity to the availability of incoming materials. This demonstrates that it is possible to serve more clients by increasing the supply of materials.

The last point for discussion is related to the variations observed when applying PI concepts to layouts of varied sizes. The experiment revealed that regardless of the size of the RTIs service provider, the findings remain consistent, that is, the company experiences enhanced throughput, reduced cycle times, decreased inventory levels, and improved adaptability to demand, because the system consistently adjusts as required.

6. Conclusions

The case study presented shows the potential advantages that the adoption of PI principles can provide for RTI service providers, and this claim can be extended to companies in general, when demand is variable, and flexibility is needed to manage this variability promptly. Modularity provides the required degree of freedom to adjust production levels in response to changes in demand, reducing the risk of shortages and overproduction. The information presented in Table 2 illustrates that the most significant performance improvements were accomplished with modularity, resulting in higher throughput per week, lower cycle times of the process and an increase in the ability to transform inventory on hand to final products ready to be dispatched.

In addition to modularity, cargo consolidation also plays a significant role. By consolidating cargo, workers can focus on activities that truly generate value rather than simply moving RTIs across the process. Consolidation enables a more strategic flow of RTIs, thereby minimizing the distance traveled by workers and facilitating smoother operations within the service provider. This reduction in congestion enhances overall productivity. It is important to remark that the improvements achieved, in this case, through cargo consolidation were limited by the incoming flow of materials; this presents an opportunity to extend the case study and explore the impact of receiving enough incoming pallets to fulfill additional demand.

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Can the Physical Internet pave the way to a Mobility of Entities?

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Abstract:

Despite using the same infrastructure, passenger and goods transport are typically perceived as distinct systems and are managed, analyzed, and considered separated from each other, particularly in urban areas. Hence, one of the key approaches of a more efficient and sustainable transportation system is the integration of freight and passenger transport.

In future, the network of mobility systems will be able to orchestrate itself. The IoT network will allow a seamless connection between various transport-related IoT-devices, transport modes, transport means, infrastructure, flows, and information. Assuming this and considering the principles of the Physical Internet (PI) of "physical, digital and operational interconnectivity through encapsulation, interfaces and protocols" (cf. Montreuil et al. 2013), it should not matter if encapsulated goods, or encapsulated passengers are moving. Passenger and freight transport could be orchestrated synergistically if technology was ready and used for a holistic optimization of the system. The concept of the PI could be transferred to individual mobility, and thus evolve to a "Mobility of Entities". Entities are, in that case, understood as objects, or modules, that either move goods or passengers.

Our vision assumes that passengers and goods are encapsulated and move within the same transport system. The capsule, the "PI-box" is, in that case, an autonomous transport module, or unit. Each unit can join and detach with other units – together, they function as a swarm of vehicles. In such units, either passengers or goods can be transported. Hence, the units have physical and digital interfaces, and protocols.

This paper aims at introducing the vision of a "Mobility of Entities" via modular transport units - an integrated freight and passenger transport system.

Keywords: *integrated freight and passenger transport, modular transport units, transferability of the PI*

Conference Topic(s): *autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms) business models & use cases; Modularization; PI impacts; vehicles and transshipment technologies*

Physical Internet Roadmap (Link): Select the most relevant area(s) for your paper:☐ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.

1   Introduction

Despite using the same infrastructure, passenger and goods transport are typically perceived as distinct systems and are managed, analyzed, and considered separated from each other, particularly in urban areas. Hence, one of the key approaches of a more efficient and sustainable transportation system is the integration of freight and passenger transport.

A classification of potential solutions for combining passenger and freight transport was suggested by *Trentini and Mahléné* (2010). That classification is comprised of three primary categories: utilization of shared road capacities, utilization of shared public transport services, and utilization of shared consolidation facilities. In 2016, *Arvidsson, N.; Givoni, M.; Woxenius, J.* tackled last mile synergies in passenger and freight transport and provide various examples of sharing resources for transport of passengers and freight. The conclusion drawn is that the integration of passenger and freight transportation in urban areas shows great potential for addressing the last mile problem. *Cavallaro, F. and Nocera, S. (2022)* conducted a broad concept-centric literature review on the integration of passenger and freight transport, focusing on the operational organization of an integrated passenger–freight system. They state that the implementation of this scheme could already be observed for long-distance transport modes, such as airplanes, ferries, ships, and a limited number of trains that permit the joint use of vehicles for both passenger and freight transport. However, an operational integration of passenger and freight transport is less prevalent in short-distance urban transportation and, in terms of transport modes, in road transport (cf. ibid.).

Bruzzone, F., Cavallaro, F., Nocera, S. (2021) discussed potential approaches for addressing certain challenges associated with the first-last mile transportation of passengers and freight, that involves promoting greater integration between transport systems. They introduce a tool for performance monitoring of possible passenger/freight transport integrations (cf. ibid., p. 46), that is considered vital for a holistic optimization.

While the Physical Internet (PI) is concentrating on the transport of physical objects, the concept provides principles such as the "physical, digital and operational interconnectivity through encapsulation, interfaces and protocols" (cf. *Montreuil et al. 2013*) that could be merged with individual mobility aspects. *Ouadi et al. (2021)* state that the integration of passenger flows into the concept of the Physical Internet (PI) would be an "innovative idea that could improve the openness and interconnection of universal transportation" (ibid., p. 428). They name numerous challenges and solutions the PI suggests, including the standard PI-elements such as containers, protocols, hubs, standardization, modes, or sensors (ibid., p. 429).

Matusiewicz, M.; Możdżeń, M.; Paprocki, W. (2023) introduced a concept for merging the PI with passenger air transport. While the potential use of the PI concept for passenger air transport has yet to be examined, their demonstration has illustrated that its feasibility is supported by the significant degree of sector integration and the advancement of technologies such as the Internet of Things and Artificial Intelligence.

Overall, literature suggests that integrating passenger and freight transport can lead to significant benefits in terms of efficiency, sustainability, and economic competitiveness. However, successful integration requires careful planning, stakeholder engagement, and the development of appropriate infrastructure and regulatory frameworks.

Considering all such aspects, we go one step further to merging the PI-concept with road-based, short-distance, semi-urban transportation: Our concept builds on the fact that passengers and

goods are encapsulated in the same type of capsule and move within the same transport system. The capsule, the "PI-box" is, in that case, an Autonomous Modular Transport Unit (AMTU). Each module can join and detach with other modules – together, they function as a swarm of vehicles. In such modules, either passengers or goods can be transported. Hence, the modules have physical and digital interfaces, and protocols.

2   Vision of the Mobility of Entities

2.1   Basic Assumptions

The integrated freight and passenger transport system, that we call "Mobility of Entities" (MoE), is designed for semi-urban and rural regions and short-distance trips up to 50 km. According to Eurostat, the average distance travelled per day per person in the European Union in the year 2021 was approx. 38 km (cf. Eurostat 2022). This includes different means of transport (bike, car, train, bus, walking). Of course, distances can differ considering countries, regions, purpose of trips, means of transport, and more. The European Commission states that the average length of the last mile in urban areas in the European Union is approx. 4.5 km (cf. European Commission 2019). Obviously, the last mile is depending on aspects such as type of region (urban, rural), country, type of goods, infrastructure, suprastructure, means and mode of transport, and more. However, both average passenger and freight transport distances lie within a 50km radius; hence it can be assumed that most transports in average European areas could be addressed with the concept. Urban regions are not in focus, as in general, cities strive to make urban space accessible to the population again, and not to (individual) traffic (e.g., Vienna, Copenhagen).

Our vision consists of the case-by-case use of:

a) Autonomous modular transport units (modules): Modular transportation systems that enable the efficient and standardized transportation of goods and passengers. The modules could be of different sizes, e.g., for 2, 4, 6, 8, 10, … passengers, or one pallet-size, two pallets side by side, etc. Seats or load securing devices could be set up and dismantled easily, that a unit can either be used for freight or passengers. The modules could be battery-electric-vehicles (BEV) that move autonomously on short runs (< 5km). For longer runs (>5 to < 50 km), they merge with each other such that a train-like construct (swarm, or convoy) is built. In the ideal setting, this train of modules is then mounted on rail tracks and coupled with a pushing/towing device taking over the propulsion of the so-built train. When a module reaches its destination, it uncouples from the train and covers the last mile autonomously again. Recharging of batteries could be realized whilst being pushed.

b) shared-use swarms: Both passengers and freight could be transported in the same swarm, in separate modules. Each module could join and detach with other modules by automatic coupling – together, they function as a swarm of vehicles. This leads to a significant reduction of separate vehicles, improving resource utilization. The swarm could either be pushed or towed by a battery-electric (BEV) or hydrogen fuel-cell (FCV) driven device, or another alternative propulsion system.
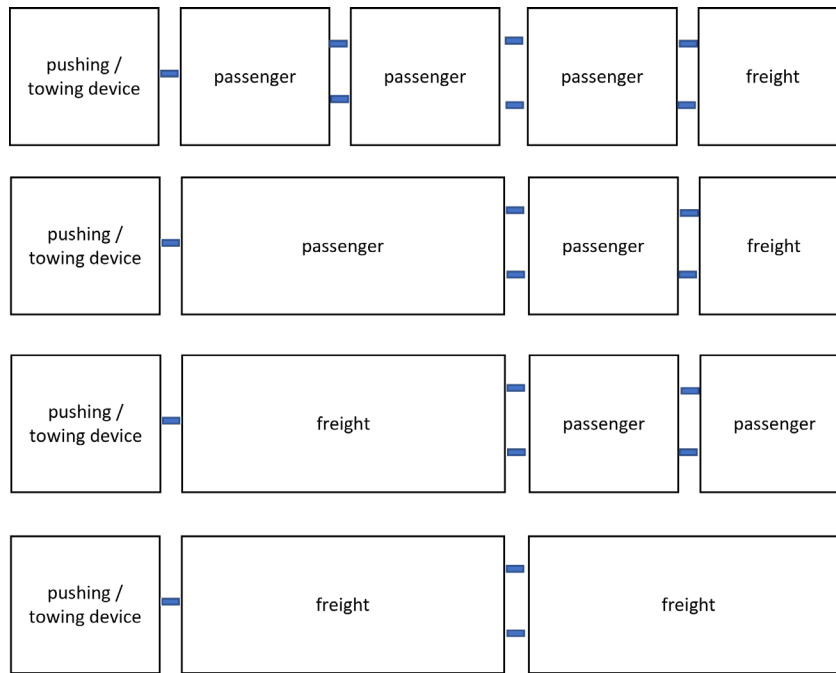
Figure 1: Illustrating different types of transport modules joined in swarms

c) integrated hubs: Integrated hubs could serve as a central location for the exchange of goods and passengers. These hubs could be designed to enable the seamless transfer of goods and people between different modes and means of transportation. This is important for longer transports (>50km), as there is the need to change to (synchromodal) conventional transport means.

d) dynamic ridesharing: Dynamic ridesharing systems could allow freight modules to "hop" on (freight) trains or inland vessels for the main run, or distances >50 km. If a single unit, it might also be transported within a passenger train.

2.2   Autonomous Modular Transport Units (AMTUs)

Autonomous Modular Transport Units (AMTUs) are a type of autonomous vehicle designed for freight transport, mostly. They consist of self-driving cargo modules that can be connected and disconnected as needed, allowing for flexible and efficient transport of goods. AMTUs use a combination of sensors, cameras, and artificial intelligence (AI) to navigate roads and traffic, avoiding obstacles and adapting to changing road conditions. The cargo modules themselves can also be equipped with sensors and monitoring systems to track the status and location of the goods being transported. One of the advantages of AMTUs is their flexibility and scalability. Because the cargo modules can be connected and disconnected as needed, they can be easily customized to meet the specific needs of different types of cargo and delivery routes. They also have the potential to reduce transportation costs and improve efficiency by reducing the need for human drivers and allowing for continuous operation without rest periods.

Ulrich et al. (2019) introduce an on-the-road modular vehicle concept and discuss it on technological level. The MAUDE system ("Modular, Autonomous, Updateable, Disruptive, Electric") of the German Aerospace Center, Institute of Vehicle Concepts is outlined, including its design, requirements and concepts for the drive system, battery and energy management, and automation of the vehicle concept.

Khan, Z. ; Weili, H.; Menendez, M. (2022) discuss the application of modular vehicle technology to mitigate bus bunching and take NEXT Future Transportation Pods as examples for autonomous modular vehicles (AMVs). The pods "are capable of in-motion transfer, which allows the modular units to couple and decouple while moving on roads, so that passengers can transfer from one unit to another while traveling". The pods can also be used for cargo transport.

Figure 2: Next pods (cf. https://www.next-future-mobility.com/)

Further examples for (prototype) Autonomous Modular Transport Units are:

Producer	Name of unit	Passenger / cargo	Type of unit	Type of usage
Volvo	Vera	cargo	tractor unit	Short haul in logistics centers, ports, and other industrial settings
Einride	Einride Pod	cargo	modular cargo u nit	medium distance transport
EasyMile	EZ10	passenger	modular unit	Urban areas
EasyMile	TractEasy	cargo	tractor unit	Short haul in logistics centers, ports, and other industrial settings
Lohr	Cristalya	passenger and cargo	can be operated in convoys or solo	Urban areas, geared to municipal mobility needs

2.3   Shared-use swarms

Autonomous Modular Transport Units (AMTUs) could be integrated into swarms, or train-like constructs, using v2v-communication, similar to platooning systems. To integrate AMTUs into a swarm, each vehicle must be equipped with sensors and communication systems that allow it to share information with other vehicles in the swarm. This information must include location, speed, and passenger/cargo factor/capacity, as well as data about road conditions, traffic, and other environmental factors.

Using this information, the modules in the swarm can coordinate their movements to optimize their routes, avoid congestion, and reduce energy consumption. They can also work together to handle unexpected events, such as road closures or accidents, by rerouting cargo and adjusting their routes in real time.

In addition, AMTUs may also be designed to be modular and scalable, allowing them to be quickly reconfigured to meet the changing needs of a swarm. This might include adding or removing cargo modules, adjusting the number of vehicles in the swarm, or changing the distribution of cargo among the vehicles.

2.4 Potential process

Whenever a person wants to, e.g., commute, s/he enters the autonomous module which is either parked at home (self-owned) or is brought by from a depot (mobility-as-a-service). Then, the module drives to a connection point where it is joined with other modules. Here, either a dynamic determination of connection points could be applied, or a train-station like equivalent can be used. This new built train then automatically continues its ride towards the destination, or according to a predetermined route. At some location (e.g., at the connection point), a pushing (or towing) device is connected to the train of modules. This pushing device can also connect to overhead lines, or other means of energy supply, that individual modules can be recharged during the trip. The individual modules, however, leave the train again as soon as they reached their destination (or destination station). The same concept applies for modules transporting freight.
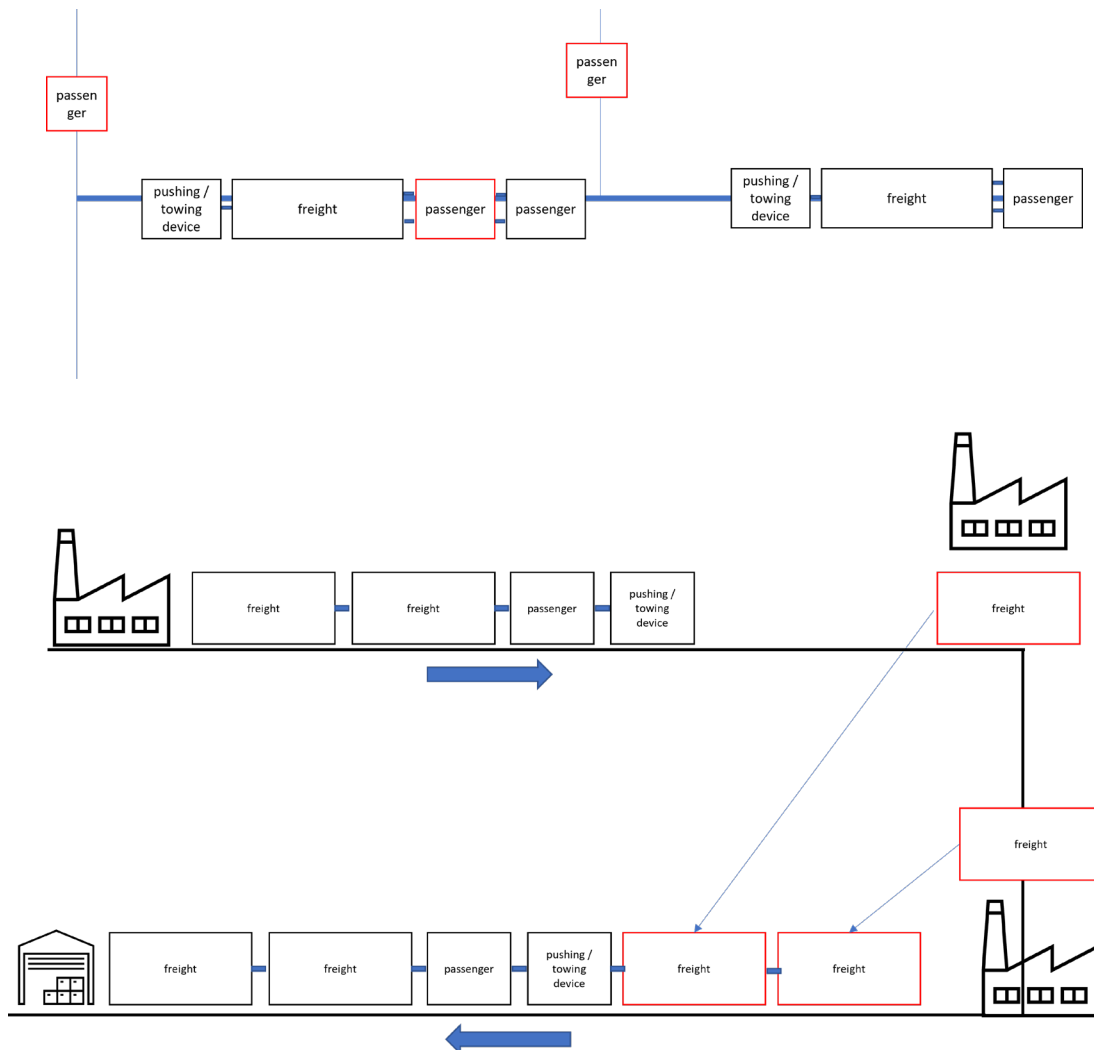

Figure 3: Rough sketches of the potential process

3 Benefits for stakeholders

We assume the following benefits for the stakeholders:
  a) For individual passengers, this kind of mobility allows for an individual experience (like in a private car) with the benefits of mass transportation (i.e., the possibility to work, read, sleep, etc.). Moreover, a significant reduction in transport time due to fully automated transport chain can be expected. Due to e-drive and module concept, a significant reduction in breakdown probability and downtime is possible. Furthermore, the investment requirement could be reduced, up to the complete offer of a mobility-as-a-service principle. All in all, it would be a smooth transition to fully autonomous driving via linkable front module.
  b) For shippers (or other stakeholders involved in the freight transport sector), the main benefits are that instead of classical transport logistics, on-demand ad-hoc transportation could be realized as each palette/set of palettes could be put in its own module and forwarded into "the system". As the building of trains or swarms would be self-organizing, shippers would not need to look for potential partners to cooperate with. Contrary, they would even be requested to not influence the transport system at all.
  c) Municipalities/state/cities/society: As the transport system would be a self-organizing swarm instead of a conventional structured transport network, traffic management would become more dynamic and plannable, as measures can be easily set. E.g., closing of a lane on the highway for construction work only needs to be communicated to the modules. They would then reorganize in other set of trains on the remaining tracks. In cases there would be traffic congestion, detours can be chosen. As trains are modular, it is even possible that some of the modules would take a detour, while others stay on track. It is, however, a necessity that the appropriate information (traffic situation, road/rail network, travel demand of others, etc.) is available in real-time. Moreover, the vision delivers a response to solve the problem of rapid wear and tear of our transport infrastructure. A flexible implementation of legal requirements regarding energy consumption and emissions would be possible, as well as its permanent control. Considering different applicable propulsion technologies, the system would be flexible and adaptable with regards to energy supply.

4 Need for research

As this vision is still a conceptual approach, we highlight that there is significant need for research until such a system could be realized. We think, however, that from a technological perspective, the main work is related to implementation than rather development, or even research.

Research is, however, important with respect to the usage of such a system. For example, it needs to be evaluated whether such a dynamic system has a positive or negative impact with respect to sustainability. On the one hand, the individual movements of persons and freight directly relates to the basic PI idea (which is assumed to be positive). On the other hand, if each palette is transported by its own device, overheads (in terms of needed hardware) are significant and will most probably reduce the positive (financial) impacts. Even more, if modules are owned by individuals, it is basically just a replacement of conventional cars with some newly designed modules. They still need parking spaces and will most probably not moving for about 23 hours per day (as it is with cars today). If they are, however, shared among different users, they need to be moved from the last location the previous customer stepped out towards the next location where the next customer wants to enter. In this case, an empty module is driving around. It can then be expected that the average number of persons per module is less than 1 (which is a major reduction compared to the even now bad value of something close above 1).

Furthermore, it needs to be investigated whether persons are even willing to accept this kind of mobility. Safety issues might be considered if self-driving modules are extensively used. Therefore, we think that research should be done in these directions. It needs, however, to be critical and not "in love with technology".

5 Conclusion

Within this paper, a thought experiment has been presented which introduces autonomous modular transport vehicles for individual use by passengers and freight. Positive effects might be the easy combination of freight and passenger mobility, the integration of individuals "taking their car" into trains, and the easiness for traffic management and congestion avoidance. Negative effects might be empty moving modules, heavy overheads (hardware-wise) compared to current technologies, and safety issues with other road users. Especially rebound effects (e.g., more energy consumption than current systems, less public transport users in the future) need to be considered. Many research questions are still open – although they are more focusing on the "soft" measures than on "hard" measures linked to the development of technologies.

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Strategic planning in multimodal transportation：

a systematic literature review

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Abstract: *Multimodal transport offers an advanced platform for more efficient, reliable, flexible, and sustainable transport for freight transportation. However, combining different transportation modes in transport chains requires cautious planning of infrastructure constructions and collaboration of the involved service providers. This study presents a structured literature review for strategic planning of multimodal transport, covering literature that deals more than one transportation modes from the past two decades. The topics encompassed include the classic hub location problem, network design problem, as well as the competitions and collaborations of multimodal service providers. The reference in each category are evaluated with on problem characteristics, modelling formulations and their corresponding solution techniques. In the end, this review concludes with an outlook to main future research directions.*

Keywords: *Multimodal freight transportation, strategic planning, hub location problem, network design, competition and cooperation*

Conference Topic(s): *interconnected freight transport; logistics and supply networks; ports, airports and hubs;*

Physical Internet Roadmap *(Link): Select the most relevant area for your paper:* ☐ *PI Nodes,* ☐ *PI Networks,* ☒ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

1 Introduction

Multimodal freight transportation refers to the combination of at least two modes of vehicles to move the freight from its origin to the required destination. Multimodal operators can take advantage by simultaneously exploiting the benefits of different transportation modes. The customers, including the shippers and logistic service providers, can benefit via comparing the possible service combinations and choosing the most suitable and economic one. In addition, the society as a whole can benefit from the mode shift from road towards greener modes, which can also lead to reduced pollutant emissions and accidents.

The multimodal transportation is one of the road-maps of the Physical Internet (PI) initiative (Alice roadmap to physical internet, 2023). From the view point of operators and customers, PI encourages " implementation of flexible contracts giving freedom for design and operation of multi-modal transport networks to avoid fixed specifications for routes, modes, inventory locations and timeslots" via the hyperconnected logistics network. Furthermore, PI supports the transition towards Zero Emissions Logistics via the mode shift.

Despite the potential economic and environmental benefits, multimodal transport still has yet to gain widespread acceptance and application. Unimodal road transportation remains dominant European inland transportation, 76.50% of freight was transported by road, whereas only 18.00% and 5.50% by rail and inland waterways(EUROSTAT, 2018). One reason for this is the complex nature of multimodal transport, involving more component parts and transshipments. This can leads to complicated process and concerns about flexibility and reliability.

Planning models can provide sufficient support to handle the complexity of the transportation to promote its acceptance and application. Generally, there are three levels of planning regarding to the planning horizons: strategic, tactical and operational planning. Of these three levels of planning, The strategic level involves long-term investment decisions on infrastructure planning, and hyperconnected network design. Its will have a considerable long lasting effect for the subsequent tactical and operational planning.

However, the strategic multimodal freight planning is a growing and evolving field. The well-known literature review of SteadieSeifi (2014) requires an update due to the significant amount of studies published in the past decade. Additionally, to the author's knowledge, there has been no literature review so far that expand the competition and collaboration among the stakeholders of the multimodal transport, despite the collaboration is encouraged by PI. This paper aims to fill these gaps by discussing strategic planning issues encountered in multimodal freight transportation, reviewing peer-reviewed papers published mostly between the year of 2015-2022, and some early but seminal papers.

The rest of the paper is constructed as follows Section 2 describes the research questions and methodological approach of the literature review. The collected studies are classified according to their main problem characteristics, which are described in section 3. In the end, section 4 gives a brief conclusion and a few possible future research directions.

2 Research questions and Methodology

This section describes the methodological approach of the literature review. In order to address the aforementioned gaps, this paper conducts a systematic survey of strategic multimodal freight transportation planning, mainly answering the following research questions(RQ).

RQ1: How can the research literature conducted on strategic multimodal freight transportation planning be systematically collected?

RQ2: In which way is the multimodal planning is distinguished from single-mode transportation in terms of planning concerns, problems characteristics and model formulations?

RQ3: Which problems characteristics, models are already considered and which fields requires further research?

To address RQ1, we used the Scopus, one of the largest peer-reviewed databases for scientific publications. We performed four different search runs using various query strings for title, abstract and key words within the Scopus database.

(1): ("strategy planning" or " strategic planning") AND (transport* OR freight) AND (intermodal OR multimodal OR physical internet); (2):"hub location problems" AND (transport* OR freight) AND (intermodal OR multimodal OR physical internet) ; (3): "network design" AND (transport* OR freight) AND (intermodal OR multimodal OR physical internet) (4): "hubs" OR "consolidation" AND (transport* OR freight) AND (intermodal OR multimodal OR physical internet)

The abstracts of collected studies were screened to obtain relevant literature for future analyses (RQ2). The criteria for reserving papers for the next steps are as follows: (i) the main topic should be about the strategic planning, dealing with long term investment. (ii) the paper should explicitly deal with more than two transportation modes. Papers that claim multimodal/ intermodal/ syncrhomdal transport but assume homogenous vehicle set will not further studied. Additionally, both papers cited in the screened papers, and paper citing the screened papers are checked during the review process to ensure the broad coverage of review (RQ1). The

classification and a detailed review of the chosen studies (RQ2) are presented in section 3. The answers to RQ3 is discussed in Chapter 5.

3 Results of the literature review

The studies on this topic can be divided into three groups: (i) multimodal hub location problems, (ii) multimodal network design problems, and (iii) competition and cooperation among the service providers. The ***hub location problem (HLP)*** deals with the location selection of a set of nodes to place hub facilities, whereas ***network design (ND)*** additionally makes decisions on the selection of the links to connect origins and destinations, possibly via hubs, as well as the routing of commodities through the network. ***Competition and cooperation*** discuss in which way the port operators improve their competitiveness to attract more customers. Cooperation, on the other hand, study the alliance of different operators such as their combined interest is maximized.

Table 1 summarizes the literature in this domain, indicating their investigated transportation mode, formulations, solving methodology and other concerning characteristics. It should be noted that in the literature HLP and ND are sometimes intertwined and a few studies fall into overlapping areas.

3.1 Hub location problems

In this subsection we briefly review the multimodal HLP regarding their involved modes, concentrated problems and the model formulations. For an extensive study on HLP without considering the multiple transporation modes, readers can refer to Alumur et al. (2021).

There are two main protocols for assigning demand (spoke) nodes to the installed hubs: single allocation (SA-HLP) and multiple allocation (MA-HLP). In the first category, all outbound or inbound flows of any node must travel directly from or to a certain specific hub. Whereas in multiple allocation network, flows of a given node can go directly from/to different hubs.

The goals of port authorities when planning the hub locations are two folded: (i) to **increase profits** as operator-oriented and (ii) to **improve service quality** as customer-oriented. The pursuit of profit at strategic level planning can be achieved mainly from *lowering operating cost* and *enhancing business volume*. The approaches to improve the service quality include but are not restrict to *shortening delivery time*, *providing smooth transhipment* among different modes at hubs and *maintaining reliable and robust hub services*.

3.1.1 Operators oriented planning

The *scale of economics* resulting from freight consolidation at hub terminals can bring down the operating cost. Racunica and Wynter (2005) incorporate the scale economies of (semi-) dedicated freight rail lines which could make use of shuttle trains between hubs. The authors adopt a *discount factor* on the inter-hub links, resulting a lower per unit price than that on extremal non-rail links. The inter-hub cost term was a concave increasing function of flow, which is accomplished through a non-linear formulation. Kurtulus (2022) uses piece-wise linear cost function to formulate the volume discount of consolidated rail transport. It is particularly worth noting that Kurtulus (2022) considers the repositioning of empty containers, whose considerable sizes accumulate into a significant portion of total transportation costs.

Another approach to enhance profit is to *uplift the market share*. Some shippers with *price sensitive demands* generally send their commodities in the cheapest way, while some with *elastic demands* usually do not choose long term contract but intermittently switch to other carriers. *Attracting and retaining customers* can be achieved via proper price policy of the hub

Table1 literature of strategic planning of multimodal freight transportation

reference	Transportation modes	allocation	Centralized or decentralized control	formulation	Additional considerations
1. Hub location Problem					
Merakli and Yaman (2016)	intermodal	multiple	centralized	linear MIP	polyhedral demand uncertainty
Kurtulus (2022)	rail, road, sea	single	centralized	piece wise linear MIP	empty container relocation and volume discount
Zhang et al. (2022)	ground, air	multiple	centralized	non-linear MIP	incomplete connectivity and deliver time restrictions
Mohammadi et al. (2019)	multimodal	single	centralized	non-linear MIP	Effect of uncertainties and congestion
Alumur et al.(2012a)	ground, air	multiple	centralized	linear MIP	time-definite delivery
Teye et al. (2018)	rail, road	single	centralized	convex, non-linear MIP	shippers use the ports or not
2. Network design problem					
Alumur et al. (2012b)	ground, air	single	centralized	linear MIP	small package delivery considering cost and service levels simultaneously
Meng and Wang (2011)	sea,rail,roa d	single	decentralized	non-linear MIP	user equilibrium
Wang and Meng (2017)	sea,rail,road	single	decentralized	non-linear MIP	re-design an existing intermodal freight transportation network
Wang et al. (2018)	rail, road	single	centralized	linear MIP	uncertain demand, cost and time
Serper and Alumur (2016)	ground, air	single	centralized	linear MIP	multiple vehicle types
Yang et al. (2016)	intermodal	single	centralized	non-linear MIP	mixed uncertainties of cost and time
Real et al.(2021)	heterogeneous vehicles	multiple	centralized	linear MIP	flow-dependent transportation cost
3. Competition and cooperation					
Xu et al. (2018)	intermodal	multiple	decentralized	game-theory	port competition, shippers' route choice behaviours and stakeholders' environmental concerns
Zhang et al. (2018)	intermodal	multiple	decentralized	MIP	port competition & shippers route choice
Jiang et al. (2020)	multimodal	multiple	decentralized	non-linear MIP	port competition and shippers' choice
Mahmoodjanloo et al. (2020)	multimodal	single	decentralized	non-linear MIP	hub location, assignment and pricing decisions based on elastic demand
Tamannaei et al. (2021)	Rail road	single	decentralized	game-theory	duopoly competition and government intervention
Gong and Li (2022)	intermodal rail, sea	multiple	decentralized	game theory	social welfare maximization considering the competition and cooperation
Wei and Lee (2021)	rail, sea	single	decentralized	hybrid method	a coordinated horizontal alliance system, cross border logistics

services. Mahmoodjanloo et al. (2020) study how to attract customers as an entrant company by deciding a convenient location (as the main problem of the bi-level model) and subsequently setting proper price for its transportation services (sub-problem). In areas far away from sea ports, inland railway terminals or airports act as promising and sustainable solutions to attract customers from pure road transportation. According to Kurtulus (2022), the success of an intermodal rail terminal hinges on its location. We add a side note here that the role of a rail terminal has evolved as the development of multimodal transport. They have taken on new roles as extensions of the seaport, which has little room for physical expansion to accommodate the ever-growing freight demand, into the hinterland. Therefore they are named as dry ports, inland ports, inland terminal, and inland container depot, etc.

We note here there are abundant studies on single mode HLP concerning profit (O'Kelly and Bryan (1998), Alibeyg et al. (2016)) and service quality (Elhedhli and Wu (2010), Yang et al. (2016)). However, these studies are not discussed in this work as the aim herein is to focus on multimodal transport.

3.1.2 Customers oriented planning

Delivery time is a key concern in the e-commerce logistics, with 'next day delivery' or 'delivery within 24h' promises posing challenge for logistics companies to balance among the delivery time, operating costs and mode shifting. Alumur et al. (2012b) explore the combination of air cargo with ground transportation in Turkish market. Zhang et al. (2022) address delivery-time restrictions in the air-ground HLP, considering both single (SA-HLP) and multiple (MA-HLP) allocation scenarios. They find that the operation cost in SA-HLP is far higher than that of MA-HLP due to increased travel time between O-D pairs and restricted path choice with higher travel cost to meet the delivery time requirements.

Consolidating flows makes planning more vulnerable to uncertainties and disruptions, which can cause substantial recovery time and thus a lower service level. The uncertainties or disruptions can rise exogenously, such as the uncertain demand Meraklı and Yaman (2016) and endogenously, for example, random travel time, random transportation cost, or unreliable routes (Mohammadi et al. (2019). The HLP therefore considers *reliability* and *robustness* in the strategic level to hedge in advance against various uncertainties.

Reliability concerns computing, estimating, or maximizing the probability that a network remains connected in the face of random failures. Stochastic technique, which *assumes foreseen probabilistic information and corresponding parameters*, is a common way to deal with future uncertainty. Mohammadi et al. (2019) consider stochastically degraded capacity of hubs and links to minimize both the total cost and the transportation time. There are also uncertainties that with *no information about their probability distributions*. Wang et al. (2018) rely on fuzzy optimization techniques to handle the uncertain information in the network design problem. Teye et al. (2018) use the entropy function to maximise all possible states. The goal is to select the most likely state consistent with all the information available about the containerised transport system.

On the other hand, *robust optimization* does not make assumptions about the probability distributions but assumes that the data belongs to an uncertainty set. A robust solution is one whose worst case performance over all possible realizations in the uncertainty set is the best. Meraklı and Yaman (2016) adopt two polyhedral uncertainty sets from the telecommunications literature, namely hose and hybrid models, to represent the uncertainty in the demand data.

A particular application associated with the multimodal HLP but not involved in a single-mode HLP, is the *mode-change transhipment lines at hubs*. A transhipment line represents a collection of infrastructure facilities such as yard cranes, vehicles and straddle carriers, needed

to accomplish container mode changes (Meng and Wang (2011)). Transhipment will cause additional cost and time. Meng and Wang (2011) use a trans-log cost function to estimate transhipment costs in a context where *multiple* types of containers need to be transported.

Hub congestion problems arise with the growing freight demand, which can reduce serve level. Contreras et al. (2012), Elhedhli and Wu (2010) and Alkaabneh et al. (2019) study the SA-HLP with capacity and congestion considerations. These works use a convex fractional function of flow, which is asymptotic to the hub capacity. If flow is close to the capacity limit, the asymptotic behaviour of the cost function implies a more severe impact of congestion. Similarly, Cagri Ozgun Kibiroglu et al. (2019) address congestion using a rational function flow. Teye et al. (2018) assume that the maximum quantity of cargo that each port must not exceed the hub's handling capacity, which however may not reflect the real-world scenarios. Meng and Wang (2011) and Wang and Meng (2017) employ the BPR (US Bureau of Public Roads)-form time function developed to convert the congestion affect to longer travel time on the arc of a multimodal hub network design problem. To the authors' knowledge, there is room for further research on congestions and the corresponding influences in multimodal HLPs.

3.2 Network design problems

Multimodal network design (ND) problem not only deals with the hub locations (main task of the HLP), but also establishes the connectivity between hubs, determines capacities of hubs, determines which transportation modes to serve at hubs, allocates non-hub nodes to hubs, and decides the number of vehicles of each mode to operate on the hub network to route the freight between origin-destination pairs. For example, the multimodal ND studies encompass the connectivity among hubs. HLPs usually assume a fully or complete inter hub connectivity, which is not true in the real application (Zhang et al. (2022), Real et al. (2021)). Readers can check (Basallo-Triana et al. 2021) for a literature review on the single mode ND problems. The subsection concentrates on the literature within the last decade implicitly mentioning multimodal transportation in the ND problem.

3.2.1 Operators oriented planning

From the profit maximization viewpoint, the network designers deal with operating costs, including not only fixed costs of establishing hubs with different capacities, but also the cost to set the connections, purchasing and vehicle operating costs, transportation costs and material handling costs (O'Kelly et al. (2015), Real et al. (2021) Wang and Meng (2017), Serper and Alumur (2016)). Real et al. (2021) argue that the scale of economics is suitable for the interhub operating, but is too oversimplified to be applied on hub arcs. The authors calculate the arc transportation costs via the fixed cost of using a vehicle and distance-dependent cost. This is to avoid miscalculations of the total network cost, as well as erroneous decisions of hub locations and non-hub allocations. Wang and Meng (2017) examine the costs of building up or enlarging a link among already existing hubs to decide the expansion of the hub-and-spoke network.

3.2.2 Customers oriented planning

Multimodal ND considers the *mode choice* of customers not only within the hubs but also in the connections among hubs. The concept of mode choice in the ND literature was first introduced literature by O'Kelly and Lao (1991). The authors consider two hubs, one master and one mini hub, at fixed locations, and analyse the allocation decisions for air and ground transportation modes. A series studies, Alumur et al. (2012b) and Serper and Alumur (2016) consider the mode choice for the small parcels delivery in the Turkeish market. The delivery firm operates its own fleet on the network connections and makes crucial decisions about which

links to operate its air crafts and trucks. Serper and Alumur (2016) consider which transportation modes to serve at hubs and the number of vehicles of each type on the links in the intermodal network planning. Teye et al. (2018) include the multiple shippers' choices whether or not to use the multimodal transport or road-only transport at the first step of network planning. Real et al. (2021) study the itineraries for the selected vehicles for an incomplete multimodal ND problems.

Multimodal ND can promote the mode shift from a systematic level. Kurtulus and Ismail Bilge Cetin (2020) investigate the potential for mode shift in short-distance inland container transport by considering behavioural aspects of inland container transportation mode choice. Their study based on Turkey's rail-road intermodal indicate that the transportation cost has the biggest impact on shippers' mode choice and the modal shift is more sensitive to the road transport costs than to intermodal rail cost. Both studies by Kurtulus and Ismail Bilge Cetin (2020) and Kurtulus (2022) reveal the importance of providing enough capacity of the railway links for achieving low emissions in Turkish transportation system. Zhang et al. (2021) evaluate the environmental benefits of modal shift from trucks in Shenzhen, China. However the Kurtulus (2022) argues that modal shift should not be seen as a miracle solution for emissions reduction but as a first step before the adaptation of high energy-efficient rail transportation technologies.

3.3 Competition and cooperation

This subsection explores the topic of competition and cooperation among the multimodal service providers at the strategic level. Multimodal transport involves the competitions among a wide range of stakeholders and requires the cooperation of service providers involved. Competition among ports is defined as the pursuit of customer capture (Marianov et al. (1999)), in the form of hub locations and pricing strategies, during strategy planning. Horizontal cooperation is defined by the European Union (2001) as concerted practices between companies operating at the same level(s) in the market.

3.3.1 Competition

A common type of competition at the strategic level can be observed between two dry ports serving overlapping hinterland areas, which naturally have a contest relationship (Zhang et al. (2018), Jiang et al. (2020)). These competitions are usually studied via game theory using either *Nash equilibrium* (Zhang et al. (2018), Xu et al. (2018), Tamannaei et al. (2021)) or *Stackelberg equilibrium* (Jiang et al. (2020)) models. In the Nash game, each player is assumed to know the equilibrium strategies of other players, and no one has anything to gain by changing only one's own strategy. Stackelberg models investigate the decisions of two planners in which the leader firm moves first and then the follower firms move sequentially.

Competition between two ports can have different goals, to have the maximizing profit (Zhang et al. (2018)) or capturing the maximum flows (Jiang et al. (2020)). Competition strategies may involve setting convenient hub locations (Mahmoodjanloo et al. (2020)), facility locations (Zhang et al. (2018)) and pricing strategy (Jiang et al. (2020), Mahmoodjanloo et al. (2020)).

The competitions can be classified into three types in terms of time sequence: *static competition*, *dynamic competition*, and *competition with foresight* . If the existing rivals (i.e., incumbents) do not react to the entrance of a new competitor, this is a static competition. In this situation the entrant(s) consider(s) hub location and price, taking into account the effect of their rivals (Mahmoodjanloo et al. (2020), Jiang et al. (2020)). In dynamic competition, competitors simultaneously determine their competitive factors. Zhang et al. (2018) study the competition between dry port Dalian port and Yingkou port in China, analysing their locations and pricing strategy to maximize profits from the view point of the port operators. In

competition with foresight, a competitor will react to an entrant's decisions sequentially. In Mahmoodjanloo et al. (2020), the incumbent port adjusts facility location and price to react to an entrant.

The game theory competition models can also explore how competition is influenced by *outside force*, such as the shippers' preferences or the government policy intervention. The shippers' discrete choice behaviour is mainly embedded with nominal logit models (Xu et al. (2018), Jiang et al. (2020)). Xu et al. (2018) study the competition with consideration of shippers' choice especially with environment concern on emission reduction. Jiang et al. (2020) study the joint choice of shippers on port, transportation mode and dry port, using data collected by revealed preference and stated preference techniques. Mahmoodjanloo et al. (2020) consider the effect of customer loyalty and elastic demand. Tamannaei et al. (2021) investigate the role of government intervention (taxes on fuel usage based on environmental, economic, and social concerns) in different sustainability dimensions of a competitive freight transportation market.

3.3.2 Cooperation

The profit-driven competition among the shippers can lead to information isolation, non-coordination and inconsistency operations among the operators, which are not beneficial to the multimodal transport as one service portfolio. There are recent projects such as synchromodality, physical internet or (single mode) vehicle platooning, which aim to remove the barriers and promote the cooperation among different members within the system. Most of the literature concentrate the flexible and cooperation from the tactical and operational level planning. Here we review the limited literature on the coordinated strategic planning.

Wei and Lee (2021) establish a coordinated horizontal alliance system for inland ports with China railway Express platforms. The case study reveals that the agreed-upon policies and activities agreement in the alliance governance mechanism, the joint planning and scheduling of routes, and shifts of the railway Express in the alliance operation mechanism can effectively promote the global cooperation. However, Gong and Li (2022) find that the cooperation of China-Europe Railway Express company and the international liner shipping company yield a lower total social welfare compared to that under competition. Not two entities always produce a higher return together than on their own, which is the ground for cooperation. A real world practice, the integration of Ningbo Port and Zhoushan Port, takes place to mitigate excessive port competition and avoid misallocation of resources. This port integration, which occurred from 2006 to 2016, was under strong government leverage. Readers can check Dong et al. (2018) to for further details about quantitative measures the effects of regional port integration.

4 Conclusion and a few future research directions

This presented literature review examines studies on multimodal transport planning mainly from 2015 to 2022. It updates the literature review ever since SteadieSeifi et al. (2014). In addition, it discusses the competition and collaboration among the service providers, of which the collaboration is important but has not been thoroughly reviewed in this field. The overarching topics (hub location problems, network design problems, competition and collaboration) are discussed in detail in terms of the involved transportation modes, problem characteristics and model formulations.

An outlook for few possible future research directions (RQ3) can be given. Firstly, it is worth noting that there are more studies about competitions than collaborations for the strategical planning of multimodal freight transportation, as can also be seen from Table 1 and subsection 3.3. The ongoing multimodal freight renovations such as Physical Internet, Synchromodality

and other similar projects, provide clear information that participants can benefit more from the collaborations. The progressing technologies, such as digitization and data sharing, support the cooperation and make cooperation more conductible. The collaborations therefore will be a promising direction.

Furthermore, strategic level planning for coordinating multimodal long-haulage and last -mile delivery is limited. Last mile delivery, as the subsequent procedure of long haulage, is also undergoing changes such as crowd-shipping, dial a ship, and the involvement of unmanned aerial vehicles (UAVs). Each of these variants has its own pros and cons, and it is necessary to study how each adapts as the subsequent chain in the rear of long haulage transportation from the strategic level such as the warehouse choices, the service zones defining.

Last but not least, the polycentric characteristic of multimodal transportation is rarely discussed in the strategic planning. The polycentric framework naturally lies in the multimodal transportation due to geographical distribution, organizational structure, financial settlement and other reasons. Strategic planning cannot design an alliance and synergy if it ignores the rooted poly-centrality.

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Consumers' perspective on automized circular packaging for e-grocery deliveries

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Abstract: In recent years, the continuous rise in packaging waste has been primarily attributed to the growing popularity of e-commerce. Currently hardly any reusable or circular packaging schemes have been implemented in Austrian e-commerce operations. The reason is mostly because there is no cost-effective way to realize reusable packaging as handling are critical to the profitability of the packaging scheme. To address this circumstance and potentially promote the further implementation of circular packaging, the aim of this paper is to present a new circular packaging technology which is based on automized and modular packaging units. For the success of such a new packaging technology, consumers have a critical influence. Therefore, a survey is conducted to evaluate consumers' perceptions on circular packaging for e-grocery deliveries. The delivery of deep-frozen bakery products will be taken as a use case to study the acceptance of circular packaging. Consumers are aware of the sustainability problems bound up with packaging waste. Consumers attach a very high importance to sustainable packaging. However, the survey results also show that consumers are rather convenient. They appreciate personal delivery service and only a small number of survey participants are open to using new delivery concepts.

Keywords: Reusable packaging, green packaging, parcel delivery, circular economy, consumer preferences, e-commerce.

Conference Topic(s): autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms) business models & use cases; Modularization; omnichannel & e-commerce logistics; PI implementation.

Physical Internet Roadmap: ⊠ PI Nodes, ☐ PI Networks, ☐ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.

1 Introduction and motivation

In online retailing, logistics constitutes a central economic function, regardless of the sector. Increased use of online grocery shopping has been noticed in recent years: An above-average growth was recorded in the course of the pandemic and is predicted to continue. The delivery of online groceries poses particularly high requirements on logistics due to the necessity of handling temperature-sensitive goods (Lagorio and Pinto, 2021; Zissis et al., 2018). The emitted greenhouse gas emissions and resource consumption caused by logistics are increasingly moving into the focus of consumers (Rausch et al. 2021; Boz et al. 2020). While packaging waste has risen continuously in recent years, a lack of sustainable alternatives for e-commerce

can be witnessed. The paper addresses this gap and presents an option for reusable e-commerce packaging which is in line with the fundamental principles of the Physical Internet (Montreuil, 2011). We will present a new circular packaging technology which is based on automized and modular packaging units. For the success of such a new packaging technology, consumers have a critical influence. Therefore, a survey is conducted to evaluate consumers' perceptions on circular packaging for e-grocery deliveries.

To evaluate the urgency of the problem at hand, an analysis of the development of e-commerce in Austria was conducted beforehand. The development of e-commerce can be seen as a key driver of parcel logistics. The analysis clearly shows that the online share of retail spending in Austria has been rising steadily since 2017 and already reached a share of 14 percent of all spendings by 2022. (Statista, 2023) Moreover, experts expect shares to rise to 23 per cent within the next few years (McKinsey, 2023).

Consumers increasingly demand higher sustainability in parcel logistics. Recently conducted surveys indicate that up to 79 per cent of consumers consider sustainability as being important for e-commerce, representing a major increase compared to past surveys (CGS, 2022). In addition to the increase in relative and absolute figures, further challenges for parcel logistics can also be identified. 92 percent of consumers consider the availability of free delivery to be important; 42 percent of survey participants rate the option of same day delivery as important.

In a customer experience study conducted by BOOXit, 82 percent of consumers stated that the sustainability of parcel delivery is very important or important to them. In addition, other important factors can be defined from the consumer's point of view; the efficiency in processing is just as important as the cost efficiency of delivery and/or return processing ("BOOXit" Customer Experience Study, 2022)

As mentioned above, consumers rate the possibility of free delivery and return as being pivotal while simultaneously demanding fast, flexible and sustainable delivery (Nguyen, 2019). This field of tension creates a need for increased automation and cost efficiency in logistics processes.
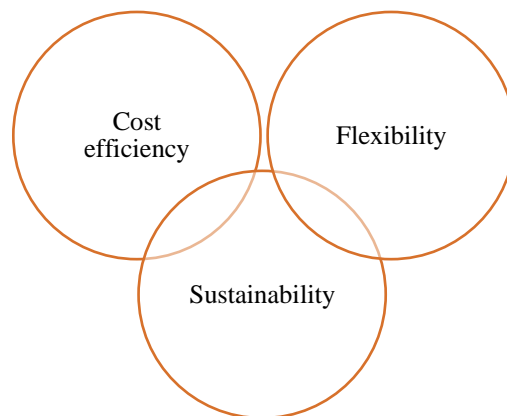

Figure 1: Current field of tension in parcel logistics

2 Objectives of automated circular packaging

In order to increase consumer satisfaction, the packaging technology "BOOXit" (BOOXit, 2023) addresses the key factors of cost efficiency, flexibility and digitalization as well as sustainability.

To increase process efficiency and thereby reduce process costs, the automated circular packaging approach is used. The term of automated circular packaging refers to reusable packaging which can be handled automatically by robots thereby reducing process costs which are, among others, caused by human errors. Further technological aspects foster the mentioned decrease in costs providing comparative advantages, i.e. automatized loading of boxes, AI-based route optimization and reduction of picking time using the pick-by-light-approach.

In addition to the increased efficiency that results in reduced costs, the issue of flexibility and digitalization is also well-addressed by this system as "BOOXit" implemented digital connectivity in their system. Using an app, consumers are not only given the opportunity to track their delivery in real-time but are also enabled to manage returns easily by simply scanning the code on the box. Moreover, "BOOXit" offers many further digital components based on latest technology advancements such as CP33-level communication for Industry 4.0 or the implementation of Blockchain technology to safely track processes. Connecting all relevant components, such as delivery boxes, shelves and the app to each other using a centralized database ensures maximum transparency for all stakeholders.

Lastly, the increasing demand for more sustainability along supply chains is fulfilled by using circular packaging thereby reducing packaging waste. Boxes are available in several dimensions using a grid system based on the palette measures of 120 x 80 centimeters. Twelve different box sizes cover approximately 82 per cent of box sizes currently used for delivery. According to the company, the amount of CO_2, which is currently emitted during parcel delivery processes, can be reduced by 92 per cent using circular packaging systems. Moreover, an increase in resource efficiency can be witnessed as cardboards are no longer needed and thereby saving further resources such as timber and water.

3 Methodology and case description

Referring to the challenges of parcel logistics in general, it must be noted that the specialized field of grocery logistics must fulfill further consumer demands in terms of delivery. First and foremost, goods are often temperature-sensible and therefore require constant cooling throughout the whole delivery process in order to maintain product quality. To meet these requirements, the packaging technology "BOOXit" also involves the possibility of active cooling and is therefore well suited to transport temperature-controlled goods such as e-groceries.

3.1 Use case description

The delivery of deep-frozen bakery products will be taken as a use case to study the acceptance of circular packaging. Austrian consumers are well used to being delivered with deep-frozen bakery products. The delivery of deep-frozen bakery products already dates back to the time before the e-commerce business accelerated and many consumers already have a lot of experience ordering deep-frozen bakery products. We therefore consider this as an appropriate field to introduce a new innovation such as automated circular packaging.

Robots allow for the (automated) loading and unloading of the parcel delivery vehicles, so that ideally a package only needs to be handled by the recipient at the destination, and not by postal

employees in the distribution centers. For this purpose, the start-up BOOXit developed modular boxes which can be gripped by a robot gripper arm and loaded into a trolley. This trolley can then either be pushed manually into the delivery vehicle by an employee, or automatically be lifted into the vehicle (which is also equipped accordingly with the aid of transport rails mounted overhead). This new packaging process allows for "one-shot-load" logistics operations, i.e. multiple packages can be handled at the same time, reducing the amount of handling time and costs. The modular design is in line with the fundamental considerations for containers in the Physical Internet (Landschützer et al., 2015).

For delivering the parcels, the postman can take individual packages out of the trolley and hand them over at the doorstep of the consumer. A pick-by-light systemsupports the postman in quickly finding the right parcel. Another option is to place the trolley containing the packaging at a public space and use it as a parcel locker. The parcel locker functions an automated postal box that allows users for a self-service collection of their parcels as well as the dispatch of parcels or return of empty packaging.

3.2 Survey description

For the success of such a new packaging technology, consumers have a critical influence. It is the responsibility of the consumers to use and return the circular packaging – without consumers' acceptance, the circular packaging system will fail. The aim of this survey is therefore to evaluate consumers' perceptions on circular packaging for e-grocery deliveries. It will be assessed what preferences they have regarding the delivery of e-groceries conducting a consumer survey.

An online survey has been conducted to evaluate what preferences the customers of deep-frozen bakery products have regarding the use of an automized circular packaging system as described above. In particular, it will be examined which delivery options consumers prefer – being directly delivered at home or picking up the delivery at a parcel locker or at a local store, and which framework conditions must be given for each of these options.

The invitation to the online survey was sent to 43,067 customers of a deep-frozen bakery retailer. To provide an incentive for participation in the survey, a lottery was offered for the respondents. In the end, 2,283 consumers completed the survey. The survey was conducted in May 2022.

4 Results

4.1 Consumers' perspective in terms of cost efficiency

In terms of consumers' demands regarding delivery costs, the survey provides a clear picture. 81 per cent of survey participants stated that a free delivery is very important, further 14 per cent considered this aspect important (n= 2123). These figures are also supported by other recently conducted surveys. For instance, the latest e-commerce dossier compiled by statista.de shows similar figures regarding costumers' sensitivity in terms of delivery costs (Statista, 2022).

In order to provide insights to consumers' perspective in terms of alternative forms of delivery, such as Click and Collect, drive-in-solutions, pick-up stations or unsupervised home-delivery, the conducted survey provides a diverse picture. On the one hand, consumers' willingness to use such facilities for last-mile-delivery strongly depends on the consumer's age, as younger participants are more open to these new approaches than more experienced consumers (Figure 2).
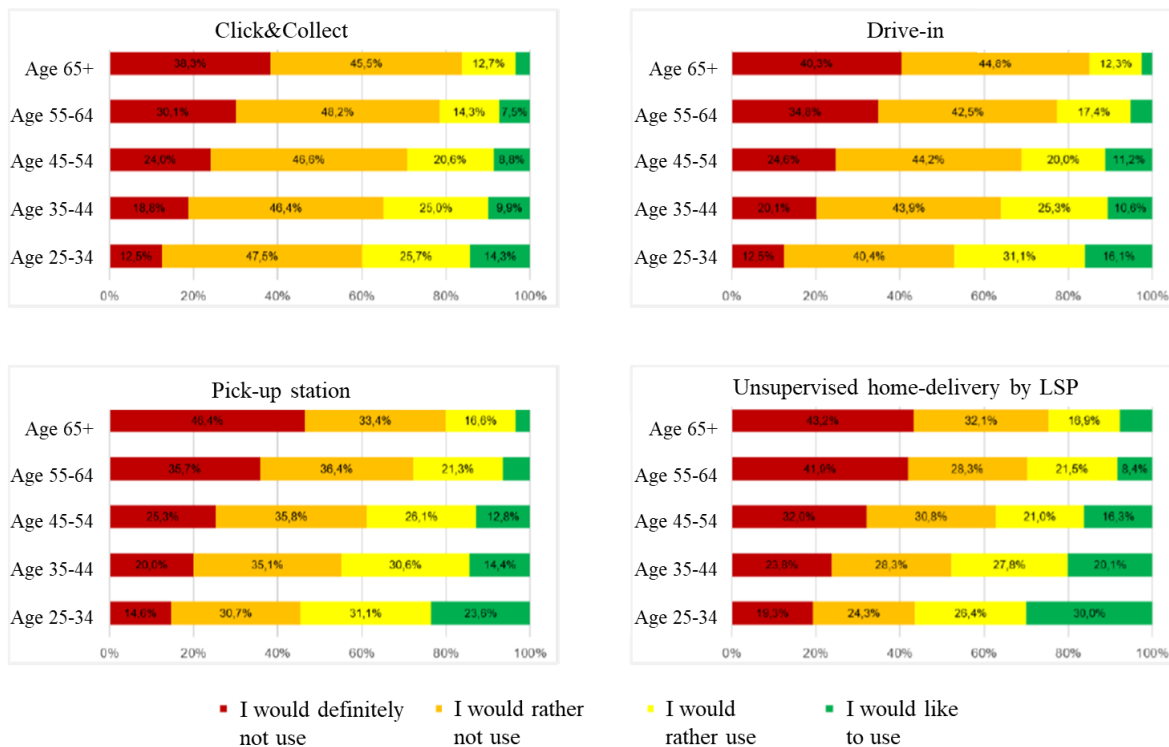

Figure 2: Acceptance of last mile delivery options (n=2,283 consumers)

On the other hand, willingness to pay for the above-mentioned approaches is generally low (Figure 3). Consumers are not willing to pay any extra fees for "Click and Collect" (83.1 per cent not willing to pay), "Drive-Ins" (89 per cent not willing to pay) or pick-up stations (78.9 per cent not willing to pay). Therefore, personal delivery to the consumer's home or alternative address can be noted as being vital for last-mile-delivery, yet 56,8 per cent of surveyed consumers would still not accept additional costs for home-delivery provided by a logistics service provider.
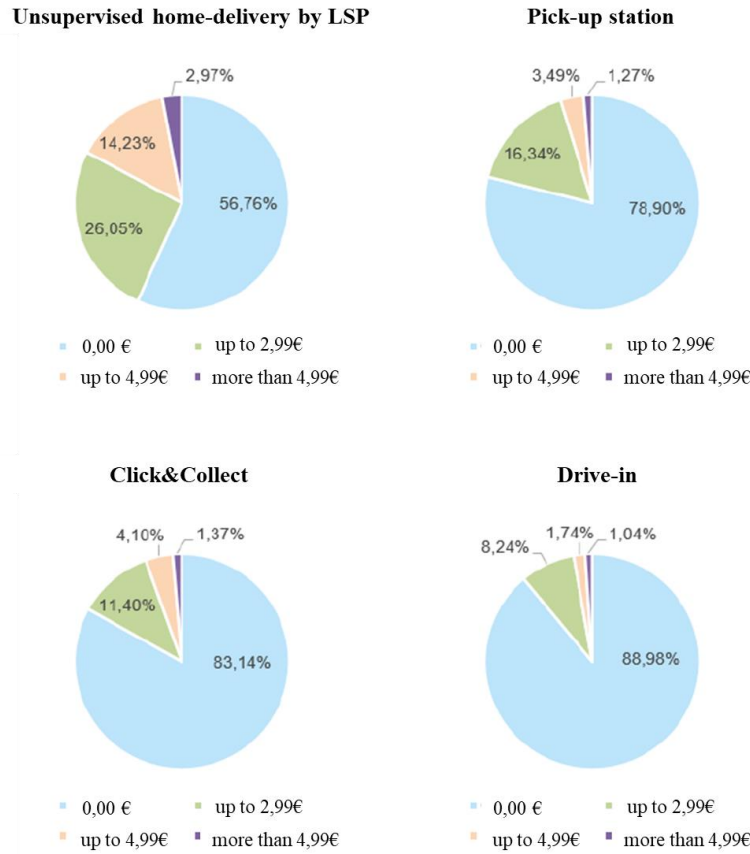
Figure 3: Willingness to pay for last mile delivery options (n=2,283 consumers)

4.2 Consumers' perspective in terms of flexibility

The results showed that younger generations are more open to new delivery alternatives, so that the potential for using "BOOXit" as a parcel locker station should be given among younger customer groups. Those consumers who are willing to pick up their parcel would accept a detour of up to three kilometers. The older the survey participants, the less willing they were to make a detour for picking up a delivery. Throughout the survey, participants were also asked how they would arrive at the parcel locker (Figure 4): Only a small percentage (3.6 per cent) would use public transportation for pickup. 84 per cent of respondents indicated that they would use the pick-up service in the course of their way home (e.g. from work or in combination with other shopping activities). 21.5 per cent of the surveyed customers would be willing to pick up the goods on foot or by bicycle. Approximately one fifth of respondents (21.1 per cent) would accept an additional car journey for the self-collection service, which is the least sustainable way to realize self-pickup.
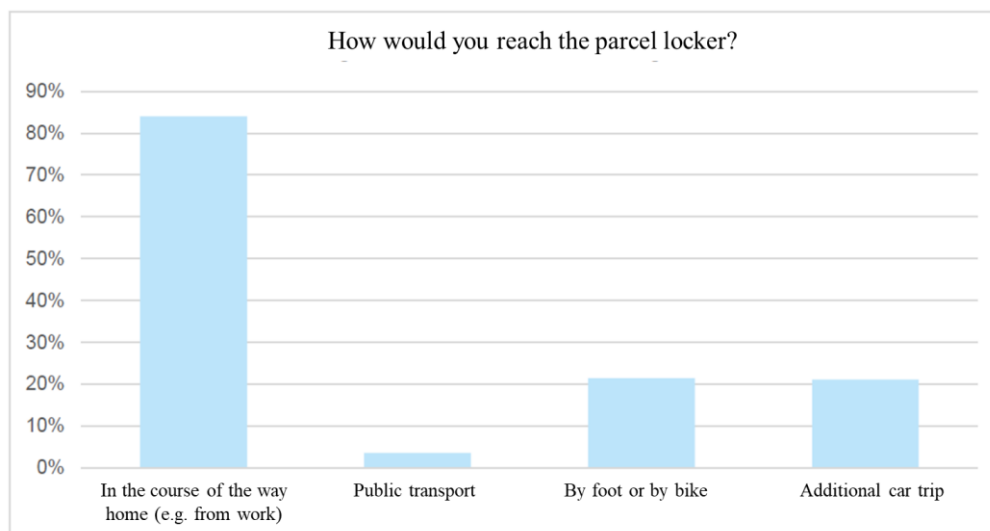
Figure 4: Arriving the parcel locker (n=2,283 consumers)

As it can be seen that customers' openness to alternative delivery options is still low, especially smaller households (i.e. a maximum of two residents) prefer receiving their orders directly and consider this as being very important (51.9 per cent) or at least important (54.8 per cent). Furthermore, the survey shows that flexibility in terms of timeframe for delivery is also important to customers. The majority of survey participants state that intimating a preferred timeframe for delivery is very important to them, further 21.2 percent responded with important. Surprisingly, the availability of timeframes for delivery in the evening hours is less important to customers. Almost two thirds of the surveyed customers see this option as being either less important (31.3 per cent) or even unimportant (34.6).

4.3 Consumers' perspective in terms of sustainability

Consumers are well aware of the sustainability problems bound up with packaging waste. Some consumers are even prevented from ordering e-groceries because of the packaging waste. Consumers attach a very high importance to sustainable packaging. They state that they would prefer those retailers which offer sustainable packaging options. However, the survey results also show that consumers are rather convenient. They appreciate personal delivery service and only a small number of survey participants are open to using new delivery concepts.

The conducted survey clearly shows the paramount importance of circular packaging, with almost 91 percent of the participants considering sustainable packaging very important (61 percent) or important (30 percent) yet both genders replied differently as female participants consider sustainably packaging as being more important (92.1 per cent) than males (85.7 per cent). Another survey, which was conducted by the company "BOOXit" itself states, that 80 per cent consider circular packaging to be more sustainable than cardboard, thereby addressing the issue of sustainability in parcel logistics (BOOXit, 2022).

Besides the issue of packaging, 54 per cent of the survey participants consider ecological delivery (e.g. by using e-cars) to be very important or important. This result aligns with society's strong demand for a decrease in CO_2-emissions.

5   Conclusion and outlook

To sum up the gathered information, it can be said that customers' demand for more sustainability in e-grocery delivery is currently rising following the zeitgeist. The COVID-19 pandemic served as an accelerator to a observable increase in e-commerce acceptance among consumers thereby leading to an increase in packaging waste. Moreover, customers are not willing to lower their demands in terms of flexibility and cost-efficiency creating a field of tension for logistics providers.

Circular packaging – in combination with digitalization and process automation – addresses this field of tension by reducing handling costs through automation while simultaneously fulfilling customer demands in terms of sustainability as packaging waste can be dramatically reduced.

Even though a small number of consumers is already willing to use alternative forms of last-mile-delivery, convenience among customers is still widely spread. Receiving the ordered items directly still represents the most appreciated form of delivery. Moreover, it can be said that customers are generally not willing to pay extra fees for circular packaging. It can therefore be derived that suppliers must carry possible extra costs for circular packaging yet following this approach holds the potential of creating a comparative advantage.

Therefore, creating a sustainable, flexible, and cost-efficient approach to circular packaging is paramount in achieving customer satisfaction and should be implemented to meet the growing demand for e-commerce.

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An Artificial Intelligence-based software module for the optimization of collaborative delivery in last-mile logistics

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Abstract: This paper presents a route delivery planning and simulation module that forms a core part of the ICT Platform of the H2020 SENATOR project, which aims to enhance the sustainability of cities by developing a new urban logistic model. The module utilizes AI-based optimization algorithms to support the matching of supply and demand, identify the best fleet mix, and estimate the best delivery route based on real-time conditions. It also allows last-mile delivery planning using different transport modes, inter-modality, and driving restrictions, and simultaneously optimizes different performance indicators. The paper provides a detailed description of the AI-based optimization method and the architecture and components of the software module. Finally, the software module is validated in two scenarios (current operations and implementation of a Low Emission Zone) using real shipment data from a postal operator company in the living lab that the SENATOR project is implementing in Zaragoza.

Keywords: last-mile logistics, vehicle routing problem, optimization, dynamic planning, multi-modal, collaborative delivery.

Conference Topic(s): distributed intelligence last mile & city logistics; PI modelling and simulation; technologies for interconnected logistics (5G, 3D printing, Artificial Intelligence, IoT, machine learning, augmented reality, blockchain, cloud computing, digital twins, collaborative decision making)

Physical Internet Roadmap (Link): Select the most relevant area(s) for your paper:☐ PI Nodes, ☐ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☒ Governance.

1 Introduction

The growth of last-mile logistics is a continuous trend, driven mainly by urbanization and changes in consumer behaviour. The surge in online retailing, e-groceries, and e-commerce has contributed to this phenomenon (European Commission, 2023). This trend has resulted in an increase in freight traffic in urban areas, which negatively impacts the sustainability and livability of our cities. The additional traffic generated by vehicles for deliveries leads to congestion and emissions, with $CO2$ accounting for 25% and PM and NOx accounting for 30-50%. Furthermore, heavy vehicles also reduce road safety (European Commission, 2020). On top of that, the COVID-19 pandemic has further accelerated the growth of online purchasing and logistic innovations(DHL, 2023). However, despite efforts to improve logistics sustainability, the challenges of the entire process are still subject to debate. Nevertheless, new technologies, processes and distribution strategies offer significant potential for enhancing the impact of last-mile deliveries in urban areas.

With these challenges in mind, the SENATOR project[1]aims to create a new urban logistic model for enhancing the sustainability of cities. For this purpose, the project will develop a smart network operator, as a control tower supported on an ICT Platform that will work as a support tool for decision-making, integration and planning of all logistics operations. In consequence, it will minimize the negative impacts that this distribution causes in the cities and will constitute an effective means of collaboration between agents (citizens, operators, carriers, and administrations).

The objective of this paper is to present one of the core parts of the mentioned ICT Platform. Concretely, the route delivery planning and simulation module whose aim is to support the matching of supply (vehicle, transport operators, etc.) with demand; to identify the best fleet mix (e.g. fuel, electric or zero-emission vehicles, cargo-bikes) to fulfil the customer demands while reducing pollution; and estimate the best delivery route according to real-time or historical traffic conditions (e.g. traffic congestion, etc.), to avoid the overlapping between different logistic/transport operators routes when possible to reduce traffic, and to overcome unexpected events that might arise, such as traffic disruptions or vehicle breakdowns thanks to the AI-based optimization algorithms. Furthermore, to show the capabilities of the software module, we validate it in a real scenario using shipment data from a postal operator company in the living lab that the SENATOR project is implementing in Zaragoza. The first scenario is based on the current operations of the postal operator, whereas the second one is based on the implementation of a Low Emission Zone in the city centre of Zaragoza.

The rest of the paper is structured as follows. Section 2 reviews other tools currently available that are similar to the one presented in this paper. Then, Section 3 is devoted to describing the AI-based software module for collaborative logistics. After that, the experimental setup and the results obtained by the system presented are detailed in Section 4. Finally, the main conclusions gathered from this paper a discussed in Section 5.

2   Related work

This section discusses various tools available for solving the Vehicle Routing Problem (VRP), that are similar to the one presented in this paper and provides a comparison among them.

- **JSprit[2]** is an open-source VRP engine written in Java and uses a generic Ruin & Recreate metaheuristic. It can solve different VRP variants, including Capacitated VRP, Multiple Depot VRP, VRP with Time Windows, VRP with Backhauls, VRP with Pickups and Deliveries, VRP with Heterogeneous Fleet, and Time-dependent VRP.
- **OR-Tools[3]** is an open-source software suite for optimization, tuned for tackling hard problems in vehicle routing, flows, integer and linear programming, and constraint programming. OR-Tools includes a specialized routing library to solve different types of node-routing problems, such as TSP, VRP, CVRP, VRPTW, VRP with Resource Constraints, and VRPPD.
- **VROOM[4]:** VROOM is open-source software written in C++ for solving vehicle routing problems. VROOM can solve several types of VRPs, including TSP, CVRP, VRPTW, MDHVRPTW, PDPTW, and a mix of these types.

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[1] https://www.senatorproject.eu/
[2] https://github.com/graphhopper/jsprit/tree/master/docs
[3] https://github.com/google/or-tools
[4] https://github.com/VROOM-Project/vroom

- **VRP Service from ArcGIS[5]** is a commercial service developed by ESRI to address different routing problems. It can be accessed in different ways such as JavaScript APIs and SDKs in different programming languages.
- **Circuit[6]** is a commercial tool available on web service, Android and iOS platforms, that allows the optimization of up to 1000 stops considering stop time windows, first and last stop, and priority levels. Its main use cases are Driver Tracking, Local Delivery, Route Planning, Proof of Delivery, and Courier Management.
- **LOCUS[7]** is a commercial tool that allows the planning and optimization of routes and vehicle assignation for orders considering problems such as Travelling Salesman, Vehicle Routing and Knapsacking. LOCUS implements exact, heuristic, and hybrid algorithms. Its main use cases are Last-Mile Delivery Routing, Field Service Dispatch Planning, Dynamic Route Planning and Optimization, Territory-Based Route Planning, and Reverse/Returns Logistics.
- **OptaPlanner[8]** is an open-source tool developed in Java that implements several optimization problems, including VRP, Capacitated VRP, and VRP with Time Windows. It also allows integration with Google Maps and OpenStreetMap.
- **HERE[9]** is a commercial tool that provides a route planning API to solve the VRP, implementing the Capacitated VRP, VRP with Time Windows, Multi-Depot VRP, Open Vehicle Routing, Heterogeneous or Mixed Fleet VRP, and Pickup and Delivery VRP. It allows the calculation of routes using real-time and historical traffic information and the re-planning of routes in real time if new orders appear.
- **GraphHopper[10]** is an open-source software tool developed in Java that uses JSprit as the route optimization engine. It provides an API to solve a variety of vehicle routing problems, including the Traveling Salesman optimization problem, and all the VRP variants implemented in JSprit. Its main advantages are the possibility of designing vehicle types and defining time windows and service times for drivers.

However, none of the tools discussed above offer at the same time the functionalities of dynamic route optimisation, multi-modal fleet optimisation, inter-modal and/or transfer route optimisation, multi-objective optimisation and consideration of driving constraints.

3   Artificial Intelligence based software module for collaborative last-mile logistics

The software module for collaborative last-mile logistics is based on the well-known Rich Vehicle Routing Problem (Lahyani, Khemakhem, & Semet, 2015) which is a class of optimization problems that represent some or all aspects of a real-world application of vehicle routing including optimization criteria, constraints, and preferences. These problems deal with more realistic optimization functions, uncertainty, and dynamism, along with a wide variety of real-life constraints related to time and distance factors, and the use of heterogeneous fleets. Specifically, this software module internally implements a more realistic and complex model of the Rich Vehicle Routing Problem than those currently available in the literature as it can simultaneously incorporate the following aspects:

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[5] https://desktop.arcgis.com/es/arcmap/latest/extensions/network-analyst/vehicle-routing-problem.htm
[6] https://getcircuit.com/
[7] https://locus.sh/
[8] https://www.optaplanner.org/
[9] https://developer.here.com/products/tour-planning
[10] https://github.com/graphhopper/graphhopper

- **Dynamism:** given that some elements of the delivery planning may change over time, the software module allows the re-adjustment of the planning (e.g. last-minute orders that may appear, a vehicle breaks down and it is necessary to assign orders to other routes)
- **Multi-modality:** the module allows last-mile delivery planning using different transport modes (e.g. walking, bikes, motorbikes, vans, etc.).
- **Inter-modality:** the software allows that one shipment can be transported by different transport modes along its route between the depot/pick-up location and the destination.
- **Multi-objective:** the module deals with the simultaneous optimization of different performance indicators (e.g. distance, time, emissions, etc.)
- **Driving restrictions:** the component allows the modelling of areas with access restrictions to specific vehicles (e.g. pedestrian zones, low emission zones, etc.)

In order to solve this highly complex Rich Vehicle Routing Optimization model, a specific sort of Artificial Intelligence techniques has been used. Concretely, we have used metaheuristics (Potvin & Gendreau Jean-Yves, 2019) because of their high efficiency and efficacy for this type of problem (Goel & Bansal, 2019). In a more specific way, the optimization algorithm designed is a hybrid metaheuristic(Gu, Cattaruzza, Ogier, & Semet, 2019) based on Large Neighbourhood Search (Pisinger & Ropke, 2019).

In the following subsections, we will describe the Artificial Intelligence-based resolution algorithm and the architecture of the software module.

3.1 Artificial Intelligence-based resolution algorithm

The Large Neighborhood Search (LNS) algorithm was employed in the resolution of the presented module, utilizing a metaheuristic in which the neighbourhood of a solution is implicitly defined through the use of destroying and repairing operators. The destroy operator eradicates a portion of the current solution, while the repair operator reconstructs the destroyed solution. The destroy method is usually implemented with some degree of randomness to modify different aspects of the current solution in order to explore the solution search space. LNS employs a larger neighbourhood exploration technique compared to other classical local search metaheuristic algorithms. The algorithm is a hybrid metaheuristic that combines various destruction and solution construction operators (ruin and recreate), as well as strategies to accept or reject solutions. Consequently, it is also integrated into numerous libraries related to the vehicle routing problem.

The optimization procedure pursued by the module is a stochastic approach based on the ruin and recreate (R&R) operator and can be summarized as follows:

1. Initiate the process with an initial feasible configuration.
2. Choose a ruin and recreate mode, i.e., a technique that will "destroy" the solution configuration, as well as the technique that will reconstruct the configuration.
3. Determine the number of nodes to be removed.
4. Ruin & Recreate. Generate a new solution using the heuristics selected in step 2.
5. Decide whether to accept the new solution based on a decision rule (Simulated Annealing, Threshold Accepting Criteria, etc.). If accepted, proceed to (2) using the new solution; otherwise, restart with (2) using the previous configuration.

3.2   Architecture and Components

The architecture of the proposed module is based on the distinct responsibilities and functionalities of its various components, each with its own distinct behaviours. It depicts the different components and their relationships. Certain components serve a specific purpose and have been designed to consolidate the optimization model. Within the optimization engine, several sub-modules are present:

- **Data Processing:** This module is responsible for processing all input data and translating it into the data structures utilized by the algorithm.
- **LLs Services:** This module is responsible for managing the different constraints and intricacies of the optimization model that must be associated with each use case.
- **Output Solution Processing:** This module is responsible for generating the output solution of the optimizer. Here, different key performance indicators (KPIs) that enable the evaluation of the solution are obtained.

The general module that encompasses the optimization engine is primarily responsible for 1) integration with the API-REST and all services; 2) the optimization engine that loads all data and creates the problem; 3) the integration with the JSprit framework; and 4) the processing the algorithm's solution to obtain the output API-REST.
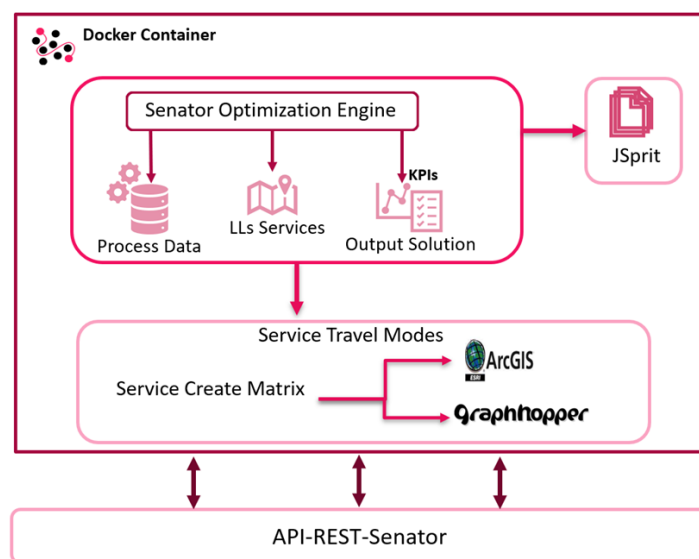
Figure 1 Architecture and components of the proposed module

Moreover, a JSprit module has been developed that bears the following responsibilities: 1) it contains the framework that implements the VRP problem, which has been modified to adapt to the dynamic delivery planning optimization model; 2) the primary modifications were made in the modelling of the constraints, operator strategies, and the computation of the fitness function.

A subsystem that is accountable for optimization has been developed based on specific tasks and requirements in the proposed model for each use case. Input data and the obtained solution will be stored in a database, which can be accessed through the API-REST. From the dynamic planning model for optimization, a last-mile route planning for different vehicles will be obtained, optimizing the use of available resources.

4 Experiments and Results

In order to validate the results of the system presented in this article, we have designed two scenarios: **Scenario 1)** which reflects the current operations of a real postal operator in the city of Zaragoza, and **Scenario 2)** which corresponds to the implementation of a Low Emission Zone in the centre of the city of Zaragoza. In addition, for each of the scenarios considered, three different fleet compositions have been simulated in terms of vehicle electrification ratio, with the aim of showing the capabilities of the tool for measuring the impact that different levels of fleet electrification would have on the two scenarios defined.

Below we provide more details about the experimental framework designed and the results obtained for the two scenarios designed and the alternative fleet compositions

4.1 Experimental framework

This section aims to define the two scenarios considered for the validation of the route optimisation software module, as well as the different fleet compositions considered in the experimentation.

4.1.1 Scenario 1: Baseline Scenario

Scenario 1 reflects the current situation of postal operations in the urban area of Zaragoza, where the following infrastructure is in place: **A) Nine Delivery Units (DUs)** distributed throughout the city and dedicated to the delivery of postal items and small parcels. Most of the routes are done by postmen/postwomen on foot; **B) Two Special Service Units (SSU)** that are located in the northern and southern areas of the city, respectively. They specialise in the delivery of larger parcels and therefore all routes are done with a motorised vehicle.

Figure 2 A) shows the distribution of the DUs and SSUs in the city of Zaragoza. As for the operation of the routes, the postal operator works in two shifts, one in the morning and one in the afternoon. The morning shift runs from 7:00 am to 3:00 pm, while the afternoon shift runs from 3:00 pm to 10:00 pm. Since postmen need time at the beginning of the shift to sort and prepare the items to be delivered and at the end of the shift to dispose of undelivered items, the time slots in which postmen run their delivery routes are from 8:00 am to 2:00 pm in the morning shift, and from 4:00 pm to 9:00 pm in the afternoon shift. As for the demand data, for the purpose of analysis, we have chosen the data on deliveries made by the postal operator on 13 and 14 September 2022, which we show in Table 1 as distributed by day and by shift.

4.1.2 Scenario 2: Deployment of a Low-Emission Zone

The second scenario we have defined for this analysis considers the deployment of a Low Emission Zone in the historic centre of the city of Zaragoza, whose delimitation is shown in Figure 2 B). The deployment of this Low Emission Zone implies that polluting vehicles cannot enter the area between 7 am and 11 pm. This would affect postal operations in the area since combustion vehicles would not be able to access the zone for delivery. Only postmen/postwomen on foot or electric vehicles would be able to deliver items to the designated area. The percentage of the orders that would be affected by the Low Emission Zone is shown in Table 1. As can be seen, the percentage of orders falling within the Low Emission Zone ranges between 9% and 15% depending on the shift and the day.

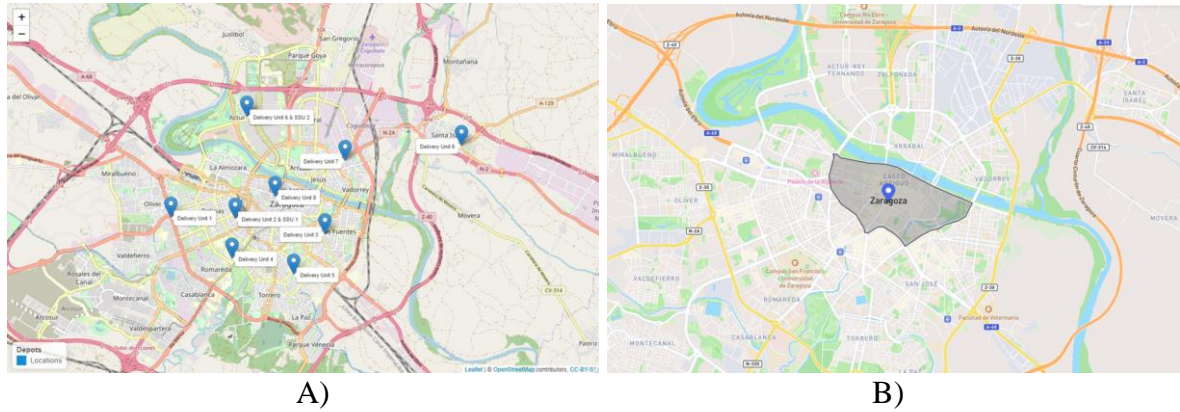A)   B)

Figure 2 – A) Image of the area of study for the Zaragoza Scenario 1 and location of the DUs and SSUs, and B) Delimitation of the area considered for the deployment of the Low Emission Zone in Zaragoza

Day	Working Shift	Number of Shipments	% of shipments in the Low Emission Zone
Sept 13, 22	Morning	11723	15%
Sept 13, 22	Afternoon	3794	9%
Sept 14, 22	Morning	11429	15%
Sept 14, 22	Afternoon	4296	13%

Table 1 Number of shipments per day and shift, and percentage of shipments in the Low-Emission Zone in each zone

4.1.3 Alternative fleet compositions

As mentioned before, have defined three different fleet compositions in terms of fleet electrification in order to understand what impact it may have in environmental and operational terms. The three fleet compositions considered are as follows:

- **Current fleet composition:** in this alternative, the fleet has the same composition as the current postal operator fleet shown in Table 2.
- **Electrification 50%:** in this case, a fleet electrification of around 50% is considered, following the same composition in terms of vehicle typology.
- **Electrification 100%:** in this last alternative fleet composition, 100% electrification is considered, i.e., all vehicles in the fleet are electric. Similar to the previous case, the typology of the vehicles is maintained with respect to the current composition.

Vehicle Type	Technology	Current composition	Electrification 50%	Electrification 100%
Large Van	Combustion	9	9	-
Large Van	Electric	-	-	9
Motorcycle	Electric	12	27	27
Small Van	Combustion	37	15	-
Small Van	Electric	2	24	39

Table 2 - Number of vehicles per type and technology for each of the fleet composition alternatives

4.2   Result analysis

In this section, we will analyse the results obtained by the software module presented in the two scenarios defined and for each of the fleet compositions. For this analysis of the results, we will consider the indicators shown in Table 3, which are provided by the route optimisation system presented in this article. In the two following subsections, we discuss the results obtained in each of the scenarios. More details about the calculation of the indicators can be found in (Vincenzo et al., 2022).

Impact area	Criteria	Indicator	Data/unit
Environment & Society	Air quality	CO concentration	g/day
		SOx concentration	g/day
		NOx concentration	g/day
		NH3 concentration	g/day
		PM10 concentration	g/day
	GHG emissions	CO_2	g/day
		CH4	g/day
		N2O	g/day
	Social costs	Social costs of air quality and GHG emissions	€/day
Transport & mobility	Accessibility	Number of shipments	n./day
		Number of routes	n./day
		Total km covered (including walking)	km/day
		Total km covered by green modes (including walking)	km/day
		Total veh-km covered by freight vehicles	Veh-km/day
		Total veh-km covered by green freight vehicles	Veh-km/day
	UFT vehicles	Vehicle utilisation factor	%/day
	Operative costs	Fixed costs	€/day
		Running costs	€/day
		Capital costs	€/day

Table 3 Indicators considered for the analysis of results

4.2.1 Results for Scenario 1

Table 4 shows the results for scenario 1 with the different fleet compositions. As can be seen, with the current fleet having a high percentage of conventional vehicles, the environmental impact is high, reaching a social cost of more than €17,75 per day. However, by increasing the electrification of the fleet, emissions are reduced by around 85%, as is the social cost. This more than 50% increase is due to the fact that the postal operator fleet is oversized to cope with peak demand. Therefore, with 50% of the current fleet electrified, emissions would be reduced by 85% in periods of intermediate demand. With 100% electrification of the fleet, as expected, the environmental impact is reduced by 100%.

Furthermore, as we can see and as expected, the impact in terms of operations is nil as in all cases the same service levels are maintained. However, in terms of operational costs, the electrification of the fleet implies a slight increase in fixed costs and mainly in capital costs (60%), due to the higher price of electric vehicles. On the positive side, however, running costs would be reduced by 40%.

4.2.2 Results for Scenario 2

The results of scenario 2 for the implementation of a Low Emission Zone are shown in the table below. If we look at the environmental impact of the different levels of electrification, we see that the results are very similar to those of the previous scenario, as is to be expected. Where we do see some differences is in the number of shipments delivered, which increases by around 1% with higher electrification of the fleet, which is the same as the decrease in the number of shipments delivered when compared to scenario 0 for the current postal fleet. This 1% increase is due to the fact that with increased electrification of the fleet, more vehicles can access the Low Emission Zone and therefore deliver more parcels.

Indicator	Scenario 1 Fleet Compositions			Scenario 2 Fleet Compositions		
	Current Comp.	50% Electric Vehicles	100% Electric Vehicles	Current Comp.	50% Electric Vehicles	100% Electric Vehicles
CO concentration	152,58	11,01	0,00	144,58	11,01	0,00
SOx concentration	1,00	0,14	0,00	0,97	0,14	0,00
NOx concentration	589,18	108,37	0,00	566,32	108,36	0,00
NH3 concentration	2,90	0,40	0,00	2,82	0,40	0,00
PM10 concentration	27,83	4,90	0,00	26,52	4,90	0,00
CO2	197.936,30	27.555,43	0,00	190.998,58	27.553,29	0,00
CH4	14,68	1,21	0,00	13,80	1,21	0,00
N2O	11,64	1,97	0,00	11,34	1,97	0,00
Social costs of air quality and GHG emissions	17,75	2,48	0,00	17,13	2,48	0,00
Number of shipments	8.873,60	1.240,12	0,00	14.930,00	15.058,50	15.107,50
Number of routes	15.106,00	15.083,50	15.107,50	208,00	206,00	207,00
Total km covered (including walking)	208,00	206,00	207,00	2.695,79	2.703,98	2.722,50
Total km covered by green modes (including walking)	2.722,30	2.702,36	2.722,50	1.418,84	2.519,88	2.722,50
Total veh-km covered by freight vehicles	1.390,51	2.518,24	2.722,50	1.657,42	1.665,62	1.684,14
Total veh-km covered by green freight vehicles	1.683,94	1.664,00	1.684,14	380,47	1.481,52	1.684,14
Vehicle utilisation factor	0,33	0,33	0,33	0,32	0,33	0,33
Fixed costs	24.612,49	24.683,48	25.008,18	24.328,19	24.659,85	25.008,18
Running costs	187,99	112,47	106,57	184,26	112,59	106,57
Capital costs	1.154.800	1.507.800	1.842.800	1.198.800	1.507.800	1.842.800

Table 4 – Results for Scenario 1 and Scenario 2

5   Conclusions

In this paper, we have presented a route delivery planning and simulation module that forms a core part of the ICT Platform of the H2020 SENATOR project. The module utilized AI-based optimization algorithms to support the matching of supply and demand, identify the best fleet mix, and estimate the best delivery route based on real-time and historical conditions. It also allows last-mile delivery planning using different transport modes, inter-modality, and driving restrictions, and simultaneously optimizes different performance indicators. We have also provided a detailed description of the AI-based optimization method and the architecture and components of the software module. Furthermore, the software module has been validated in two scenarios using real shipment data from a postal operator company in the living lab that the SENATOR project is implementing in Zaragoza.

The main conclusions from the two scenarios analysed and simulated with the presented tool are the following. In scenario 1, it is found that increasing the electrification of the fleet results in a significant reduction in emissions and social costs, with 100% electrification reducing the environmental impact by 100%. However, there is a slight increase in fixed and capital costs due to the higher price of electric vehicles. In Scenario 2, the results show that the environmental impact reduction of fleet electrification is similar to Scenario 1. However, there is an increase in the number of shipments delivered with higher electrification of the fleet due to higher access to the Low Emission Zone.

Overall, the presented tool has shown that increasing the electrification of the fleet is an effective way to reduce the environmental impact of postal operations, with the added benefit of increased access to Low Emission Zones. The drawbacks found by the tool are that there may be some additional costs associated with electrification.

In short, these results have validated that the presented tool is novel and that it allows the optimisation and simulation of last-mile logistics considering different elements of high relevance nowadays such as fleet electrification or the implementation of low-emission zones. More details about the results of the algorithm in other scenarios and using real data from the city of Dublin can be found in (Vincenzo et al., 2022)

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Enabling the PI to solve multi-layered problems of the Last Mile Logistics

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Abstract: The increase in last mile delivery poses numerous challenges for cities worldwide. Concepts such as the Physical Internet (PI) should support them on their way to more sustainable last mile logistics. Within the EU project DECARBOMILE, different approaches arise from a common overarching framework to decarbonise the last mile logistics and will be tested in four different cities. The measures to be implemented must be adapted to the respective local conditions according to their specific setups. After identifying, analysing and clustering the challenges of the different cities, the methodology involves to identify numerous gaps between the current and the desired situation. In order to close these gaps on the way to decarbonising the last mile logistics, the project proposes a digital infrastructure concept with the two main components of a basic decision-support service with simulation capacities and a public-private digital infrastructure based on a decentralised Data Space architecture that will be developed within DECARBOMILE. The use of other IT tools depends on the specific challenges of the cities. With its architecture, the proposed digital infrastructure core allows each city to operate as a local node of a decentralised, federated, pan-EU network compatible with the PI paradigm.

Keywords: cities challenges, last mile logistics, PI gap analysis, decarbonisation, sustainability, EU Single Data Market, Common Data Spaces, extensive collaboration, coopetition, capillarity, cycle logistics

Conference Topic(s): business models & use cases; networks; interconnected freight transport; distributed intelligence last mile & city logistics; modularization; omnichannel & e-commerce logistics; PI implementation; PI modelling and simulation; technologies for interconnected logistics (Artificial Intelligence, IoT, machine learning, digital twins, collaborative decision making); vehicles and transshipment technologies.

Physical Internet Roadmap (Link): *Select the most relevant area(s) for your paper: X PI Nodes, X PI Networks, X System of Logistics Networks, X Access and Adoption, X Governance.*

1 Introduction

The increasing volume of last mile delivery is challenging cities worldwide. By 2030, in the ten most populated cities, an increase by 36% in the number of delivery vehicles is expected (Johnson and Chaniotakis, 2021). Drivers of this development are, among others the rising e-commerce consumption, accelerated by the covid-19 pandemic, the trend of urbanisation or a change in customer expectations regarding delivery time or service quality (Özbekler and Akgül, 2020; Ferrari *et al.*, 2022). While the logistics in the cities keeps them attractive and livable and provides them with the goods needed (Maes et al. 2015; Montwiłł, 2019), the

increasing delivery traffic is leading to undesired effects like congestion, air pollution, noise pollution, greenhouse gas emissions, accidents or habitat loss (Ranieri et al., 2018; Brusselaers and Mommens, 2022; Demir et al. 2022). At the same time, the last mile logistics comprises between 28 % to 55 % of the total delivery cost (Ranieri *et al.*, 2018; Atos, 2021). As awareness for external costs grows, there are various approaches to overcome the negative effects, such as the concepts of City Logistics (CL) or the Physical Internet (PI) or the implementation of new logistics features to establish a more sustainable last mile logistics (Maes et al. 2015; Kubek and Więcek, 2019).

The research paper contains a brief literature review of relevant work on PI and city logistics/last mile logistics and introduces the project DECARBOMILE and its four living labs (pilot cities in the project) as well as the planned implementation of innovative solutions based on five fundamental pillars, focusing on the project's contribution to the implementation of PI. The baseline to ensure the development of suitable PI solutions in the further course of the project is the identification of the challenges of last mile logistics in the four living labs. After outlining these challenges, a gap analysis is conducted to identify the possible approaches to solve the challenges through the use of the PI. Based on this, the technical concept proposal of DECARBOMILE to deploy sustainable last mile logistics is presented, covering the gaps identified to cope with the relevant challenges. After discussing the holistic methodological framework for developing this concept, a conclusion is drawn on how it aligns with and complements the PI, and next steps are described, which include technical development and testing under real conditions.

2   DECARBOMILE

Within the European Union (EU) project "DECARBOMILE" (DECARBOnise the last MILE logistics), different approaches to decarbonise the last mile logistics will be tested in four living labs (Istanbul (Türkiye), Nantes (France), Hamburg (Germany) and Logroño (Spain)) from 2022 to 2026. The four cities differ in terms of geographical coverage, urban fabric, status and population and therefore also in their challenges regarding last mile logistics. During the project, different approaches will be taken in the four living labs that involve the five different areas of PI (Governance, Access and Adoption, System of Logistics Networks, Logistics Networks and Logistics Nodes) and their respective generations of the PI roadmap (ALICE, 2020) contributing to implement the PI by developing tailored solutions and demonstrate their full potential to decarbonise the last mile logistics in the living labs.
Within the project, five key pillars to deploy sustainable last mile logistics systems in cities were postulated: collaboration, business models, urban integration, regulation and digital infrastructure. Therefore, based on these pillars, a methodological framework is under development and will be tested to address the challenges identified in each living lab, defining and prioritising use cases to increase the sustainability of last mile logistics and providing technological tools that will be tested and validated against the implemented use cases. These include different kinds of software and hardware, such as simulation-supported decision systems, digital twins, Internet of Things (IoT) enabled vehicles, containers and collaborative consolidation centres.

All this forms the basis for DECARBOMILE to enable the PI to fill the gaps to cope with the challenges of sustainable last mile logistics.

3   PI and City Logistics in the Literature

Since 2015, the idea of the PI started to rise with the aim of making logistics more efficient, sustainable, resistant, adaptable and flexible (Montreuil et al. 2012; Edouard *et al.*, 2021). Among the key concepts for the PI are cooperation and consolidation as well as the "physical, digital, business and legal connectivity" (Crainic and Montreuil, 2016 after Montreuil, Meller and Ballot, 2012). According to the PI-roadmap (ALICE, 2020), in the years 2020-2025, rules and governance for asset-sharing platform (area Governance), sectorial, regional, seamless vertical PI demonstration (area Access and Adoption), network interconnectivity (area System of Logistics Networks), operational synchromodality / Physical Intranets (area Logistics Networks) and open and seamless nodes service offerings (area Logistics Nodes) are the targeted generations of PI-development.

Improving the sustainability of logistics in cities is also the goal of the city logistics concept, which aims to reduce the negative impacts of freight movements (Taniguchi et al. 2003, 2014). Within this approach, e.g. the number of vehicles is to be controlled and reduced while at the same time the "efficiency of freight movements and their environmental footprint" is to be improved (Crainic and Montreuil, 2016 after Benjelloun et al., 2010, Dablanc, 2007). For this reason, the urban freight stakeholders, activities, processes and material flows should be optimised as "an element of an integrated logistics system" [and] "with support of advanced information" (Kubek and Więcek, 2019). The five different groups of stakeholders that are involved in city logistics are according to Olsson et al. (2019): public authorities, residents, shippers, carriers and receivers.

These concepts aim to reduce congestion, emissions, noise and pollution and improve the quality of life of residents as well as the quality, reliability and effectiveness of last mile logistics (Kubek and Więcek, 2019) while adapting the relevant business models across its value chain.

The two concepts can be seen as complementary and their combination has been studied by different authors (Crainic and Montreuil, 2016; Kubek and Więcek, 2019). Changing the logistics system is difficult, as it "requires the involvement of various stakeholders to act together for all types of operations" (Demir et al. 2022, p. 559).

In the past, several approaches have been taken to implement sustainable solutions, facing different barriers and challenges. For example trust issues (Serrano-Hernandez *et al.*, 2016) or uncertainties around financial stability insecurity were identified as challenges regarding collaboration (Paddeu *et al.*, 2018), while new business models were often not economically viable (Dreischerf and Buijs, 2022) and it was not clear, how savings and costs would be shared (Hezarkhani et al. 2019). Challenges such as the acceptance of local politics and residents as well as institutional barriers also prevented the successful implementation of new solutions (May et al. 2006).

4   Methodology

In order to identify the challenges in the four living labs, two-day technical visits to the four cities were conducted in January 2023 to update the initial baseline information provided by local stakeholders. These visits included site visits to relevant logistics facilities and discussions mainly with representatives of the local project partners and representatives of public authorities. Following the visits, four local stakeholder workshops were held from January 2023 to March 2023. In each workshop, local members of the project partners and external local

stakeholders identified and discussed the needs and challenges of the last mile logistics in their cities to define the use cases to be pursued during the project.

Based on the results of these tasks a gap analysis was conducted. For this, the challenges of the baselines were compared with technical capabilities of the consortium to identify current gaps of the logistics sector in general, including the PI, and to formulate a base concept to fill the gaps. The developed holistic method should help to develop effective measures and align it with other products to decarbonise last mile logistics and enrich the PI development.

5   Challenges of the Last Mile Logistics

The wide range of challenges identified during the dedicated workshops in the living labs of DECARBOMILE form the base for the development of the PI solutions and will be further analysed and clustered according to their:

- Location – where they appear
- Sustainability – what sustainability aspects do they impact
- Agents – what stakeholder is affected by the challenge and is compelled to act
- Action – what measures can be taken to address them

The first category (Figure 1) allows further exploration of how to relate the challenges to specific conditions in different locations.
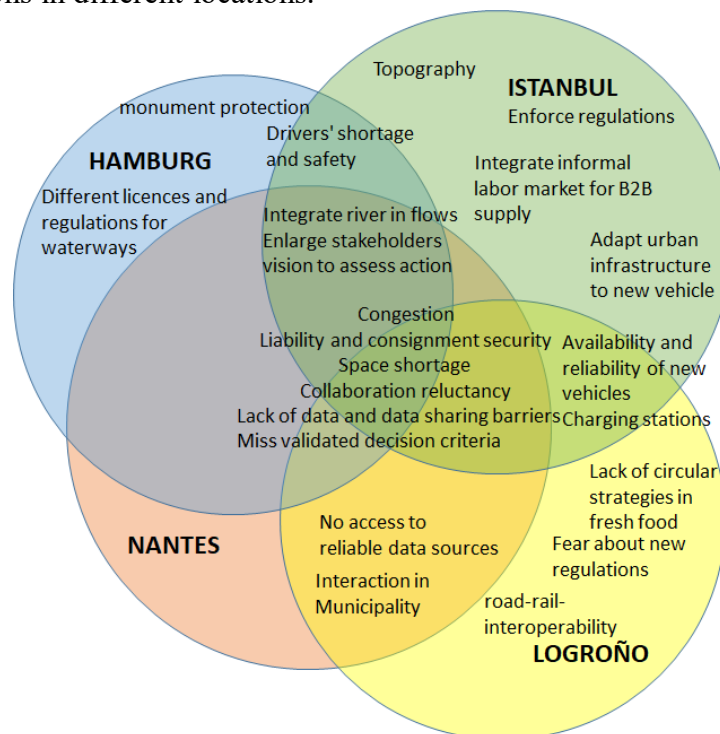
Figure 1: Selection of challenges of the living labs for last mile logistics

The challenges were first analysed for each living lab and were checked for potential overlaps with other cities. This overlapping of challenges is shown in the intersections of the circles in Figure 1. For example, in all living labs, the congestion, shortage of space, a lack of data and data sharing barriers, liability and consignment security and the reluctance of the stakeholders to collaborate could be identified as a challenge. In Istanbul and Logroño, the availability and reliability of new vehicles is one challenge while only in Istanbul, the integration of the informal Business-to-Business (B2B) supply labour market and other crowd-logistic concepts, the enforcement of regulations, the adaptation of urban infrastructure to new vehicles and the topography was mentioned as a challenge. For Hamburg, the different licenses and regulations

for the waterways and the monument protection might be challenging when implementing the use case. Both in Hamburg and Istanbul, the drivers' shortage and safety has been named as a potential challenge. As Hamburg, Istanbul and Nantes think about using the waterways for the last mile logistics, they all mentioned the integration of the river into transport flows as a challenge. In Nantes and Logroño, the missing access to reliable data sources and the interaction in the municipality might be challenging. In Logroño, the road-rail interoperability, the fear about new regulations and the lack of circular strategies in fresh food trade were mentioned.

It has become apparent that the challenges are very broad, which is why further categorisations were carried out. Some of the challenges refer to the last mile logistics sustainability, including the ecological (e.g. pollution, non-circular supply chains), social (e.g. combination of manufacturing/trade and tourism, occupational safety, fair wage, labour conditions and road safety and livability) and economic (business model sustainability, vehicle production and cost linked to the structural changes of the national energy matrix) aspects. This classification helps to link the challenges to specific impacts and will later be related to relevant Key Performance Indicators (KPIs), which make it possible to track the planned actions that address the challenges and monitor their effectiveness. Other challenges mainly concern physical elements of the transport system such as movables (e.g. availability and reliability of new vehicles), facilities (e.g. integration of consolidation centres), infrastructure (e.g. narrow streets), goods (e.g. goods safety) and activities (e.g. social habits of receiving home deliveries) (Flämig et al. 2002) as well as data and digital tools.

The last two clusters focus on the design of the actions to address the challenges.
As the workshops brought together stakeholders from the municipalities and economic actors, the challenges also reflected the different points of view of city and entrepreneurial dynamics. From the viewpoint of the city, for example how to prioritise measures and regulations to adapt urban infrastructure to new vehicles and reduce congestion and pollution are major challenges, while from the entrepreneurial side, how to cope with new access regulations, special permits or different licenses for the transport of goods or drivers' shortage are challenging. Both, cities and enterprises agree on the need to overcome the reluctance of sharing data or the shortage of parking spaces.

The last clustering approach (Figure 2) points out the levers of action to address the challenges along the five pillars of DECARBOMILE.
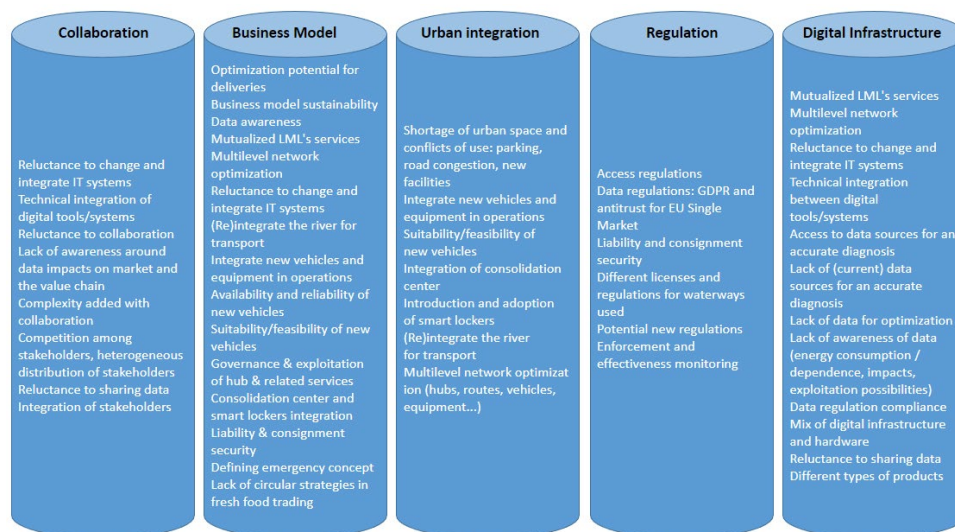

Figure 2: Identified challenges according to the five pillars of DECARBOMILE

For the pillar of collaboration (either horizontal or vertical), the challenges of reluctance to change and integrate IT systems, the rising complexity with collaboration or to collaborate at all appear along with the general lack of awareness around data, including insights of both how to improve operations, and the impact of data on the trends that are changing the market and the value chain. For the business models, the lack of mutualised capillary delivery services, the integration of the new movables (barge, cargo bikes) and facilities (micro hubs, consolidation centres) and the business model sustainability is challenging. In the pillar of urban integration, especially the shortage of space for new facilities and of parking space but also conflicts of use of space are the main restriction for optimising city networks on the way to make last mile logistics more sustainable. Regarding the regulation pillar the focus is both on defining regulations (access regulations in general and possibly new regulations, including antitrust data rules for business services, as well as the different operating licenses) and on how to enforce and adjust them after verifying their effectiveness. The challenges of the digital infrastructure pillar focus on seamless access and interoperability, for the integration of IT systems and between different IT tools/systems, on the combination of digital infrastructure and hardware, and on the lack of data or the missing access to data sources.

This clustering approach is the basis for the gap analysis and lays the ground for the development of the concept proposal of DECARBOMILE to overcome the challenges of last mile logistics by developing actions out the five pillars.

6   Findings from the Gap Analysis

The cluster approach with the five pillars shows the fields of action to address the identified challenges and allows to relate them with the impact areas, considering the stakeholders involved or to be involved in each location, leading to the identification of the gaps.

A first main gap distilled from the challenges is the general lack of awareness around data. Coupled with other challenges such as the lack of proper tools to get, access and treat data, this appears to hamper the perception of stakeholders about collaboration as a key resource for sustainable last mile logistics, as well as for the development of new business models with value-added services.

Concerns and issues have arisen about data usage regarding customer privacy and unfair competition. They come with the installation of the consumer-centric focus on value chains driven by digitalisation, which has turned logistics and its business logic around as the sales profits are largely dependent on urban logistics (Arora et al. 2017; World Economic Forum, 2020; Mangano et al., 2021; Dolan, 2023). The data on customers preferences is key to profits (Arora et al., 2021) and processes are increasingly dependent on a dedicated digital infrastructure (World Economic Forum, 2020) and digital services.

All this has an impact on the income and cost structures of all the stakeholders in these value chains. In this playground, two main types of commercial players coexist, competing for customers and resources. While conventional players struggle to adapt to the new world of digital interaction with customers, new players are striving to make their business models viable by making the most out of their data advantage.

In such a context, the European Commission (EC) has been working on updating regulations (*Regulation (EU) 2022/868*, 2022) and the playground for coping with data issues and concerns, with the vision of enabling a digital version of the EU Single Market through a digital infrastructure that enables access to services and makes businesses in the digital realm complying with new regulations.

Also digitalisation triggers a subsequent rise of individual last mile logistics solutions with low efficiency and severe environmental and economic impacts, which has put collaboration at the

centre of the sectoral and political discussions including the PI roadmap (ALICE 2020). Despite some successful pilot tests (Prance-Miles, 2019; capillarIT, 2020), barriers to collaboration between businesses (including fears to lose competitiveness and market share), and a general lack of capacity to analyse and make visible the trade-offs of collaboration in already complex scenarios prevents independent stakeholders from spreading collaborative practices, which turns out to be a gap to be covered.

Meanwhile the new players that are driving last mile logistics disruption have a full stack approach to commerce and they are building their own new logistics networks to master the mutualisation of resources across all stages of the consumption value chain with the unresolved matter to make their business models viable (capillarIT, 2022). Hence, the main conceptual gap that the conventional siloed management of the logistics value chain confronts is including the customer-centric focus in its scope. This reflects a subsequent gap: the conventional logistics management focuses on the offer side rather than the demand side and the factors that drive it. This neglects the contribution that profiling customer behaviour across channels makes to optimising last mile logistics.

The latter two gaps prevent the development of tools/business models/logistics concepts to put into place the new logistics that fulfills such customers' needs, including for instance a criterion for densification of activities to optimise parcels per time-kilometre based on dedicated geographic analysis of demand and offer that increases resources' productivity and profits and reduces emissions in a target cluster. From both also derive a set of subsequent gaps including those above mentioned:

- Data-economy awareness with the direct and indirect exploitation opportunities
- Rules and agreements for data exchange
- Data tools, for capturing missed data or having access to existing data
- Strategies for the mutual use of logistics resources, including collaboration with stakeholders and competitors (coopetition), with their relevant business, operational and governance rules
- A common language for seamless interoperability according to the required level of collaboration
- Tools for optimising the design of logistics networks considering all different sale channels
- Tools and criteria for optimising the design of municipal measures

7 PI-enriched concept of DECARBOMILE

All identified gaps can be mapped to the five pillars proposed by DECARBOMILE to provide a model to identify which gaps need to be addressed when developing solutions for sustainable last mile logistics and organise the appropriate resources and actions for their deployment. Two target features emerge from all the analysis that should guide such process on the playground described above:

1. **Business advantage**, that depends on operational and data interoperability to scale and enact collaboration, together with data exploitation strategies engaging with customers beyond conventional business to support decision-making processes,
2. **Compliance verification**, including digital/data, and sustainable logistics.

Based on that the concept proposal focuses on three baseline functions:

- Effective application of **collaborative intelligence and governance in the decision-making process** to design services and the supporting urban networks for sustainable

last mile logistics, and optimise its execution by **orchestrating the interests and resources** of the stakeholders in the living labs.

- **Raise awareness** of the value of data, the potential to exploit it and how to do it.
- Enable a **controlled operational environment** that ensures that the services and tools comply with all relevant regulations, in particular to ensure sustainable urban mobility and the new rules enforced by the EC to preserve free competition in the EU Single Market and its digital extension.

Accordingly, the proposal is to enable the core of the digital infrastructure that allows any solution required by the living labs to be activated. In each living lab the digital infrastructure consists of two main components: a basic decision-support service with simulation capacities to cope with the first two functions; and a public-private digital infrastructure based on the decentralised Data Spaces architecture (Ahle and Hierro, 2022) promoted by the EU[1], which means that data is stored at the source and only transferred when agreed, ensuring data sovereignty and broader participation of the benefits of its exploitation for all. Such an infrastructure results from the combination of the infrastructures of the different stakeholders involved, equipped with a set of common basic modules (e.g. Key Rock, Trust and Authentication providers, Marketplace...) that ensure compliance with relevant regulations and the resulting customised data policies and data transfer agreements between data producers, users and traders. These modules include the definition of seven key elements, including **Data models** (related to the input and output data of each service), **a common Application Programming Interface (API)** (for exchanging data between data providers and consumers), a **common identity and authorization manager** (to ensure a unique authentication system for users and to assign permissions to the different services offered through the **Data Space policies**), **City public standards to access the Data Space** (including regulations and certified labels to guarantee **sustainable logistics performance**), **Licenses for data exploitation** (to allow data producers to decide how their data can be managed and used), **Marketplaces with field-specific service filters** (to increase the visibility of the service offer) and **Data Wallets (**for enabling data producers to source their data from different services and get insights about their valuation opportunities and strategies).
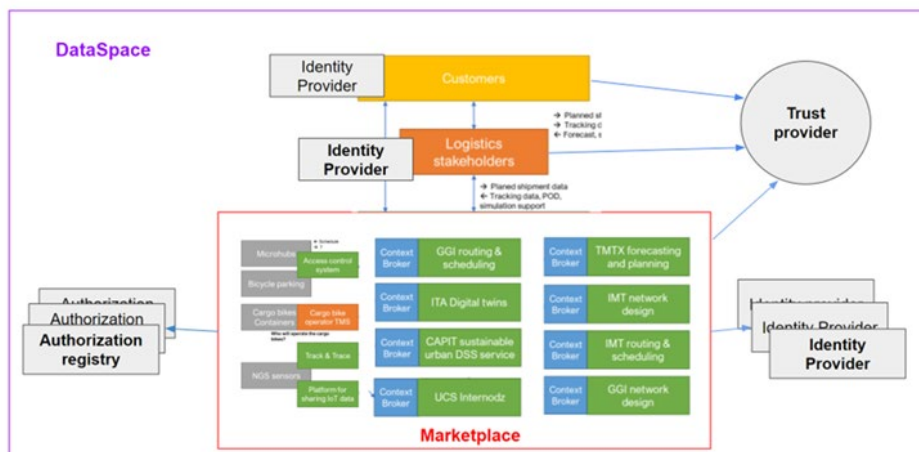

Figure 3: Digital Infrastructure of DECARBOMILE as baseline contribution to PI (DECARBOMILE, 2023)

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[1] "A data space is a decentralised infrastructure for trustworthy data sharing and exchange in data ecosystems, based on commonly agreed principles" (International Data Spaces Association, 2021). It enables "a type of data relationship between trusted partners who adhere to the same high standards and guidelines in relation to data storage and sharing" (Gaia-X European Association for Data and Cloud AISBL, 2023).

This sets up a public digital environment with a local digital market that allows 'authenticated' users to access 'authenticated' last mile logistics services, and operate them according to a scheme of licenses, while securing the exchange of information in a distributed logic. The services can combine different software and hardware tools, such as the basic urban logistics simulator supported by an urban digital twin included by default as core services for meeting common needs of the living labs (Figure 3). The use of other more advanced tools will depend on the specific challenges to address, such as Artificial Intelligence (AI) for demand forecast to feed richer simulations along with network design algorithms and trip planning and dynamic routing. Other possible tools that might be used are micro containers for loading and operation optimisation, load pooling, end-to-end tracking of goods and orders, real time transport monitoring and control, urban micro hubs with digital access control, or business intelligence and data valorisation services.

8 Discussion

With its architecture, the proposed digital infrastructure core allows each city to operate as a local node of a decentralised, federated, pan-EU network (Figure 4), which is compatible with the PI paradigm. The nodes can be interconnected to each other, allowing mutual visibility and interoperability between them to compare and share developments, services and data for the construction and validation of the target model of DECARBOMILE. The network is transferable to other cities and works as a local chapter of an EU Digital Single Market interconnected to other chapters. Hence the proposed concept contributes to the deployment of the PI roadmap and of sustainable last mile logistics networks that comply with data regulations enabling it to overcome the relevant gaps identified.
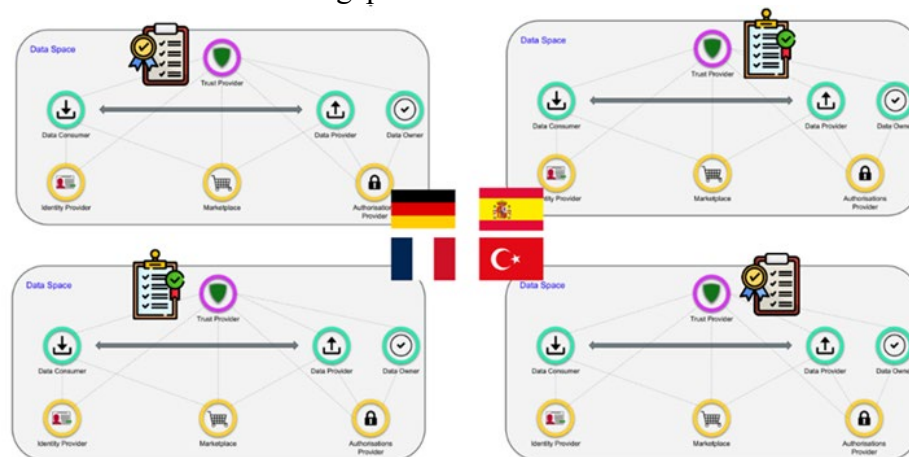

Figure 4: Conceptual architecture of the living labs as interconnected chapters of the EU Single Digital Market (Own Figure based on EU i4Trust project architecture)

The main challenge to effectively enable the PI to design, deploy and enforce sustainable last mile logistics networks is to combine its operational approach with an enriched functional approach to sustainability, taking into account practical issues for adopting its innovations linked to the identified gaps, for example in terms of providing a seamless, unified authentication experience for logging in to any Logistics Node offering services within the PI System of Logistics Networks. This also helps in designing customisable, dynamic tariffs supported by AI tools that can make them sensitive to the level of collaboration achieved in the PI asset-sharing platform, and its subsequent impacts on costs and benefits. Assuming that a clear split of costs and/or benefits between shippers or logistics operators whose accounting systems are based on different systems of tariffs, sets a fundamental base for defining rules for resource sharing and access, this kind of tariffing is a key enabler to define the most adequate

PI governance structure in charge of such rules. Furthermore, it also is key to verify their compliance through the relevant authentication tools, and of monitoring their effectiveness to guide further developments of the PI-platform.

Articulating such functional approach involves two aspects: The first is to review the logic by which environmental, social and economic aspects are incorporated into sustainability assessments in order to overcome the conventional mindset that ends up confronting them and looking for trade-offs instead of creating the win-win or exponential-win constellations that the PI paradigm announces. The second is to update the optimisation criteria and algorithms, as well as the logic and functionalities of the decision-support systems to provide proper assessments of the benefits of collaboration, which are essential to foster data sharing and systems' integrations on top of the trust gears provided by the Data Spaces architecture.

Based on it, a new framework for the deployment of sustainable last mile logistics systems in cities is under discussion in DECARBOMILE. It aims to be more holistic and to include a more refined classification of challenges by considering the gaps, the levers for action and the correspondent stakeholders and PI elements to address them. It also includes the relevant impact areas to track the effectiveness of the actions undertaken. These actions build on the proposed core concept that will be developed and tested together with the other software and hardware developments, through the use cases in the living labs. This is the case for instance in Istanbul, where stakeholders are considering testing simulations fed with intelligent demand forecasting based on a cross channel characterisation of end-customers. In Logroño, a main question is how to address pricing services and splitting costs between users of a minimum viable urban system of micro hubs, multimodal fleet of electrically assisted cargo bikes and light commercial vehicles, tailored micro containers, and sensors, that allow the stakeholders to optimise their current operations in critical access areas of the city by mutualising needs and resources. This approach should help to identify and validate through further quick testing target areas for further development of online channels of retailers involved, both individually or/and combining flows with logistics services providers, optimising the relevant logistics resources (facilities and fleets) to align profits, reduce emissions and improve conditions for workers and the overall urban experience.

9 Conclusion

The research paper introduces the different challenges arising from last mile logistics in four different cities in Europe. While some challenges such as congestion, lack of data and data sharing barriers are relevant for all cities, others such as the road-rail-interoperability are only relevant for one city. The challenges could be clustered according to the three dimensions of sustainability (ecological, social and economic) and according to the stakeholders' point of view (city or enterprise). Allocating the challenges to the pillars collaboration, business model, urban integration, regulation and digital infrastructure sets the ground for a gap analysis. The general lack of awareness of data (its value and how to exploit it) and the inability to analyse and visualise the benefits of collaboration in already complex scenarios creates barriers to integrate collaboration into business models and triggers the subsequent discussion about change strategies, starting with management of sharing resources and set up of incentives based on savings issued from collaboration and benefits from the new services and/or data sharing and exploitation. The main gaps identified were the conventional siloed management of the logistics value chain and the focus of conventional logistics management on the offer side instead of the demand side, which are to be closed by the concept developed. This concept consists of two main components: a basic decision-support service with simulation capacities and a Data Space distributed framework that involves the seven key elements Data models,

common API, common identity and authorization manager, city public standards to access the Data Space, licenses for data exploitation, marketplaces with field-specific service filters and data wallets. This concept will enable stakeholders in each city to use the potential of collaboration. Each city also acts as a local node that can be interconnected with other nodes (cities) to enable mutual visibility and interoperability between them, to compare with each other and to share developments, services and data for the construction and validation of the Network, starting with its expansion to the four satellite cities of the DECARBOMILE consortium. In this way, the digital infrastructure becomes a key instrument to enable the PI to materialise its desired developments, starting with overcoming the barriers to collaboration through new business incentives that promote coopetition in the logistics value chain from the urban arena.

10 Further need for research

The proposed concept builds the base for further developments within the project. The PI approach with a holistic methodological framework will be updated and tested under real-life conditions during the project lifetime to solve the problems of the last mile logistics in a systematic process that builds in ongoing work in other projects (capillarIT, 2022). It also lays the foundation for the development of tools/business models/logistics concepts that can be used to introduce new logistics that meet customers' needs and create sustainability. In the next steps, the holistic framework discussed here will be completed, the use cases of the different living labs will be finalised and the sustainability measures will be further developed. The future aim is to formalise a criterion to densify activities to optimise parcels per time-kilometre based on dedicated geographical analysis of demand and offer that aligns the axes of sustainability by increasing resource use, profit and social output while reducing emissions in a target cluster (ibidem). For each use case, specific KPIs will be developed and tracked. The core tool of simulation will be enabled with this intelligence and the relevant interfaces to activate it and to support making more holistic and accurate decisions.

By the end of the project, a new PI logistics model for decarbonising last mile logistics would have been developed and tested, based on the five pillars. Normally, after analysing the status quo at each location, the measures and actions are defined according to the identified categories of challenges and priority impacts. The new model aims to increase the replicability of the actions by considering how the end customers are influencing the dynamics of urban logistics, as they are already included in the definition of the use cases of the project and the requirements for the IT services.

Note

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Can adding the 5th Transport Mode - Capsule Pipelines enables Physical Internet, 15-minute City, Circular Economy, Automatic Retailing, and reduce Climate Impact?

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Abstract*:*

Vehicles on streets dominates last-mile transport. With increased e-commerce congestion, emissions, and cost increase. Delivery boxes and sidewalk robots reduce cost, but congestion prevails. Air drones reduce congestion but cannot take the expected volumes and are weather sensitive. Water and rail are not omnipresent. Underground pipes are used for transport of water, sewage, and gas, and was 1853-2002 used for transport of mail in capsules in 44 large cities. Pipes are now used in hospitals for capsules with test samples, blood, and medicine.

This project explores reinstallation of capsule pipelines for the general public. It reduces traffic and operating cost. It can accommodate very large volumes but requires large investments in infrastructure. A 5 kg capsule can, in many cases, automatically do the same job as a motor vehicle with 500 times larger mass and a driver. In one scenario, 30% less traffic and CO2, the freed space paid for installation of the whole system 1.6 times, and cost reductions resulted in a payback period of less than one year. The pipes can also be used for storing which reduces need for space in buildings and enables automatic retailing.

Finally, recommendation for further R&D are proposed.

Keywords:

Last/first/mile/yard transport; Capsule as package/unit-load/vehicle; Automatic micro-fulfilment centers; E-commerce; Waste removal; City logistics; Urban planning; Circular economy; 15-minute City; Climate Impact

Conference Topics:

autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms); business models & use cases; interconnected freight transport; distributed intelligence last mile & city logistics; logistics and supply networks; Modularization; omnichannel & e-commerce logistics; PI implementation; vehicles and transshipment technologies.

Physical Internet Roadmap:

Select the most relevant area for your paper: ☒ *PI Nodes,* ☒ *PI Networks,* ☒ *System of Logistics Networks,* ☐ *Access and Adoption,* ☒ *Governance.*

1   The challenges for Urban Logistics

Researchers agree that current technologies will not be sufficient to achieve the Paris Agreement or the goals of Fit for 55. Each year 3 million die due to air pollution, mainly from motor vehicles in cities. Citizens are increasingly realizing that the street space should be used for other things than motor vehicles, and many cities are implementing car-free zones. The concept of the 15-minute city requires arranging access to services and products within short walking or biking distance. A large share of mobility of persons is due to the need to move smaller items and not people. About 45% of car trips in cities are for that mission. It is a pressure to increase the re-use and the life span of packaging, products, components, and materiel. Such circular flows require more transport than today's linear flows. Storage of things, food, and waste occupy a considerable part of the space in buildings both in apartments, retail stores, and workplaces.

2   The state-of-art

2.1   Urban Logistics

For last-mile transport, cars and vans on streets are dominating. With the expected growth in e-commerce and circular economy, congestion and operating cost will increase. Cargo bikes and delivery mopeds are labor intensive and demand street space. Lockers and sidewalk robots can reduce labor cost but does not reduce need for space. Air drones can reduce street congestion but cannot take the expected volumes, are weather, and has a high operating cost. Water and rail are not available everywhere. Most pilots with urban consolidation and micro-hubs for load-pooling have not been successful, partly because the customers demand ever faster delivery and difficulties with sharing data among competing companies.

2.2   Underground Logistics
Several underground freight transport systems have been proposed with tunnel diameters of 90 – 250 cm. Wikitia 2023 reports on the following:

- *CargoCap[15] is a German company launched in 2002 under the direction of Prof. Dr.-Ing. Dietrich Stein. It promotes a freight system capable of transporting capsules containing two euro-pallets through 2.0 meter (6 feet) diameter tunnels or pipes, over distances up to 150 km (90 mi).[9][16]*
- *Mole Solutions Ltd.[17] is a British company founded in 2002 aimed at developing underground logistics systems or freight pipelines. It has developed a demonstration project in Cambridgeshire, UK featuring a 1.3 m (4 feet) diameter pipe equipped with rails and linear induction motors.[18][19][20][21]*
- *FoodTubes[22] ("Really fast food") was a 2008 British proposal by Noel Hudson for a 1.2 m (4 feet) diameter polyethylene tube system through which 2 m long capsules would travel at speeds up to 60 mph, powered by air pressure. It would be a packet-switched-style network connecting food producers and retailers. Costs were estimated at 5 million euro per kilometer. [8][7][23][24][25]*
- *Urban Mole was a 2009 concept for the transportation of packages through urban sewer systems.[26]*
- *Cargo Tunnel[27] was a concept published in 2009 by Russ Tilleman et al. They envisioned a 4-feet (1.2 m) diameter tunnel network connecting homes and*

businesses, enabling automated delivery of cillindrical packages up to 18x18 inches (45x45 cm). Delivery would take place through access cabinets, each equipped with an elevator to access the tunnel system.[10][11]

- *Cargo Sous Terrain is a planned system to complement the Swiss road and rail network, in development since 2013. It will feature 6.0 meter diameter tunnels and transport euro-pallets and shipping containers.*[28]
- *Magway*[29] *is a British start-up founded in 2017 aimed at developing a pipe network for the delivery of packages to consumers and businesses. It plans to use small HDPE pipes with a diameter less than 0.9 m (3 foot), equipped with magnetic propulsion.*[30][31][32]
- *JD.com launched an Urban Smart Logistics Institute in 2018 to study underground logistics systems for their fulfillment centers.*[33] *No details have been published, but animations show a system similar to CargoCap.*[34] *JD.com is reported to be collaborating* with the American firm Magplane Technology Inc. to develop a magnetic levitation *system.*[35]

2.3   The 5th Transport Mode - Capsule Pipelines

The 5th transport mode, pipes, is since long dominating for the transport of water, sewage, heating and gas. Underground pneumatic pipes were used in 44 cities for transport of letters in capsules from 1853 to 2002, but were outcompeted by motor vehicles, and e-mails, and unable to carry the packages that dominate post services today. Today pneumatic transport systems are used within buildings, e.g., most hospitals for samples to labs, banks, and retail for cash, and in government agencies for sensitive documents.

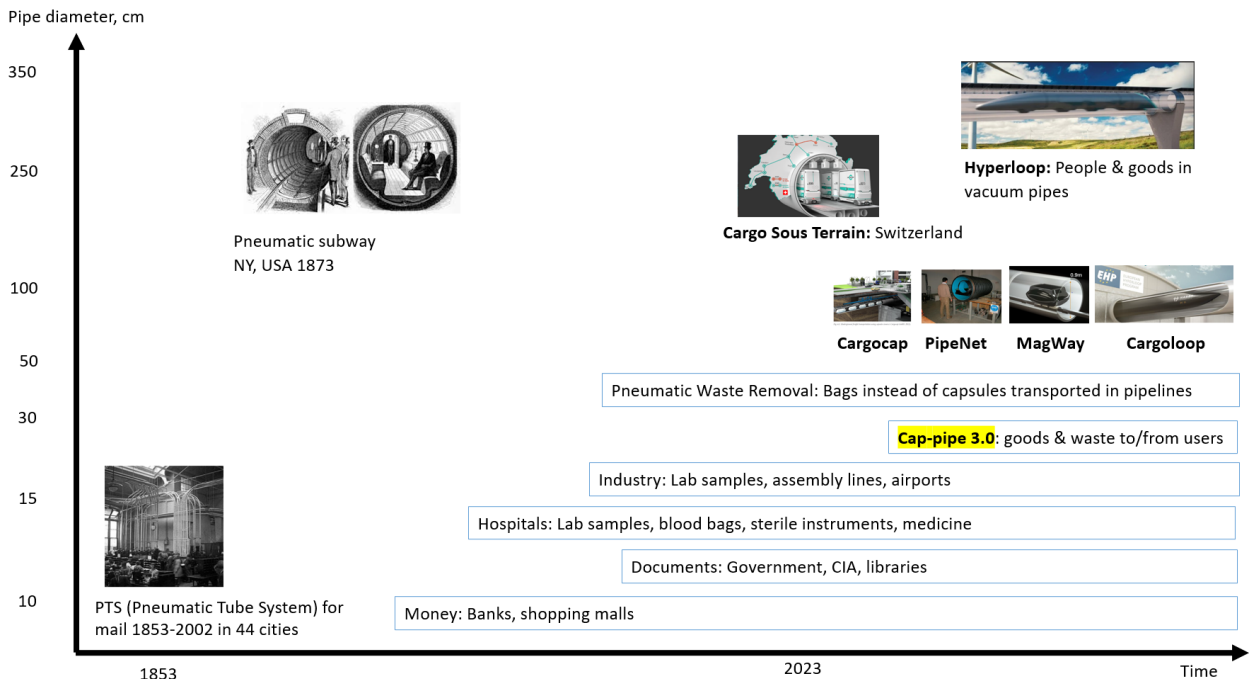The timeline of the most important capsule-pipe systems is shown in Figure 1.

Fig. 1. Capsule-pipeline transport yesterday, today, and tomorrow

We have found four companies developing capsule-pipe system for transport of small items and waste in cities. It is CargoFish 2023, Pipedream Labs 2023, Omniloop 2023, and Tubular Networks 2023. The first two uses electric motors and wheels on the capsules while Omniloop uses a combination of pneumatic and electromagnetism to propel and steer the capsules.

3   Purpose and research questions

The purpose is to explore the addition of the 5th Transport Mode, Capsule Pipelines, to urban logistics by answering the following research questions:
- Is it technically feasible?
- For what will it be used? At home? At work?
- Pain points, risks, and challenges? How can these be mitigated?
- What are the benefits of each service? How much are users willing to pay?
- Is it economically feasible for society? For each stakeholder in the ecosystem?
- How can it enable: Physical Internet? 15-minute City? Circular economy? Retailing?
- Impact on CO_2 emissions, environment, and street space?
- Need for further research and development?

4   Design/methodology/approach

An assessment of the state of the art was made based on the analyses of about 3000 articles reporst and patent applications together with participation in some 50 workshops and conferences for five years.

A first basic design was made based on the pneumatic technology used in hospitals and industry as depicted in the central part of Figure 2.
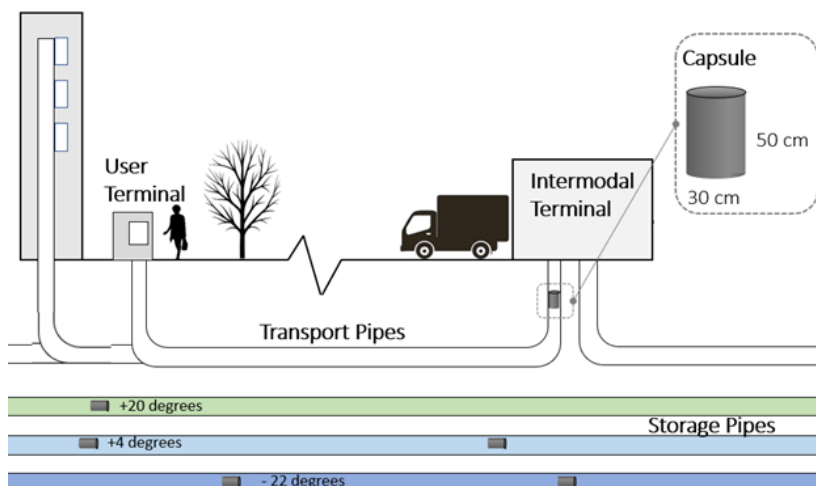
Fig. 2. Basic Urban Capsule-pipe Logistic System

About 40 people were interviewed about using the system in their daily life at home and at work. Based on the requirements from these use cases a second design was made and used in more interviews. We formed the company Omniloop and filed patents that describe the

innovations required to provide these service use cases. A LEGO model illustrating some of these use cases was built and displayed at exhibitions, conferences, and workshops.

5 Research Findings

5.1 Potential uses of an urban capsule pipeline

After two years of iterations with some 300 interviews about 30 generic use cases with new technical solutions were developed as illustrated in Figure 3.
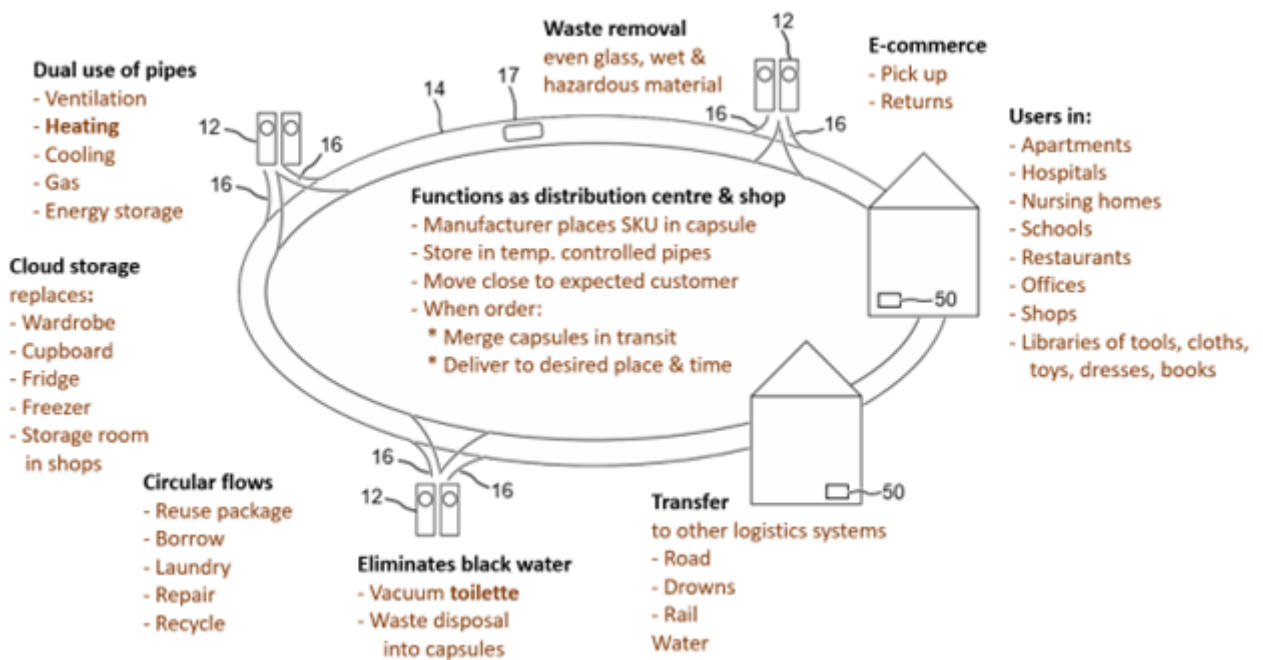

Fig. 3. Examples of services based on the capsule pipe infrastructure

The LEGO model was displayed at a LEGO-exhibition with were 81 filled in our survey. The results of the survey are reported in Wandel et.al. 2022.

5.2 Technical feasibility

From the 30 generic use cases we identified technical requirements. During two years of iterations, sprints as called in agile development methods, a comprehensive system was developed and described in several patent applications. The latest application has 35 pages and 38 claims. Then we know that it is technically feasible.

5.3 Contributions to the concepts:

5.3.1 Physical Internet

Based on the description of the physical internet concept in ALICE 2020 and in Milnkovic 2022 we found:

- The capsule in the capsule pipeline system can be considered as PI container.
- Both the capsules and the infrastructure with pipes, switches, and terminals are shared among all logistics providers

- Since capsules can be moved and parked at low cost the usage of the infrastructure is optimized in real time.
- Cloud/shared warehouses. Goods in capsules are automatically stored in zones with deferent temperatures and automatically retrieved and delivered within minutes. This enables automatic order fulfillment.
- One SKU of a product can be packed in a capsule at place of production, stored in speculation in the pipes, and delivered when the customer orders it. No terminals, warehouses, picking, consolidation, or de-consolidation needed. Even private items as shoes, cloths, tools, toys, wine, and food can be stored in the pipes.
- All shipments to and from a user are consolidated into the same pipes and terminals. Products to users and from users packaging for reuse and waste reduces empty runs
- The system enables marketplaces and circular economy business models
- The integration with other transport means is done with open software
- Physical Interoperability of assets and resources (load units, transshipment, etc). Capsules are automatically transferred to/from load units suitable for other transport means, e.g., boxes for cargo bikes, sidewalk robots, and drowns, pallets or swap bodies for trucks and trains, and containers for sea and air transport
- Synchromodality, (intermodal) routing. Capsule-pipeline can be operated both in sequence with other modes and in parallel to enable load balancing.
- All capsules and components of the system have many sensors and actuators that are connected using Internet of Things protocols, preferably 5G low bitrate
- The capsule is both a unit load, a secondary packaging, and a vehicle

5.3.2 The 15-minute City
- Everyone citizen, shop and establishment have access to a user terminal in the yard outside the front door or in the apartment or workplace.
- Most merchandizes can be shipped with about 5-minutes lead time 24/7
- Products can be sent for services as cleaning and repairing without any person traveling with it

5.3.3 Circular Economy
- Much easier to recycle and reuse packaging and products
- Enabling circular economy concepts such as borrow, share, repair, reuse, and recycle.
- One direct channel between users and providers both up and downstream.

5.3.4 Automatic Stores and Order Fulfillment
- The user can decide when and where to pick up a shipment since it is parked in the pipes close to were the reciever is expected to be.
- Goods can be stored in capsules in pipes in different temperature zones.
- Capsules with items can automatically be stored, sorted, and retrieved
- Thereby replacing some wardrobes, freezers, parcel lockers, micro-fulfillment centers, and even complete retail stores

5.4   Economic Feasibility
Using data from a small town we analyze costs and space saved. We assumed an installation cost of 2 400 EUR per user if 50 persons share one user station. This is twice the cost of a pneumatic waste collection system. To calculate the benefits, we estimated cost savings per type of service from an average person living in the town as shown in Table 1.

Table 1. Economic benefits per user in EURO in one scenario.

Service\Benefit per user	Vehicle km/year	Transport-cost/year	Space saved sqm	Rent for space/year	Cost reduct./year	Pay back year
Waste remowal	7	9	0.21	16	25	96.0
Distribution of mail & newspapers	251	359	0.76	60	419	5.7
Bought delivery of merchandises	528	756	1.60	126	882	2.7
Own picking up merchandises	786	658	1.23	87	745	3.2
Total to/from home	1 581	1 782	3.80	289	2 071	1.2
To/from work places (30% of above)	474	535	1.20	87	622	3.9
All above services	2 055	2 317	5.00	376	2 693	0.9

Additional results from the economic analyses were:
- The value of the saved space was 1.6 times larger than the investment cost
- It was profitable to install a user terminal in a kitchen if the investment cost was less than 40 000 EUR

5.5   Reduction of Climate Impact in the scenario

- A 5 kg capsule does, in many cases, the same job automatically as a motor vehicle with 500 times larger mass and a driver.
- 2 055 less vehicle*km/year per user means 30% less traffic parking, emissions of harmful particles and noise
- Emissions of CO_2 were reduced by 760 kg/year and user, which is 30% of per capita CO_2 in Sweden
- Less need for private cars. About 45% of trips by cars are today only for the transport av items and not people

6   Suggested Research and Development

Even though the proposed urban capsule pipeline system seems technically and economically feasible, societies are not yet prepared. We have identified the following remaining research questions:
- Suitable planning, legal, and institutional framework?
- Regulations regarding safety, security, standards, and cerification?
- Actors in the future ecosystem and their business models?
- Integration with other logistics systems? Information system with AI?
- Simulation models to analyze the best mix of last mile transport means for different types of cities as density; mixt of workplaces, residences, commercial areas; green or brownfield; and future technical year?
- Where to start? Inside buildings, e.g., shopping centers and airports? Between courtyards? Between cities and major air- and seaports?
- Where to place terminals? Courtyards, entrance, shop, or kitchen?
- How far upstream the supply chains? City outskirt? Place of production? For the pipes? For using capsules as the secondary packaging?
- Cost-benefit and life cycle cost analyses?
- Drivers, pain points, and barriers for all stakeholders? Strategies for mitigation the barriers?

- Is it cost-effective to invest in infra-culverts underground and multi-shafts in buildings to prepare for future capsule-pipe systems?
- How to design ventilation, heating, and cooling systems using the same pipes as the capsules?

To achieve all this, we suggest to establish a cluster of researchers to answer the questions above, to develop and test prototypes of the components, a demonstrator, and a full-scale pilot, and plan for scale up.

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Leveraging Customer Conversion Behavior in Hyperconnected Networks

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Abstract: *This paper focuses on how leveraging conversion rates in hyperconnected networks can help retailers face the challenge they face to meet customer expectations with efficient and effective supply chains with increased. The conversion rate is the percentage of visitors to an online platform who finalize a purchase, and understanding and estimating such curves help shape key supply chain decisions. However, decision-making in the industry generally assumes that all customers want their products delivered as soon as possible, overlooking the complexity of customer conversion behavior. This paper challenges this notion and explores how the concept of different customer behaviors can be leveraged in hyperconnected networks with the Physical Internet (PI) with the added information on conversion rates. The paper characterizes the diverse types of customer behaviors relative to delivery/pickup time sensitivity, develops the Physical Internet levers to enhance conversion rates, and analyzes how leveraging different customer behavior types in the Physical Internet may lead to higher conversion rates in an efficient and sustainable way. The study contrasts the relative impact of PI's interconnectivity levels on conversion with three representative scenarios: independent retailer, independent retailer with flexible mode options, and retailers in a hyperconnected network. The paper provides conclusive insights and avenues for further research.*

Keywords: *e-commerce, conversion rate, web retailing*

Conference Topic(s): *business models & use cases; logistics and supply networks; omnichannel & e-commerce logistics*

Physical Internet Roadmap *(Link): Select the most relevant area for your paper:* ☐ *PI Nodes,* ☐ *PI Networks,* ☒ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

1 Introduction

With rising global demand and increased competition, retailers are faced with a challenge to meet customer's expectations with efficient and effective supply chains. Customer conversion rate, or the percentage of visitors to an online platform that finalizes in a purchase, has become a key metric to be studied to measure the effectiveness in meeting customers' expectations and supply chains. By definition, increasing the conversion rate leads to higher sales. However, increasing the conversion rate can be costly, as it often requires concurrently offering competitive prices with fast and flexible delivery options. Retailers are then faced with a

challenge to weigh these tradeoffs and decide on the combination that best meet their customers' needs and maximize the profit.

Because conversion rates are affected by various factors including pricing, user experience, shipping and delivery, examining the relationship between any single factor and the conversion rate is a challenging task. Further, as most companies log sales data but do not log demand data, conversion data is sparse, and the existing data is oftentimes unreliable, further skewed by other factors.

In this paper, we focus on conversion rates as a function of quoted lead time that affect the resulting demand. We challenge the notion that all customers ubiquitously desire to get the products as soon as possible, in line with early research in Montreuil et al. (2013) and explore how this concept can be leveraged in hyperconnected networks with the Physical Internet (PI).

Since faster delivery usually requires more expensive modes of transportation (for example, air cargo, less-than-truck services, or parcel delivery vans) the trade-off between delivery speed and lost demand from not meeting customer delivery expectation must be studied to maximize the overall profit while maintaining high customer satisfaction. However, while decision making in the industry have generally assumed that all customers want the products as soon as possible, some customers might be either insensitive to the quoted lead time or have specific time window such that getting the product delivered earlier than the start of the time window could in fact decrease the conversion rate. Such complexity in customer conversion behavior can be observed for different product types, customer groups, seasonality, and whether the products are customized or not.

In the past decade, some retail industry leaders, namely Amazon or InstaCart, have begun to offer specific time windows for product deliveries, since customers in these industries tend to be more time-sensitive than those in other industries. For these products, the time of delivery could be a deal breaker for most customers (they do not want food items to be spoiled, etc.). For most other industries, guaranteed delivery in a certain time window is more expensive and logistically difficult, especially for retailers selling big and bulky products with high costs such as furniture, large electronics, or vehicles. However, the Physical Internet and the interconnectivity it provides with the hyperconnected logistic networks and supply chains allows a more flexible, efficient, and responsive logistical system in which we could leverage the understanding and estimates of customer conversion behavior to maximize profit and/or customer utility.

In this paper, building on a systemic literature review, we first provide a characterization of diverse types of customer behaviors relative to delivery/pickup time sensitivity. Second, we develop in deeper mode the Physical Internet levers usable for enhancing conversion rates. Third, we analyze how leveraging the different customer behavior types in the Physical Internet may lead to even higher conversion rates in an efficient and sustainable way. We contrast the relative impact of PI's interconnectivity levels on conversion with three representative scenarios: independent retailer, independent retailer with flexible mode options, and retailers in a hyperconnected network. We finally provide conclusive insights and avenues for further research.

2   Literature Review

The concept of the Physical Internet, introduced by Montreuil (2011), is an approach to allow and enable an open, hyperconnected logistics system grounded on interconnectivity on multiple layers including but not limited to physical, digital, and operational levels. For an introduction to and formalization to the concepts of the Physical Internet and hyperconnected logistics systems, refer to Montreuil (2013).

Best to our knowledge, the role of conversion rates in hyperconnected networks has not been formally studied. However, with e-commerce shaping the landscape of retailing in the past few decades, an abundance of literature on conversion rates study methods to improve conversion rates, either through artificial intelligence and machine learning algorithms or through creating a better user experience (UX) design. The former takes advantage of the now available data on customer behavior and preferences to improve personalized recommendations and targeted marketing. Childers et al. (2001) and McDowell et al. (2016) are examples for the latter in which the authors study how web design and enhancing online shopping experiences relate to conversion rates. Zimmermann and Auinger (2022) also provide a marketing optimization framework for driving sales through optimizing the conversion rates. While various factors contribute to conversion rates (e.g., website design, user experience, marketing), we primarily focus on the time-sensitive aspects and how the lead times impact the conversion rates and thus sales.

Traditionally, researchers have recognized the role of lead times in customer utility and thus sales (Brynjolfsson et al. 2009, MH&L 2016, and Kumar et al. 2000, So and Song 1998, de Treville et al. 2014, to name a few). The relationship between lead times and conversion rates have been studied by researchers in different disciplines with the notion that by decreasing the wait times, customer utility increases, including methods to offer quick delivery to remain competitive (Kumar et al. 1997 and Brynjolfsson et al. 2009). Following this assumption, researchers have modeled demand or sales as a linear decreasing function of time (either wait times or lead times) as shown in the early models of intertemporal choice such as the work by Samuelson (1937).

However, more recent works show that such assumption might be over-simplifying the time-sensitivity. For instance, Thaler (1981) showed that consumers have a higher sensitivity for low-priced products. In fact, in addition to prices, other product attributes are linked to varying lead time sensitivities as Cui et al. (2020) shows. Xia and Tahagopalan (2009) study how lead time sensitivity differs for various product categories. Lead time sensitivity also varies by customer groups and thus it is important to adjust the impact of quoted lead times on demand accordingly for each group of customers (Jin 2013, Fisher 2019). Montreuil et al. (2013) creates different client profiles and purchasing behaviors as a function of lead times for each client profile. With the representation of such client behaviors, they provide a simulation approach aiming to estimate a business's ability to meet delivery deadlines in a make-to-order environment.

Further, Montreuil et al (2013) challenge the notion that all customers prefer shorter waiting times in all of their purchases – depending on the client profile, some are either less sensitive or insensitive to the lead times, or would prefer a certain time window rather than getting the products as soon as possible. Marino et al. (2018) also notes that in some instances, "consumers might prefer to delay an event's occurrence". In this paper, we continue to challenge the idea that all customer groups share the same behavior and desire for products as quickly as possible. Instead, we show how retailers can leverage the characterization and

analysis of customer conversion behavior with varying lead time sensitivities in hyperconnected networks.

Building on the early work of Montreuil et al. (2013), we provide exemplary models of customer behavior profiles with utility, and thus the likelihood of purchase, as a function of lead time. The assumption that all customers have pre-determined preferences relative to lead time which varies by different customers and different products is made. Sales is represented as conversion rates, or the fraction of website visits that translates to a purchase in e-commerce retailing. In such settings, lower conversion rates correspond to lost sales from potential clients, whether because of pricing, product attributes, user experience, etc. We focus on the time-sensitivity aspect of conversion rates, and aim to represent the change in customer preferences and thus the fraction of actual purchase from change in lead times.

Three customer behavior patterns are introduced as a basis for representing more complex customer conversion behaviors in response to lead times: as soon as possible customers, target time, customers and patient up to a threshold customers. The design and characteristics of each customer behavior pattern is now explained.

3 Characterizing Customer Group Behaviors

3.1 As Soon As Possible Customers

We first present the as soon as possible customers, that desire the product to be delivered to them immediately. Customers in this group exhibit decreasing utility and thus decreased likelihood of purchase as the waiting time increases for them. The curves are represented as concave curves that exhibit the maximum sales in the lowest lead times, and the conversion rate decreasing in decreasing increments as the lead time increase – such shape represents the higher time-sensitivity closer to the desired delivery time (in this case, 0). Figure 1 shows example conversion curves with varying parameter values, with the horizontal axis representing quoted lead times shown on an e-commerce website, and the vertical axis representing the conversion rate. The leftmost curve (labeled ASAP 1) represents the most impatient customer as the curve sharply drops to null value after the desired delivery time of 0. The rightmost curve (labeled ASAP 8) represents the most patient customers with the conversion rate dropping by the least amount compares to all other customers. The curves in the middle represent the customers with time-sensitivity between the first and the last ones, with decreasing time-sensitivity as we move to the right.

This group of customer behavior represents the assumption that has been made in many of the past studies, that the customers want the products as soon as possible, and the utility decreasing as the delivery time shifts further from the time the order is placed. In fact, adjusting the parameters so that the curve becomes completely linear, we would get the conversion rate graph as a linear function of lead times, the equation that had been used in studies from multiple fields to represent customer behavior.

Note that in these illustrative examples, we assume that the conversion rates are function of a lead time only and thus all customers will purchase after a visit if and only if the quoted lead time is acceptable for them, thus the maximum value of 100% attained at some point in all

scenarios. However, in reality, multiple factors affect conversion rates and even if the quoted lead time is acceptable for the customer, a visit does not always lead to a purchase. In fact, the average conversion rate is only around 4% (Lee et al. 2012). The rates shown in these illustrative graphs should thus be understood as relative fractions of the maximum attainable conversion rates given all other factors, and estimated from empirical examples.
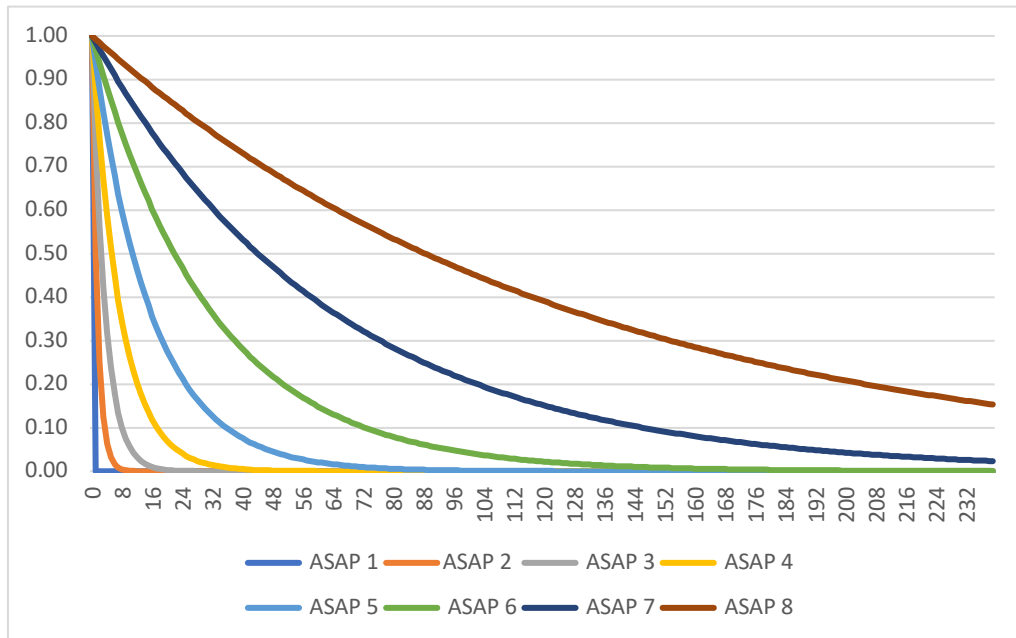

Figure 1: Example Curves for As Soon As Possible Customers

3.2   Target Time Customers

Challenging the common assumption made for the as soon as possible customer group that customers want the products immediately after they make an order, the second customer group profile represents the customers that ideally desire to receive the product at some point in the future. The utility and thus the conversion rate for these customers is the maximum at the points near their desired delivery time, and decreases as we deviate in either direction from this point. In fact, the conversion rate starts at a certain value (determined by the parameters) at lead time of 0, and then increases until the desired lead time is reached. Then as the lead time increases after that point, the conversion rate drops to eventually reach a null value. Note that the second portion of the graph consisting of the point in which the target time is reached until the end of the graph is similar to the first customer group curve for the as soon as possible customers. Varying levels of time-sensitivity is observed for either portion of the graph similar to the first set of curves illustrated.
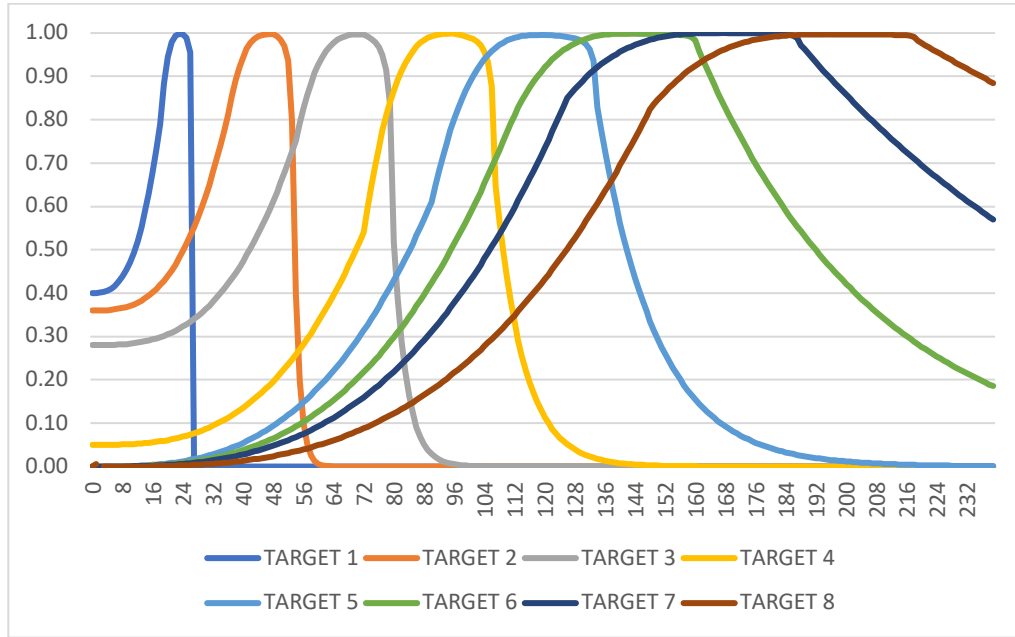
Figure 2: Example Curves for Target Customers

3.3   Patient Up To a Threshold Customers

The third type of customer conversion behavior is patient up to a threshold customers (PUTT) who ideally desire the product immediately, similarly to the as soon as possible customers, but are more willing to wait up to a certain point. These customers are patient until this set point and thus the first leg of the curve is concave. However, once that threshold point is reached, the conversion rate drops rather sharply. The second part of the curve, from the threshold point to the remaining lead times, is again similar to the as soon as possible customer group curves with concave curves of varying sensitivities that eventually reach the null value.
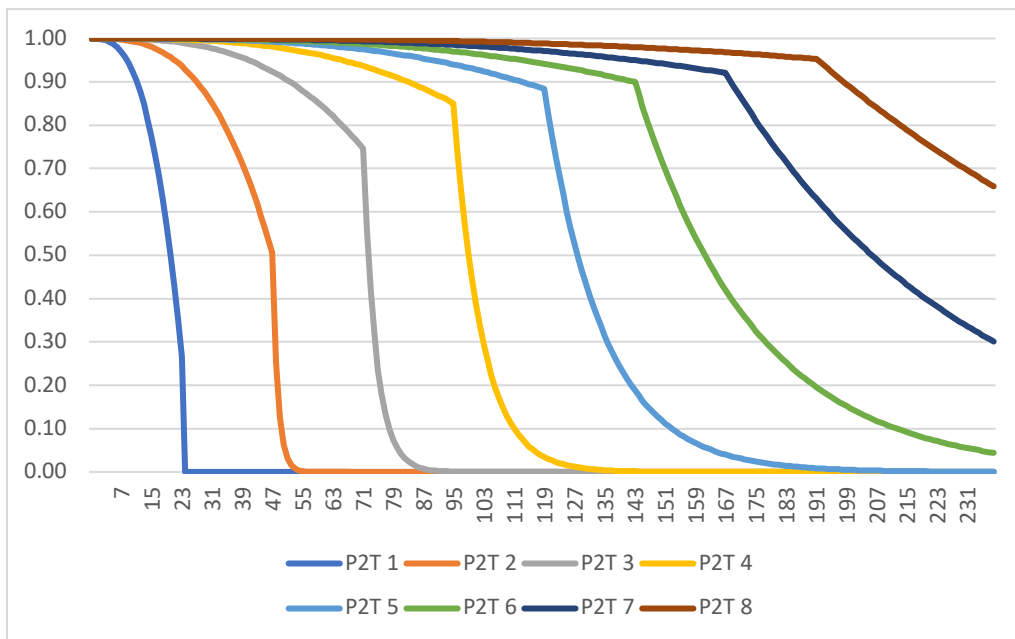
Figure 3: Example Curves for Patient Up to a Threshold (PUTT) Customers

4 Physical Internet Levers

Universal interconnectivity (interconnectivity in multiple layers including physical, digital, operational, transactional, and legal interconnectivity) is key to making the Physical Internet an open, global, efficient and sustainable system (Montreuil et al. 2012). With the Physical Internet, interconnectivity in the following levels can be achieved, that are particularly relevant in the context of conversion rates:

1. Physical Interconnectivity: With physical interconnectivity, physical objects (trucks, parcels, etc.) are able to flow seamlessly across parties, facilities, and modes through the hyperconnected networks, in which they are "moved, handled, and store ubiquitously" while meeting regulatory, security, and other operational constraints. Thus, in a supply chain in which the physical interconnectivity is ensured, the orders customers place online would be flowing seamlessly and at a greater flexibility in terms of when and how the items are delivered from the source (manufacturer, supplier, etc.) through intermediate nodes (hubs, warehouses, etc.) to the final delivery point (retail stores for pickup, customer homes, etc.).

2. Digital Interconnectivity: With digital interconnectivity, information is shared seamlessly across the entire network and with all stakeholders and entities. This informational interconnectivity allows transparency including tracking the status and location of the objects moving in the network, as well as real-time update on the changes in customer demand and the availability of the products demanded from the supply side. Such real-time information is openly available not only among the virtual agents, but human actors (truck drivers, decision makers, etc.) as well, and would allow a more dynamic supply chain in response to any changes in conversion rates.

3. Operational Interconnectivity: Interconnecting the networks on an operational level among multimodal logistics and transportation service providers ensures consolidation and synchronization (Crainic et al. 2016). These synchronized in-the-field operational and business processes include using standardized business contracts as well as the operational protocols (Montreuil et al. 2016). For conversion rates, e-commerce retailers could gather crucial information on how the quoted lead time affects sales by offering a standardized procedure of asking the desired time window for when the customers desire to receive the products.

Dynamic, synchronized deployment of physical items further increases the availability of products across the hyperconnected network. With an open and transparent network of warehouses, hubs, distribution centers, and fulfilment centers, retailers can deploy the right products at the right places at the right times as the required information is readily available and with seamless delivery through different transportation modes. Sohrabi et al. (2016) and Yang et al. (2017) provide optimization and simulation-based experiments showing that such interconnected distribution result in up to 30% increase of "efficiency, responsiveness, resilience, and security, through a dynamic network approach securing supplies without duplication of safety stocks and fast fulfillment in line with market expectations" (Ballot et al. 2021).

The efficiency and responsiveness in hyperconnected networks allow for delivery speeds that are not currently achievable in many realistic cases – depending on the type of items being shipped, air cargo might not be an option and even if it is, it is usually a costly option. Moving through different phases of the Physical Internet thus provides a greater flexibility in delivery

options, allowing for a full exploitation of the conversion curves. With faster delivery, the left-side boundary of the conversion curve shifts to further left, and with effective deployment, delivery can be delayed and even finetuned as needed.

We now contrast the three representative scenarios: independent retailer, independent retailer with flexible mode options, and retailers in a hyperconnected network.

The independent retailer can only access one mode of delivery. Since it is limited to a single mode, the lead time cannot be adjusted based on the conversion rate to maximize the profit based on expected sales. Orders are shipped to the customer as soon as they are placed. Then, we have the independent retailer with flexible mode options – we can now leverage premium shipping options to increase demand when the net revenue is worth the change. In hyperconnected networks, different retailers now collaborate with real time sharing of information. For non-time sensitive goods, or products with higher conversion rates with delayed delivery, shipments are consolidated to save delivery costs. With hyperconnected network, faster deliveries allow us to use the lower lead time portions of the conversion curve.

5   Conclusion

This paper focuses on the impact of quoted lead time on customer conversion rates, which affects demand and sales by challenging the assumption that all customers desire immediate delivery. We explore how this concept can be leveraged in hyperconnected networks with the Physical Internet (PI) -- leveraging the PI's interconnectivity can lead to a more efficient, flexible, and responsive logistical system. To fully take advantage of the interconnectivity the PI provides, different customer behaviors and thus varying conversion curves are acknowledged. We thus provide a characterization of three types of customer behaviors relative to delivery/pickup time sensitivity, namely As Soon As Possible (ASAP) customers, Target Time customers, and Patient Up to a Threshold (PUTT) customers. We then develop Physical Internet levers that can enhance conversion rates, and analyze how leveraging different customer behavior types in the PI may benefit the retailers in an efficient and sustainable way. We contrast the relative impact of PI's interconnectivity levels on conversion with three representative scenarios: independent retailer, independent retailer with flexible mode options, and retailers in a hyperconnected network. This paper provides insights into how retailers can balance the tradeoff between delivery speed and lost demand from not meeting customer delivery expectation to maximize profit while maintaining high customer satisfaction.

Further research directions include further exploration of customer behavior to include more complex scenarios to refine the understanding of conversion behavior. Methods on the specification of the parameters that determine the scale and shape of the curves should be further studies as well. While the paper briefly touches on sustainability, additional research could explore the potential impact of leveraging the conversion rates in the Physical Internet settings on supply chain sustainability, including quantifying the degree of efficient use of resources, or the reduction in carbon emissions. Finally, with the potential to disrupt traditional business models in logistics and e-commerce, future works could explore the impact of the system on different types of businesses models and industries. Such continuations of work in this area can provide a better understanding of how customer conversion behavior can be leveraged in hyperconnected networks to enhance the efficiency and sustainability of the logistics system, and benefit both the customers and the retailers.

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Kit Fulfillment Centers Serving Distributed Small-Series Assembly Centers in Hyperconnected Supply Chain Networks

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Abstract: In the context of Physical Internet (π, PI) enabled hyperconnected supply chain networks, we focus on the design and performance assessment of π-enabled kit fulfillment centers (KFCs) distributed over a territory to concurrently feed multiple agile assembly centers (AACs) in their region. The AAC production is often associated with the realization of major projects for which short product runs are needed. The KFCs are designed to produce multi-level modular container kits (Montreuil et al., 2015).

The multi-level kits of the KFCs have 4 levels, task, skill, workstation, and product. The kit assembly processes are categorized into A, B, and C, according to the shape, weight, and size of their parts. The resource balancing and scheduling is done using a mixed integer programming model, whose performance is validated with a comparison experiment using synthetic data for automobile manufacturing. The process design reduces intermediate inventory space between levels of kit production to encourage space efficiency. The modular design of kitting cells enables easy and quick reconfiguration under variable demand. The multi-level modular container kits allow easy and smart transportation in the hyperconnected supply chain network and handling at AACs.

Keywords: Physical Internet, Kitting, Hyperconnected Supply Chain Networks, Distributed Small-Series Assembly, Modular Container, Multi-Level Kit, Modular Workstation Design, Line Balancing, Labor Scheduling

Conference Topic(s): PI Implementation

Physical Internet Roadmap ([Link]): PI Nodes

1 Introduction

This paper is about designing Kit Fulfillment Centers (KFCs), kitting facilities that are distributed over a territory and capable of serving multiple vicinity agile assembly centers (AACs) in a hyperconnected supply chain network, as shown in Figure 1.

Bozer and McGinnis (1992) defined kitting as the practice of preparing kits containing predefined quantities of parts that serve specific assembly efforts in the manufacturing plant. There are two ways in which manufacturers can feed materials to the assembly line: line-side feeding and kitting. Assembly line feeding methods can be selected depending on product customization and storage space constraints in a facility (Hu et al., 2020). In general, line-side feeding requires more space around the assembly line, while kitting is more labor intensive. In the context addressed by this paper, the AACs assemble complex, large products with many parts. This means we need several different parts for each assembly station, which could make line-side feeding impractical.

Challenges in designing the KFCs include: (1) due to the dynamic nature of demand from the AACs, the designed KFCs must be able to readjust and reconfigure quickly to changes in demand; (2) due to the complex and large nature of the products of the AACs, the scheduling of kit production and the compactness of kit structure in the KFCs must be designed to be space efficient; (3) under the setting of the hyperconnected supply chain networks, the designed KFCs must produce kits that are

(a) easy and safe to transport between KFCs and AACs, (b) easy and safe to handle, distribute and use in AACs, and (c) efficiently recycled in the hyperconnected supply chain networks.
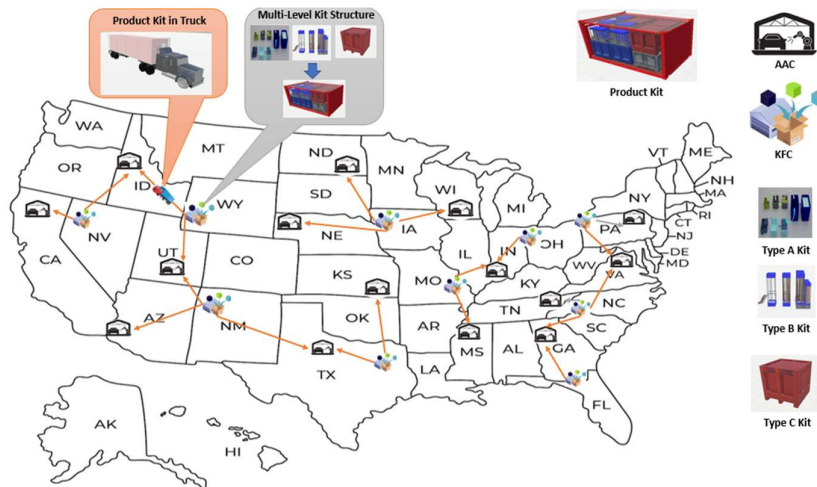

Figure 1. KFCs Feeding Multiple AACs Over a Territory

The full paper is structured in the spirit of (Meller et al., 2014; Babalou et al., 2021). We first analyze the related literature to position our research contribution. Second, we define performance and capability criteria driving KFC design. Third, we address the design of kitting processes and operating models for the multi-level kitting. Fourth, we elaborate on the roles, benefits, and challenges of modular multi-level kit containerization. Fifth, we address the design of modular kitting cells enabling operational efficiency and easy quick reconfiguration. Sixth, we elaborate on takt time driven resource balancing and scheduling, which are done by the KFC configuration and labor scheduling model (KFC-CLSM). Seventh, we describe key KFC layout concepts. Finally, we provide conclusive insights and avenues for further research.

2   Literature Review and Contribution

Kits can be categorized into stationary kits and traveling kits (Schmid and Limère, 2019), and the kits produced by the KFCs are stationary kits, not traveling kits. However, the fact that KFCs produce kits for multiple AACs in an order fulfillment fashion makes the KFCs fall in the intersection between kitting facilities and fulfillment centers. Both kitting facilities and fulfillment centers involve order picking, but fulfillment centers fulfill demand from customers, whereas kitting facilities serve assembly plants, thus fulfillment centers typically have more dynamic demand than kitting facilities. Like the fulfillment centers, the KFCs also have more dynamic demand from multiple short run AACs.

 Bortolini et al. (2020) allocated parts in warehouse aisles for kitting by first allocating parts to aisles according to their size and weight and then assigning kits with most commonality to the same aisle. Under the setting of kitting for mixed-model assembly, Fager et al. (2019) conducted experiments to compare different picking information systems: pick-by-HUD (Head-Up Display), pick-by-paper, pick-by-light, and pick-by-voice, under different kitting batch size and picking density. Two tabu search based heuristics for order batching have been proposed by Henn and Wäscher (2012). Schmid et al. (2021) presented an optimization model for designing a single U-shaped kitting cell, assuming deterministic picking times, given kit demand pattern generated according to historical data, with the objective of minimizing investment, walking and replenishment cost. Proposed by Montreuil et al. (2021), the robotization idea of movebots moving racks to shufflebots in shuffle cells for sorting in logistics hubs can be easily adapted in order picking scenarios.

First mentioned by Montreuil (2011), the π-container is an important pillar in the Physical Internet concept. Montreuil et al. (2015) conceptualized the π-containers as world-standard, smart, green, and modular containers, and categorized them into three tiers: transport container, handling container, and packaging container. In our case, task kits may be put in packaging or handling containers; skill and workstation kits in handling containers; product kits in either handling or transport containers. Grover and Montreuil (2021) presented a mixed integer programming model for the containerization of π-containers under dynamic environment of logistics hubs. Making the π-containers smarter, Tran-Dang et al. (2017) presented a container tracking system via wireless sensor network.

In this paper, we present a use case of π-containers in kitting. The focus of this paper is on the design of a kitting facility, including organization, layout, process, configuration, labor scheduling, and final product. To the best of our knowledge, there are several points of innovations in this paper: (1) the final product kits are multi-level kits contained in π-containers; (2) the stations in the designed KFCs are modular for quick reconfiguration under dynamic demand; (3) the designed KFCs reside in π-enabled hyperconnected supply chain networks, which, along with the modular station design, allows efficient resource sharing in the network.

3   Performance and Capability Criteria

The KFC is designed based on four performance and capability criteria: space efficiency, produced kit ease-of-use, reconfigurability, and labor efficiency.

Space efficiency (discussed in section 4): The space required to operate a KFC should be as small as possible, given the required maximum capacity, to save on the fixed costs.

Produced kit ease-of-use (discussed in section 5): The produced multi-level kits must be easy to transport and easy to handle and consume at AACs. The produced kit must be easy to load onto a trailer or truck. The workstation kits inside product kits must be easy to move inside the AACs. The skill kits inside workstation kits must be easy to take out for assembly workers. The task kits inside skill kits must be easy to access for workers when performing the corresponding tasks.

Reconfigurability to different demand (discussed in section 6): Since the KFCs need to serve multiple short-series AACs with variable demand patterns, the success of the designed KFCs depends significantly on their reconfigurability to respond to changing demand patterns from AACs.

Labor efficiency (discussed in section 7): Given the demand, the number of workers required should be as small as possible to save operational costs, meaning that the average worker utilization rate should be as high as possible.

4   Kitting Process and Operating Model for Multi-Level Kitting

Ideally, for each product, there should be a product modular container kit that contains multiple workstation modular container kits, and each workstation modular container kit contains multiple skill modular container kits, and then each skill modular container kit contains multiple task modular container kits. However, the assembly of a product may require parts that come in significantly different shapes, sizes, and weights. For example, elongated parts may lead to inefficient space

Table 1. Part Categories

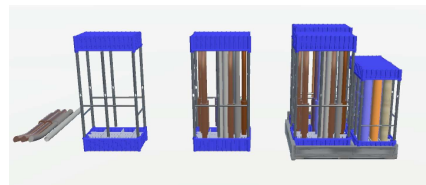| Part Category	Definition
A	Parts that fit in a modular packaging container and are not heavy.
B	Parts that are elongated but are not heavy.
C	Parts that are large and heavy.

Figure 2. Empty (Left), Single (Middle), and Combined (Right) Type B Kit Container Conceptual Drawing

utilization inside cube-shaped modular containers. Taking a large and heavy part out of a modular container task kit in an AAC assembly workstation may be inefficient and possibly lead to injuries. Defined in Table 1, the kitted parts were categorized into three types: A, B, and C. The type A parts, like the electronic parts for an automobile, are kitted into modular task kit containers, then modular skill kit container, then modular workstation kit container. The type B parts, like the long exhaust pipes in an automobile, in one task kit are bundled together and then kitted into modular type B workstation kit containers, shown in Figure 2. Each grid separated by the gray separator is a position for a type B skill kit. For ease of handling, all the type B workstation kit containers are further combined into one as shown on the right side of Figure 2. These type B workstation kit containers are designed to be easily combined to transport or split to distribute to workstations in AACs. The type C parts, like the wheels and engines of automobiles, are kitted directly into the modular product kit container in their original packaging. Each of the individual type C parts in its original packaging is a workstation kit container. The containerized workstation kits of Type A, B and C parts are then kitted into the modular product kit (transport) container for easy transportation to the AACs.

The overall organization of a typical KFC is presented in Figure 3, with the model on top showing the high-level organization, and the model on bottom showing the detailed organization. In the detailed organization, there are three streams of workstation kit containers for type A, B, and C parts meeting at the product kitting center to be kitted into a modular product kit (transport) container. The flow of materials in KFC starts from receiving parts. Then, the parts are stored in either type A/B part inventory or type C part inventory according to their part types. The type C part inventory is separated from the type A/B part inventory because the heavy and large type C parts require wider aisles for the replenishment to the product kitting center. Out of the inventory, the type A parts flow to the Type A Part Kitting Center to be kitted into multi-level modular container workstation kits; the type B parts flow to the type B part kitting center to be kitted into multi-level type B modular container workstation kits; the type C parts directly flow to the product kitting center to be kitted into the modular product kit container. After workstation kitting, the type A and type B workstation kit containers flow to the product kitting center to be kitted into modular product kit container with the type C parts. After the product kits are produced, the modular product kit containers will be moved to the Product Kit Staging, and then shipped to their destination AACs. According to the demand, there could be multiple multi-level kit assembly centers working in parallel.

The multi-level kit production is takt time driven, which is a lean manufacturing concept aiming to pace the manufacturing process to meet customer demand. Each multi-level kit assembly center has its own takt time, which is calculated by $T_k = T_a/d$, where T_k is the resultant takt time, T_a is the amount of available manufacturing time, and d is the demand. For example, assuming the available manufacturing time in a day is 8 hours and the demand for the day is 8 product kits, the takt time would be 1 hour, meaning that each hour there will be a product kit finished. The production of a product kit takes two takt times. All the type A and B part workstation kitting will be done in the first takt time, and then in the second takt time, all the type A, B, and C workstation kit containers will be kitted into the product kit container and moved to staging.
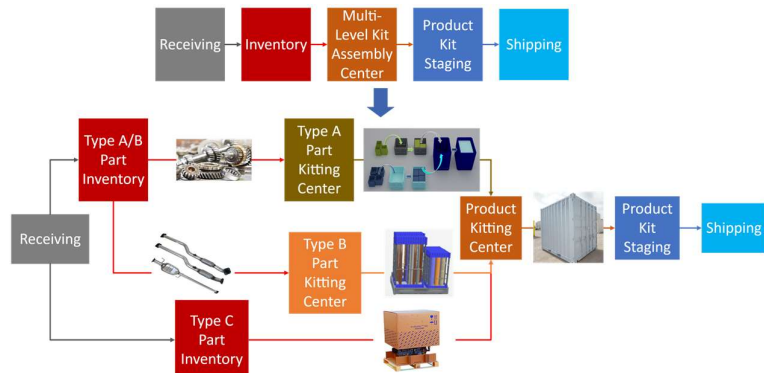

Figure 3. Organization Model of KFC (Top: High-Level, Bottom: Detailed)

4.1 Operating Model

The operating model of the KFC in Figure 4 shows the main decision makers in the KFC and their responsibilities. There are six main decision makers: KFC coordinator, kit assembly manager, logistics manager, demand manager, inventory manager, and outbound manager. The demand manager receives kit production orders from vicinity AACs in the supply chain network. The KFC coordinator then assigns kit production tasks to kit assembly centers and generates takt-time driven kit production schedules for each kit assembly center. In the meantime, the KFC coordinator coordinates communications between other decision makers. According to the kit production schedule, the kit assembly manager of each kit assembly center generates kitting cell configurations and labor schedule. During kit assembly, it assigns the assembly tasks to workers according to the schedule. According to the assembly labor schedule, the logistics manager then generates logistics task schedule and assigns them to workers. With the information of current kit production schedule and finished product kits, the outbound manager schedules outbound trucks to make sure all product kits will arrive at their corresponding AACs on time. Throughout the operation of a KFC, the inventory manager constantly monitors and manages the stock level and storage position of each part type in the inventory and sends inventory replenishment orders to external suppliers when necessary.
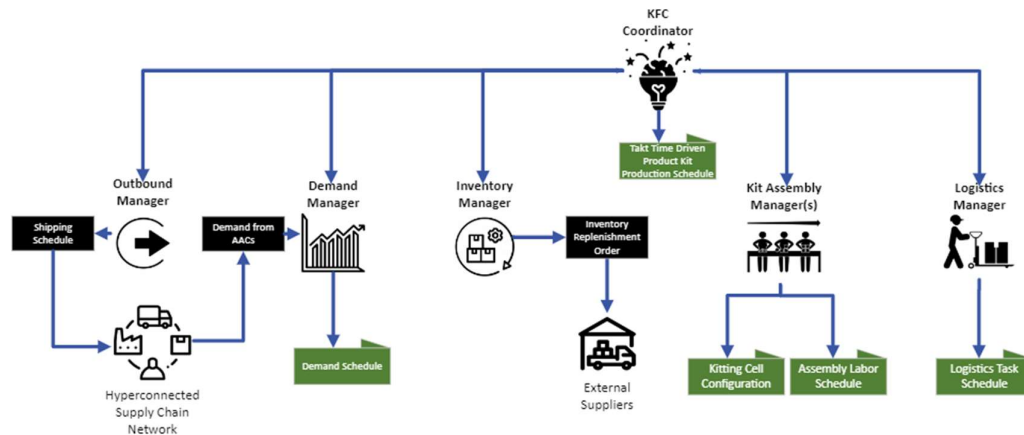

Figure 4. KFC Operating Model

4.2 Type A, B Part Workstation Kitting (Takt Time 1)

Figure 5 shows the conceptual drawing of the type A and B part kitting centers. The type A and B part workstation kitting are done by first setting up the workstation kit containers in the workstation kitting station that is surrounded by a set of modular kitting cells. The modular kitting cells then produce task and skill kits to put into the workstation kit containers. To improve space utilization, the finished task kits are put directly into skill kits and the finished skill kits are put directly into workstation kits, which prevents double handling and requires no intermediate inventory for task and skill kits under this design.

According to the synthetic automobile assembly data provided by our industrial partner, we calculate the required intermediate inventory space if intermediate inventory was used. We assume all type A task and skill kits are stored in three-level racks, all type B task kit bundles are stored in 16-position elongated part racks, and aisle width is 5 ft for easy access. The intermediate inventory space requirements for type A part kitting are 295 ft^2 for task kits and 212 ft^2 for skill kits. For type B part kitting, the intermediate inventory space requirement is 32 ft^2 for task kit bundles. There is no intermediate inventory required for type B skill kits, since the skill kits in type B part kitting are positions in the type B modular container divided by the gray dividers. According to the calculated results, our design reduces the space requirement by 539 ft^2 per kit assembly center.
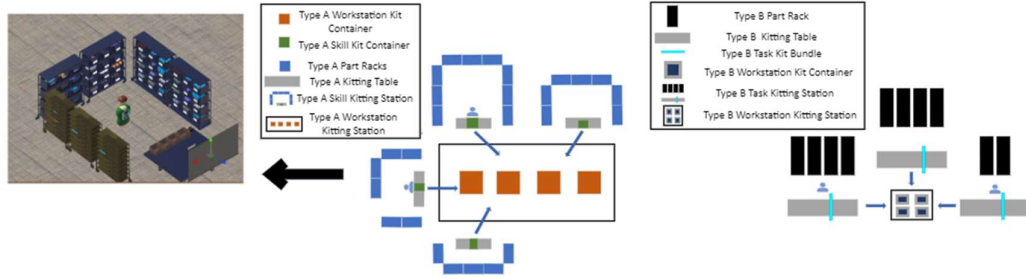
Figure 5. Conceptual Drawing of Type A (Left) and Type B (Right) Part Kitting Center

4.3   Product Kitting (Takt Time 2)

As the last step of the multi-level modular container kitting, the product kitting requires putting all type A, B, and C workstation kit containers for one product into a modular product kit container. As shown in Figure 6, there are three staging areas: type A workstation kit staging, type B workstation kit staging, and type C part staging. The type

Figure 6. Conceptual Drawing of Product Kitting Center

A and B workstation kit staging are replenished at the end of takt time 1 from the type A and B kitting centers. The type C part staging is replenished every x takt times from the Type C Part Inventory.

5   Modular Multi-Level Kit Containerization

The main role of the multi-level kitting is to facilitate the assembly work at the AAC. Therefore, the kits need to be easy to identify, manipulate and access. For achieving this, the objects inside of the container should be kitted in the reverse order of the assembly process, meaning the worker should be able to open a kit and access the objects in the order in which they will be needed for assembly. Figure 7 shows an example of an AAC that has two assembly stations. In this example, product kits (blue) will arrive at the AAC and be

Figure 7. Kit Flow Logic at the ACC

stored in a kit storage area. From the storage area, the kits will be transported to the respective staging areas by logistics workers. From staging, the assembly workers will open the workstation kit, grab the skill kit (green) corresponding to his skill and then grab one by one the task kits (purple) to be used in each one of the assembly tasks.
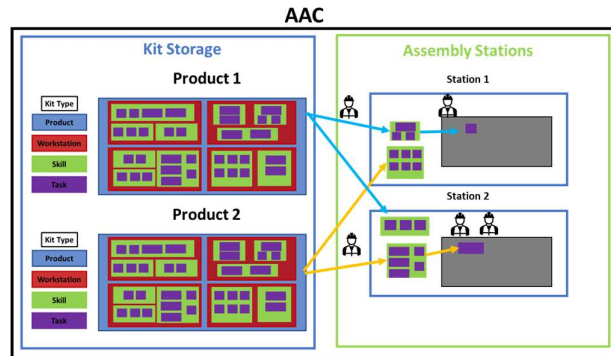
There are various benefits of using this kitting strategy. First, it makes the assembly process easier and faster for the workers. This allows a higher throughput, a lower overall labor requirement and the need for smaller AAC facilities as the space is used efficiently, enabling higher production rates in the same space compared to other feeding strategies. In some cases, land will be less expensive at the KFC compared to the AAC, as the AAC would normally be located closer to the clients and urban areas, another factor for using space efficiently. Additionally, the labor cost tends to be more expensive at the AAC, as it might require specialized labor, making the transfer of work hours from the AAC to the KFC cost effective.

There are some challenges as well for implementing this kitting strategy. One is the space utilization of the containers. As space is key in both the inventory at the facilities and the trucks that will transport the kits from the KFC to the AAC, the container selection needs to be optimized such that the empty space inside the containers is minimized. For this purpose, the two-stage parcel containerization optimization proposed by (Grover and Montreuil, 2021) was implemented. An important input to such a model is the set of potential containers, so this selection must be carefully made for the containers to be modular and easy to nest. These containers need to be strong enough to protect the integrity of the kit, should be labeled in a way that is easy for the workers to identify, and should be flexible enough to allow smooth reconfiguration in case kit contents change. Another challenge comes with the reverse logistics, as the containers are meant to be reusable, there are additional processes required to deliver empty containers from the AAC to the KFC, for which collapsible containers are recommended.

6   Modular Kitting Cells Design

Due to the variable demand from multiple AACs, the takt time for multi-level kit assembly could vary with the demand. To achieve operational efficiency, the kitting cells for lower-level kitting, which takes majority of the work, are designed to be modular, as shown in Figure 4. This modular design enables easy quick opening, closing and reconfiguration of kitting cells. The racks and tables in the modular kitting cells are all designed to be mobile, so that it can be quickly moved for opening, closing or reconfiguration of kitting cells. The specific number of kitting cells and the configuration of each kitting cell that achieves most economic efficiency under a specific demand is determined by the KFC-CLSM.

7   Takt Time Driven Resource Balancing and Scheduling

The KFC's production rate is designed to be takt time driven, as shown in Figure 9, and the KFC kitting cells are designed to be modular. To benefit from the takt time driven production schedule and modularized kitting cell design, proper resource balancing and scheduling is required for operational efficiency. This is achieved by KFC-CLSM, a mixed integer linear programming model. The objective of the KFC-CLSM is to minimize operational costs including assembly worker costs and kitting cell replenishment costs.
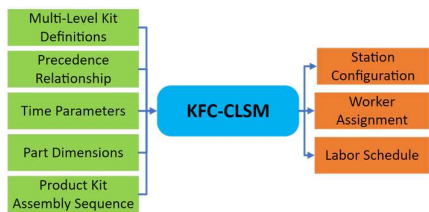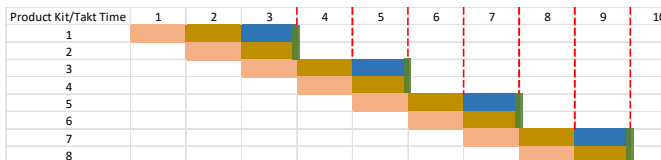

Figure 8. Input/Output of KFC-CLSM

Figure 9. Example Takt Time Driven Production Schedule: Here we assume that two product kit containers can fit into one departure truck. The actual number of product kit containers in one truck depends on both the product kit container size and the truck capacity. The shipping deadline of each product kit is labeled as red dotted edges. To produce each kit, its type A and B workstation kits will be produced in the first takt time (pink cell). In the next takt time, type A, B workstation kits and type C parts will be kitted into product kit container (gold cell). Then, if its departure truck has not arrived, it will be staged in the product kit staging area (blue cell). If its departure truck has arrived, it will be loaded onto the truck (green edge) and depart to its corresponding AAC.

As shown in Figure 8, the KFC-CLSM takes in multi-level kit definitions of different product, precedence relationship defined in process design, time parameters of tasks, part dimensions to assign rack for parts, and product kit assembly sequence to determine produced kit in each takt time. The model output includes station configuration, worker assignment, and labor schedule. The station configuration includes the opening or closing of each candidate kitting cell, the task assignment to each kitting cell, and the part and rack assignment to each open kitting cell. The model picks the type of rack for each type of part based on their volume, and from the number of storage bins assigned to each type of rack, it calculates the number of racks

required and the replenishment cost. The worker assignment means assigning tasks to kit assembly workers. The labor schedule specifies the schedule of tasks for each worker. It is possible for a worker to work in multiple kitting cells in a takt time. The KFC-CLSM finds the optimal combination of number of open cells, kitting task assignment of cells, and labor scheduling to save operational costs.

7.1 Experiment

To demonstrate the performance of the KFC-CLSM, a two-stage optimization model is designed to compare with the KFC-CLSM. The main difference between KFC-CLSM and the two-stage model is that KFC-CLSM does kitting cell configuration and labor scheduling at the same time, whereas the two-stage model does it in two stages. The first stage is kitting cell configuration. Instead of determining the configuration of kitting cells by a mathematical programming model, we have kitting cells designated to one or multiple skills. If due to short takt time, the kitting tasks cannot be finished with one set of kitting cells, another parallel set of the same kitting cells will be opened. Since different skills have distinct sets of parts, this method of kitting cell configuration would keep kits with most part commonality in one kitting cell to reduce the replenishment cost and minimize the movement in kitting. The second stage is labor scheduling. For labor scheduling, the same formulation as the KFC-CLSM will be used.

The synthetic kit definitions for two types of automobile product were provided by our industrial partner. It was observed that the number of skill kits of skill a and b in type A kitting are both around 30% of all the skill kits. Thus, for the configuration of type A kitting cells in the two-stage optimization model, we have one kitting cell designated for skill a, one for skill b, and one for the rest of the skills for each set of type A kitting cells. For type B kitting, since there was only one skill that had type B parts, we have one kitting cell for each set of type B kitting cells.

The performance of the two optimization models in terms of kitting cell replenishment and kit assembly costs will be compared under the demand scenarios of 4, 8, 12, 16, 20 and 24 product kits per 8-hour shift. The demand for the two types of products is assumed to be the same. The cost of workers is assumed to be $21 per hour per worker. The frequency of kitting cell replenishment is once per 8 takt times. The experiments were run with the Gurobi optimizer version 9.1.1 in Python on a computer with an AMD EPYC processor (2.5 GHz, 2 processors) and 230 GB of RAM. The time limit for all the experiments was set to be two hours.

7.2 Results

The two plots in Figure 10 show the comparison between the resultant costs from the KFC-CLSM and the Two-Stage model. The plot on the left for kitting cell replenishment costs shows that the KFC-CLSM has a smoother increase with the demand, whereas the Two-Stage model shows a sudden increase when the demand is 16 product kits per day. Although for the scenario of 8 and 12 product kits per day, the replenishment cost of KFC-CLSM is slightly higher than that of its counterpart, only by

Figure 10. Results Comparison between KFC-CLSM and Two-Stage Model

negligible amounts of $2 and $9 per day respectively. This is because when demand is high, the Two-Stage model had to open two sets of type A kitting cells, whereas the KFC-CLSM model smartly
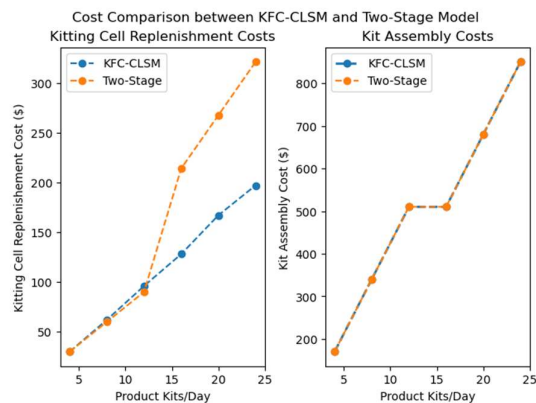
utilizes the modular design of kitting cells to assign kits with most part commonality to the same kitting cells to reduce replenishment costs while making sure the workload can be finished in a takt time. The plot on the right shows that the kit assembly costs for the two models are the same in all demand scenarios. This is as expected, since having all part types of each skill available in the designated kitting cell gives the Two-Stage model more flexibility in labor scheduling. For example, when there are two kitting cells for skill a, the skill a skill kits can be assigned to either one of the two kitting cells, meaning that the workload in each kitting cell can be easily changed to accommodate for the purpose of generating a labor schedule that will minimize the number of workers used. This proves the performance of the KFC-CLSM on finding the optimal labor schedule that achieves the minimum kit assembly cost while maintaining the replenishment cost at a much lower level.

8   KFC Layout Concepts

Figure 11 shows the high-level conceptual layout of a KFC with two kit assembly centers. Each kit assembly center consists of a type A part kitting center, a type B part kitting center and a product kitting center. According to the predicted demand from AACs, a KFC could have multiple multi-level kit assembly centers working in parallel to fulfill the demand from AACs. Each kitting cell inside the type A and B part kitting centers and type C parts in the product kitting centers will need to be replenished with parts from either type

Figure 11. High-Level Conceptual Layout of a KFC with Two Kit Assembly Centers

A/B part inventory or type C part inventory, so the inventory areas should be near to the kit assembly centers, and there should be enough aisle space for the replenishment tasks. Inside each assembly center, the type A and B part kitting centers should be near to the product kitting center, since the finished workstation kits from type A and B part kitting centers will need to be moved to the workstation kit staging areas of the product kitting center. The product kit staging between kit assembly centers and shipping needs to have enough space to act as a buffer for the finished product kit containers to be stored before departure.
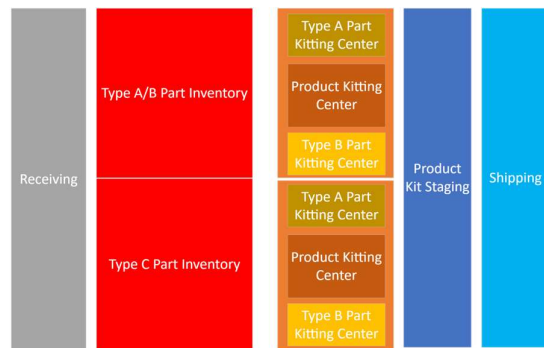
9   Conclusion

In this paper, the design of a kitting facility, KFC, that serves multiple AACs in a hyperconnected supply chain network was presented. The KFC produces multi-level kit π-containers which due to their modular design are easy to transport and handle and economic efficient, and due to their multi-level structure are easy to distribute to AAC stations and provides easy and quick access to parts down to task level for the different skilled workers in the AAC stations. The KFC kitting process has been categorized into A, B, and C types according to the size, shape, and weight of parts. The designed multi-level kitting process has been optimized to prevent intermediate inventory between different levels. The kitting cells are designed to be modular enabling easy and quick opening, closing, and reconfiguration under various demand from multiple AACs. The KFC-CLSM finds the optimal combination of kitting cell configuration and labor scheduling to save operational costs including kit assembly and kitting cell replenishment costs.

Avenues for further research and innovation include design improvements and validations with discrete-event simulation, instruction feeding for the multi-level kitting process, resource sharing in the hyperconnected supply chain network, and robotization of the kitting and inventory processes.

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Demand-supply alignment in supply chain networks with access to hyperconnected production options

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Abstract: Supply chain networks today comprise of various decentralized actors, subject to constantly evolving challenges and customer expectations, and operate in a volatile, uncertain, and disruption-prone environment. These challenges and complexities bring in informational and material flow distortions, making it hard to align demand and supply with agility. Building a centralized optimization model for such complex systems tends to be computationally expensive and unscalable for real-world application. With this motivation, we propose a novel, real-world applicable multi-agent-based approach for collaborative and agile demand-supply alignment, through dynamic prediction-driven planning and operational decision-making. We first demonstrate the applicability and configurability of our approach with a real-world supply chain network operating in a stochastic and disruptive environment, with the desired characteristics in congruence with the Physical Internet framework. We then demonstrate the simulation-testing capability of our approach by highlighting the potential benefits of leveraging a hyperconnected network of open certified production options.

Keywords: Demand-Supply Alignment, Multi-Agent Systems, Hyperconnected Networks, Supply Chain Networks, Production Options, Physical Internet

Conference Topic(s): logistics and supply networks; material handling; omnichannel & e-commerce logistics; manufacturing networks; PI impacts; PI modelling and simulation; technologies for interconnected logistics (Artificial Intelligence, machine learning, augmented reality, cloud computing, digital twins, collaborative decision making).

Physical Internet Roadmap (Link): Select the most relevant area for your paper: ☒ *PI Nodes,* ☒ *PI Networks,* ☐ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

1 Introduction

Supply chains today are complex networks with many actors such as suppliers, plants, distributors, and customers, that are often scattered around the world. Each of these supply chain networks (SCN) are interconnected as parts of global supply webs (Montreuil et. al., 2009) and as a result, their performance becomes the complex outcome of the interdependent efforts and actions of its constituent actors across the globe (Montreuil et. al., 2000).

With this complexity and continuously evolving challenges, it is inevitable to face with disruptions in information (bullwhip effect, inherent forecast errors, rapidly changing demand patterns), production (raw material, labor, machinery), or delivery (driver shortage, cargo ship problems) across the network. All these disruptions make it hard to align supply and demand

through the supply chain network, and companies see themselves either ending up with huge inventories piled up at their distribution and fulfillment centers or facing sale losses. Furthermore, the recent years pervaded with effects of the COVID-19 pandemic and a global supply crisis have highlighted the ever-increasing need for demand and supply alignment.

Achieving demand-supply alignment in a real-world SCN operating in a volatile, uncertain, and disruption-prone environment requires prescriptive planning and operations management, with the ability to dynamically adapt to evolving challenges and expectations (agility). Thinking that the planning and operation of SCNs can be represented as a single comprehensive model which can be solved optimally or near optimally in such a complex, stochastic, and large-scale context may often prove counterproductive, due to its modelling and computational complexities. So is thinking that high SCN performance in such a context can be achieved by distributing the planning and operational decisions to siloed actors with disconnected models and policies.

To overcome the complexities of centrally optimizing decisions within the SCN, and misalignment induced by decentralized decision-making, we propose a Physical Internet inspired hyperconnected approach for agile and collaborative demand-supply alignment in SCNs, with the ability to leverage external options to mitigate the effects of uncertainties and disruptions. The approach fundamentally recognizes the roles and responsibilities of each actor as a node in the network as well as the inherent interdependences between the decision scopes of agents, leveraging their collective smartness, enabling their collaborative decision-making through daily updated prediction and optimization models, and developing the collective agility of SCNs. The approach aims at continually optimizing demand and supply alignment for a complex large-scale SCN subject to a highly stochastic and disruptive environment.

Overall, this paper has two key contributions. Firstly, it introduces our novel multi-agent-based approach for demand-supply alignment optimization across various functions in a multi-echelon manufacturing and distribution network and highlights its wide applicability and ability to model networks in line with the Physical Internet paradigm. Secondly, it highlights the simulation-testing capability of our proposed approach and provides an empirical analysis of the benefits of utilizing a hyperconnected network of open certified production options for a manufacturing firm facing uncertainties and constraints in a disruption-prone environment.

The paper is structured as follows. Section 2 provides an overview of related literature. Section 3 details the overall approach and key constituents. Section 4 describes our experimental setup and simulation results. Finally, Section 5 shares conclusion and avenues for further research.

2 Related Literature

Demand-supply alignment is an important measure of a SCN's capabilities to optimize integrated supply chain management. This becomes furthermore pertinent in practice where they face continuously evolving challenges, uncertainties and disruptions stemming from demand, supply, and various operational aspects of the network (Ptak and Smith, 2018; Benaben et. al., 2021). Eruguz et. al. (2015) state that multi-echelon inventory optimization for integrated supply chain management improves the overall performance in terms of customer service level and inventory costs, although they induce significant computational complexity and are unable to model the various actors of the network intricately as in the real world.

Fox et. al. (1993) described an agent-based approach for integrated supply chain management, enabling decision-making on the strategic, tactical, and operational levels. They proposed that the next generation SCNs be distributed, dynamic, intelligent, integrated, responsive, reactive, cooperative, and adaptable among others. Multi-Agent Systems (MAS) is a modelling and simulation approach influenced by the complexity paradigm and is a suitable approach for

modelling real-world SCNs with multiple actors that are simultaneously acting, and continuously reacting to the actions of other actors (Dominguez et. al., 2020).

Researchers have widely used MAS to develop representative and detailed SCN models to predict and improve performance of various strategic, tactical, and operational decision-making capabilities. Montreuil et. al. (2000) originally proposed a MAS-based approach for operational planning that fundamentally recognizes the roles and responsibilities of each actor as a node in the network, and associates to each node a software agent, or a team of such agents, creating a network of software agents, with a high degree of development. Abid et. al. (2004) and Cheeseman et. al. (2005) utilized MAS framework for collaborative production planning and scheduling. Behdani et. al. (2019), Wang et. al. (2019), and Namany et. al. (2020) demonstrated resiliency improvement in critical supply networks, and provide a simulation framework for decision-makers to test various disruption scenarios and mitigation strategies.

Although MAS is a powerful tool for modelling and analyzing real-world distributed SCNs with constraints and options, there exists a gap in the existing literature in integrated supply chain management with dynamic predictive and decision-making methodologies to improve demand-supply alignment, when faced with uncertainties and disruptions. Furthermore, there is a lack of research in detailed modelling and simulation-based testing of complex SCNs with characteristics (modular containerization, collaboration, resource sharing, hyperconnected network) that enable decision makers to realize the empirical benefits of PI access and adoption.

3   Overall approach and key constituents

In this paper, we investigate the optimization of demand-supply alignment across SCNs subject to high volatility and uncertainty. We propose a collaborative and dynamic distributed-decision-making approach for end-to-end modeling, optimizing, and simulation-testing of a real-world manufacturing SCN using a Multi-Agent System (MAS) modelling approach.

We build on the approach proposed by Montreuil et. al. (2000) of recognizing the roles and responsibilities of each actor (facilities, humans, machines, software, or robots) as a node in the network, and associate to each node a software agent, or a team of such agents, creating a network of software agents. Our approach also encompasses the inherent interdependences between the decision scope of agents, and protocols for multi-agent interaction and accountability across the overall agent network. The decision-making process is facilitated with predictive and optimization models, along with smart and collaboration-enabling rule-based algorithms. The decision-making processes of the interacting agents consider their uncertainties, constraints, and options, with the goal of maximizing demand-supply alignment in their vicinity, and the overall system performance in both short and long-term horizons.

The fundamental driver towards achieving demand-supply alignment is the understanding that sales and demand are not necessarily the same. In an ideal setting where the availability of all products is maintained in the network, then sales and demand are identical. But, in practice, with the various uncertainties and constraints, it is not always feasible to maintain availability of all products. Then, demand must be estimated from sales by considering substitution, deferral, and lost sales in case of stock-out situations (Derhami and Montreuil, 2021). A *demand forecast agent* dynamically estimates demand, and subsequently generates demand forecasts for each product, category, and the overall portfolio in the different geo-spatial and temporal settings and propagates them in the network of SCN actors, enabling agile decision-making.

The key planning and operational decision to achieve demand-supply alignment is agile inventory management. We utilize autonomy-based forecast-driven replenishment strategies, where the medium and long-term decisions are flexible to be updated based on forecast updates.

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Autonomy denotes the ability of a SCN inventory-holding node to function seamlessly for t time units (e.g. 7 days) with r robustness (e.g. 99%), including protection relative to scenarios of interrupted supply and disrupted demand. Autonomy is computed from demand forecasts and updated daily by the *inventory agents* to estimate the inventory replenishment required.

Each manufactured product has a unique bill-of-materials consisting of different components and raw materials that go through various production processes. Raw materials and other resources necessary for production are provided by local and global suppliers that share their capacities, delivery lead times, and prices with corresponding agents. The production plants are responsible for ensuring smooth production and shipment of finished goods to distribution centers (DCs). Each production plant is modeled as a family of agents. The *resource agent* is responsible for maintaining resource and raw material availability. The *capacity agent* assesses production capacity and shares with pertinent agents to facilitate production planning. With the finalized plans, it coordinates production within the plant, and schedules jobs at work-centers.

The DCs hold inventory of finished goods to provide long-term network-wide resiliency in case of disruptions and replenish the fulfillment centers (FCs). The customer demand is satisfied by the FCs utilizing 3PL service providers, and hold enough inventory to meet customers in the short-term. The DCs and FCs are modelled as a family of agents. The *inventory agent* is responsible for keeping track of inventory levels, estimating replenishment required based on forecasts, and sharing the information with pertinent agents. The *transportation agent* schedules the various shipments to customers and within the network. As in plants, the resource agent ensures availability of resources for operational continuity. *Table 1* provides an overview of the agents associated to physical nodes of the SCN, that facilitate decision-making with their ability to perceive, react, and collaborate towards achieving their goals.

Table 1: Responsibilities of agents associated to physical nodes

Agent	Physical Node	Tracking Metric	Responsibility
Demand Forecast Agent	Customers	Sales, inventory, promotions	Estimate demand from sales, update demand forecasts daily
Inventory Agent	FC, DC	Inventory, forecasts	Estimate inventory replenishment required
Capacity Agent	Plants	Production capacity, production plans	Share available capacity, schedule production as plan
Resource Agent	FC, DC, Plants	Resources, raw materials	Procure resources based on requirements plan
Transportation Agent	FC, DC, Plants	Transportation capacity	Share available capacities, facilitate shipments on-time

We utilize *coordinator* agents that are responsible for making the connection between the actions and decisions of different agents to ensure that the collective agent decision is feasible and enhances demand-supply alignment in their vicinity, while preventing individual agents from impacting a deviation in the SCN's path towards its global objectives / goals. The

description of three primary *coordinator* agents in the SCN, namely *Fulfillment (FNC), Distribution (DNC)* and *Production (PNC) Network Coordinators* is as follows:

1. *Fulfillment Network Coordinator* facilitates the decision-making for the agents associated to the network of FCs. It manages two primary decisions: on-demand customer order fulfillment from closest FC with inventory availability; and daily FC replenishment in modular containers from DCs by collaborating with the *DNC*. FC replenishment is done by considering the unconstrained replenishment request (based on short-term autonomy at each FC) from the FC *inventory agents* and available inventory from *DNC*. The coordination enables equitable share of supply from DCs such that the minimum autonomy across FCs is maximized, while respecting full modular container constraint for all shipments as pertinent. In the case of excess inventory at any FC due to change in demand pattern, transshipments between FCs are allowed to maintain inventory balance among the FCs.

2. *Distribution Network Coordinator* manages the inventory replenishments at DCs. Contrary to FC replenishment, DC replenishment is done in coordination with *PNC* focusing on long-term demand forecasts to prevent potential lost-sales due to lack of inventory in case of disruptions and preparation in advance for upcoming seasonalities. The agent aims for medium-term autonomy at DCs to be able to serve FC requests. Since DC replenishment is constrained by production capacity and capabilities of the plants, it is crucial to utilize production capacity efficiently to build adequate inventory that is aligned with the forecasted demand. Aggregated weekly production capacities of the production plants are shared with the agent by capacity agents of each plant. In addition to production capacity, which directly depends on raw-material, labor, resource, and machinery availability, minimum and maximum batch sizes at plants also impacts the decision processes. DC replenishment plans are prepared by considering production, transportation, and autonomy constraints along with the objective of maximizing long-term profit under uncertainty and disruptiveness. Transshipment between distribution centers is considered as alternative sourcing option in the case of unbalanced inventory or autonomy levels between DCs due to unexpected demand realizations or disruptions in production and delivery.

3. *Production Network Coordinator* manages production planning in the plants network. The agent receives the production capacity at each plant along with the replenishment requests of DCs. The production plans are finalized with *DNC*, and assigned to production plants as work-orders, after detailed examination of the production plant capacities and schedules. Since an aggregated capacity model is shared with distribution network coordinator, the requests are expected to be feasible to mostly produce on-time. In case of infeasibility, the production coordinator agent allocates the capacity to requested items in a way that minimizes the deviation from target autonomy levels at distribution centers. In addition to dedicated production plants, there are open certified production centers (OCPC) that provide contract-based production capacity and enable hyperconnected production.

The proposed approach relies on information sensing, daily updates of predictive algorithms, optimization models and solution methodologies for each agent to its support decision-making role according to developed collaborative protocols. The approach leverages the agent network's collective smartness to enable the collaborative decision-making of each agent, and to develop the collective agility and resilience of the supply chain network. *Figure 1* shows our multi-agent network, where the Agent layer corresponds to the physical nodes in the network and is responsible for the functional decision scope for each node in the Physical layer.
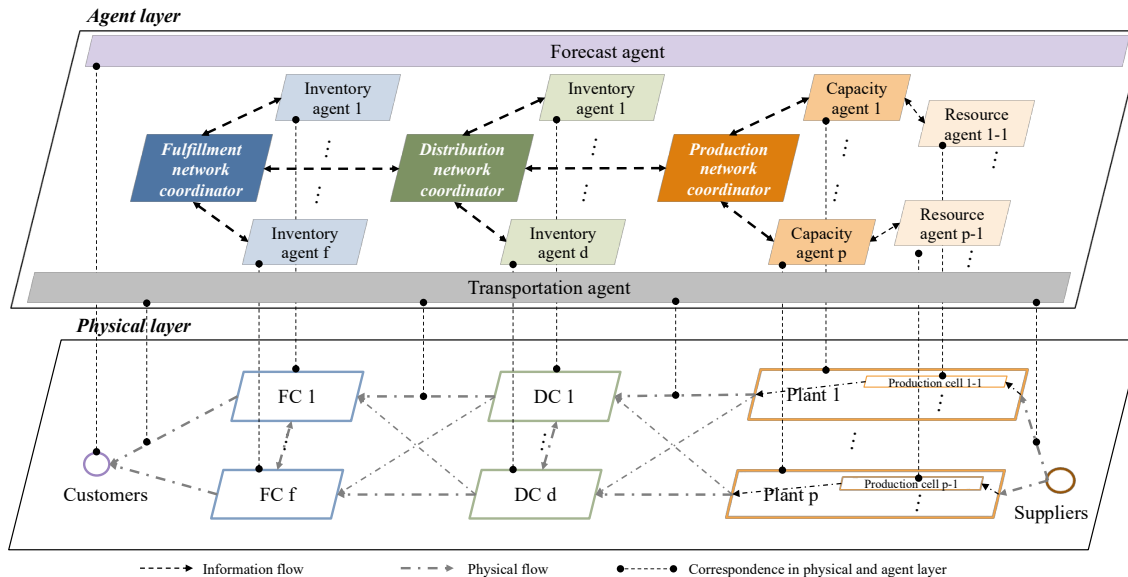
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Figure 1: Multi-agent system for the hyperconnected supply chain network

We attain informational hyperconnectivity through pertinent information access to agents based on their functional requirement, and furthermore through collaborative engagement and negotiation between agents towards collective decision making (Montreuil et. al., 2000; Montreuil et. al., 2012). The agents undertake various planning and operational decisions regarding inventory management, production planning, transportation, and order fulfillment. Physical hyperconnectivity in the system is enabled with transshipments of raw materials, intermediate and finished goods between the nodes, and access to potential production options with OCPCs through long-term contracts or spot capacity allocation (Montreuil et. al., 2012).

4   Experimental Setup and Results

In this section, we describe the experimental setup inspired by the case of one of our industrial partners, and leverage an agent-oriented simulator to dynamically experiment the collective performance of our proposed hyperconnected approach to optimize demand-supply alignment in a complex real-world large-scale supply chain network subject to a highly stochastic and disruptive environment.

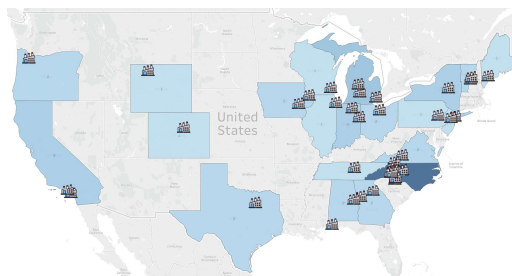*Figure 2: Nodes in the supply chain network*

Figure 3: Potential network of OCPC facilities

Our industry partner is a major producer of a portfolio of ready-to-assemble household furniture and serves customers in North America. Customer orders are fulfilled from five FCs, with orders being placed exclusively through e-commerce companies or the company's website, preventing backlog of orders. The FCs are replenished from three DCs, which are in turn replenished from three production plants. *Figure 2* shows the geographical distribution of the

nodes of our industry partner's SCN. In addition to the dedicated plant network, we consider the accessibility of a hyperconnected network of Open Certified Production Centers (OCPC) that provide long-term capacity allocation contracts, as shown in *Figure 3*. All movements of raw materials to OCPC facilities and finished goods within the network are modeled to be done using modular containers, in line with the Physical Internet framework.

4.1 Demand

With the aim of highlighting the capabilities of our proposed approach in a disruptive environment, we here consider a single product that is a top-seller. *Figure 4* shows the geographical location of customers for this product, with the color based on the closest FC. We run the agent-oriented simulation for three years: pre-disruption period (2019), COVID-19 disrupted period (2020), and post-disruption period (2021). The selected product displays a varying pattern in the three periods, with considerable stock-out durations during 2020. We begin by estimating the demand during these stock-out periods, using exponential smoothing based forecasting method (Derhami and Montreuil, 2021). *Figure 5* shows the daily sales and estimated demand for the product in the planning horizon and observe ~10.7% lost sales.
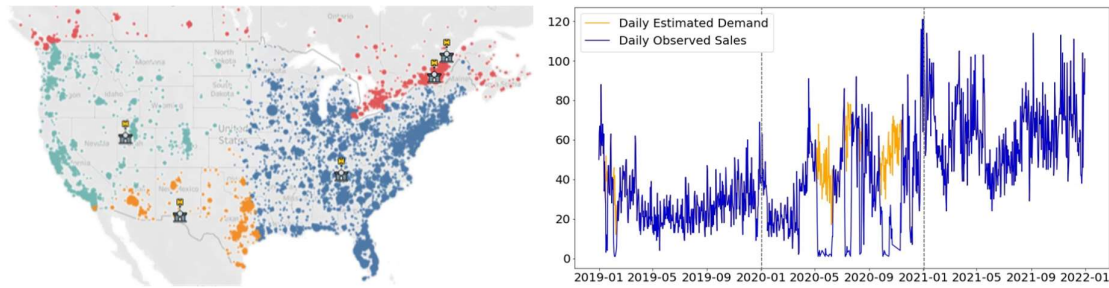

Figure 4: Geographical distribution of demand Figure 5: Daily observed sales and estimated demand

With the estimated demand, we progress to generating demand forecasts with one-year horizon, by considering the level, trend, and various seasonalities based on historical information. We utilize the Bouchard-Montreuil (BM) method (Bouchard and Montreuil, 2009) adapted from the Holt-Winters method (Holt, 1957; Winters, 1960), which considers the various seasonalities based on calendar days and by allowing defining the seasons to be based on the similarity of patterns. Forecasts are dynamically updated daily to effectively capture the demand. *Figure 6* illustrates the evolution of our demand forecasts, where each forecast *"tornado"* is the cumulative demand forecast generated on a given day for the one-year horizon. Orange regions denote the confidence intervals, and the dotted line denotes the realized demand. Even though order backlog is not permitted, we highlight cumulative forecast performance as it is used by the agents for their decision-making.
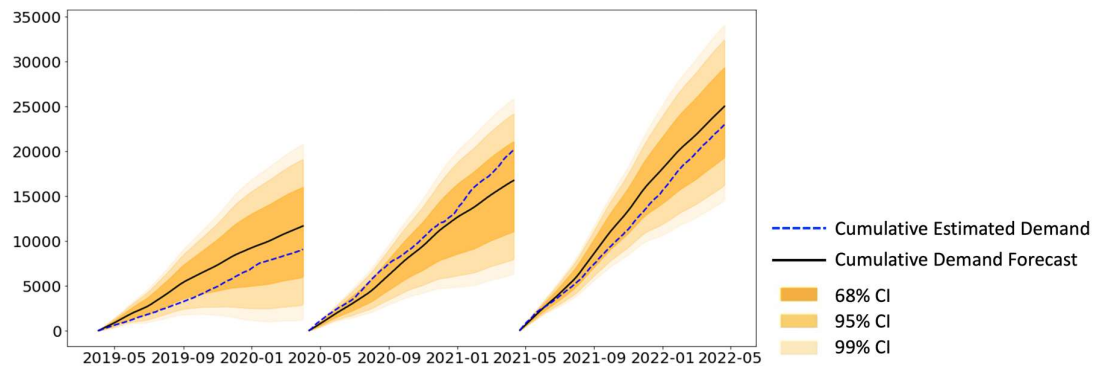

Figure 6: Evolution of cumulative demand forecasts

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4.2 Supply

We model supply with the production capacity of the plants. The plants operate for a fixed duration daily, and we estimate the daily production capacity considering historical allocation of resources to the selected product, and required capacity based on forecasts generated at the start of the planning horizon. As shown in *Figure 7,* COVID-19 pandemic impacted the SCN in late March 2020, and decreased the production capacity to zero for a month. The production capacity recovered gradually over the next months. The first month with zero capacity represents the imposed lockdowns. The following days with less than full capacity represent supplier problems, limited lockdowns, and labor shrinkage due to illness or regulations. In order to contain the complexity of this exploratory experimental setup, we assume that raw material availability is ensured in the plants, to support short-term production planning based on aggregated capacity.
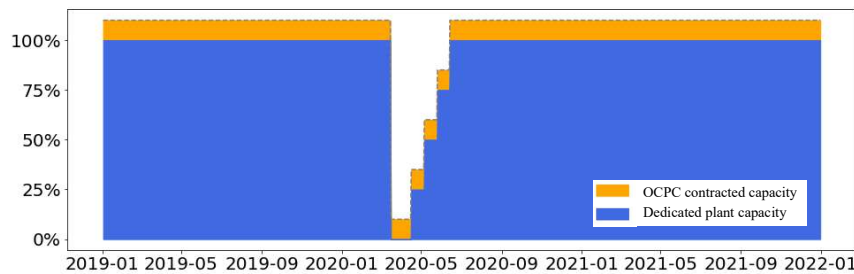

Figure 7: Daily production capacity at dedicated plants and open certified production centers

Although the production shutdown was beyond the control of the decision makers, they became aware of such a possibility in the near future early on, which we will utilize as a capacity disruption signal to demonstrate the benefit of proactively reacting to disruption signals. Additionally, the OCPC facilities offer additional capacity (20%, as shown in *Figure 7)* through long-term contracts, and serve as options during normal and disrupted periods. In this paper, we assume that from the network of OCPCs, we are assured production capacity during all periods, and becomes a potential for further sensitivity analysis on the reliability of OCPCs and disruption scenarios.

4.3 Experimental parameters

We model inventory replenishment to the various nodes of SCN based on autonomy, derived from demand forecasts. The coordinator agents aim to maintain minimum 7-days autonomy at the FCs and minimum 14-days autonomy at the DCs. All shipments between nodes are modelled as stochastic random variables, with the mean estimated based on travel time between nodes based on the average truck speeds in North America.

4.4 Experiment objective

Firstly, with the aim of demonstrating the applicability of our proposed approach and the improvement in demand-supply alignment in a real-world hyperconnected SCN, we highlight the experimental capability of our approach by comparing performance metrics in the various aforementioned periods for the following four DC replenishment strategies:

1. **Myopic Lean**: The DCs maintain a myopic view, and consider only the upcoming week(s) in estimating their replenishments based on autonomy for production planning
2. **Farsighted**: The DCs maintain a farsighted view, and consider the long-term forecasts along with autonomy required to prepare in advance for upcoming seasonalities

3. **Farsighted (Signal)**: Along with maintaining a farsighted view, the DCs proactively react to a potential plant shut-down signal to mitigate the effects of the supply disruption
4. **Farsighted (Signal, OCPC)**: Along with a farsighted view and response to disruption signal, the DCs utilize the network of hyperconnected OCPC facilities when network production capacity is unable to cater to the replenishment required by DCs

Secondly, we conduct a sensitivity analysis of capacity consideration and costs of utilizing the hyperconnected OCPC facilities, on SCN performance metrics and potential benefits.

4.5 Results

We measure demand-supply alignment performance of the DC replenishment strategies under three primary dimensions: demand fulfillment rates (lost sales), misaligned fulfillments (from further-away FCs) and average inventory levels (product availability), as shown in *Table 2*.

Table 2: Performance comparison of various DC replenishment strategies

(Pre: Pre-disruption 2019, Dis: COVID-19 disruption 2020, Post: Post disruption 2021)

DC replenishment strategy	Demand Fulfillment			Misaligned Fulfillment			Daily Average Inventory		
	Pre	Dis	Post	Pre	Dis	Post	Pre	Dis	Post
Myopic Lean	100%	86%	76%	0%	27%	42%	1,546	522	181
Farsighted	100%	100%	82%	0%	<1%	31%	3,837	2,991	285
Farsighted (Signal)	100%	100%	89%	0%	0%	15%	3,837	4,237	789
Farsighted (Signal, OCPC)	100%	100%	98%	0%	0%	3%	3,776	3,896	1,606

The SCN is able to satisfy almost all the demand from preferred fulfillment centers during the pre-disruption period. The consequences of the supply and demand disruption are profound for the myopic lean approach where it only satisfies 86% of the demand with 27% of them fulfilled from further-away fulfillment centers. The other approaches are more resilient to disruption as they can maintain their performance close to the pre-disruption period. Post-disruption period comes with an increase in demand as can be seen in *Figure 5*. With all approaches there is a decrease in performance dimensions, however, the benefit of maintaining a farsighted view and utilizing OCPCs on mitigating the impact of the demand disruption is evident.

Next, we investigate the impact of the degree of reliance on the hyperconnected OCPC network. *Figure 8* illustrates the network-wide average daily inventory levels and demand fulfillment rates along with increasing OCPC production capacities for farsighted sentient approach. Here, the capacity ratio denotes the ratio of contracted capacity to the capacity at SCN's production plants. We observe that with just 15% additional contract capacity, all lost sales are eliminated.

The average daily inventory level has an overall decreasing trend with reliance on OCPCs. The fluctuation in the trend around 20% capacity ratio is a result of the sudden unforeseen demand peak in early 2021 and is a characteristic of the demand scenario considered. With a lower capacity ratio, the SCN builds inventory in preparation for the upcoming seasonalities, when it perceives it won't be able to meet autonomy in the future with the capacity available. With 20% capacity ratio, the SCN has enough capacity, so it doesn't need to produce in advance, but when faced with the demand jump, and consequently a short-lived jump in the demand forecasts, it is restricted by capacity. On the other hand, with higher capacity ratios, the SCN produces

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excess inventory driven by the high demand forecasts. With capacity ratios over 40%, the SCN has enough capacity to cater to the upcoming long-term demand and doesn't need to produce much in advance, hence maintaining lower average inventory levels.
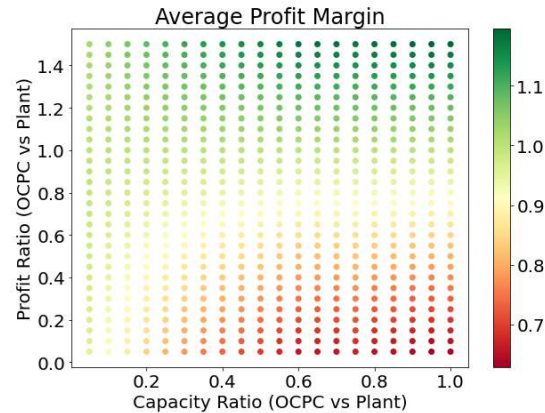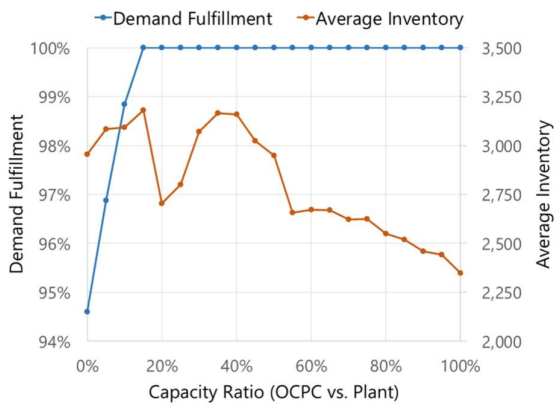

Figure 8: OCPC sensitivity on inventory and service   Figure 9: OCPC sensitivity on profit margin

Next, we conduct a sensitivity analysis on average profit margin per unit of the product with capacity ratio and profit ratio, which is a measure of the addition cost or saving from producing at OCPCs as compared to SCN's plants. *Figure 9* shows the change in average profit margin, where value of 1 represents no change on profit margin and values larger than 1 implies increased profit margins. We observe that for lower profit ratios, i.e., when producing at OCPCs is costlier than producing at plants, the profit margin decreases with increasing capacity ratio. On the contrary, for higher profit ratios, where it is cheaper to produce at OCPCs than at plants, higher reliance on OCPCs improves the profit margin, while also decreasing average inventory levels and eliminating lost sales.

5   Conclusion

In this paper, we focus on the supply-demand alignment of a supply chain network (SCN) in a volatile, highly uncertain and disruption-prone environment. To overcome the complexities of centrally optimizing decisions within the SCN towards this goal, we propose a responsibility-oriented collaborative decision-making structure with agents that can make decisions regarding their own responsibilities, while collaborating with each other. The multi-agent system (MAS) structure we propose distributes the responsibilities to agents, and each agent has a defined set of performance criteria, required input-outputs, and protocols for communication with other agents. To prevent making infeasible or local-optimum decisions at agent-level instead of optimizing the global objectives, the impact of each agent's decisions on other agents is also incorporated into decision-making processes by using coordinator agents and allowing communication/negotiation between agents. The continuous communication (information sharing) between the agents helps to decrease the bull-whip effect (limits the disruptions in information) and allows cooperative alignment of supply and demand plans.

Daily update of demand forecasts and distributed decision-making processes enable the system to rapidly react to disruptions that have occurred or sensed. The decisions or problems that would be difficult to model and solve with all the details by using a central decision-making approach can be modelled and solved with finer granularity and higher sensitivity by agents. Furthermore, the SCN model can be tested under various disruption, helping in identifying the configurations and strategies that facilitate the desired performance, resilience, and agility.

As a future research direction to effectively navigate in the unstable supply chain context, the model needs to be equipped with sentient capabilities. This involves enabling the system to perceive, understand, and analyze the situation, and transform into a goal-oriented system that can continually define and adjust its objectives based on the dynamic circumstances. Overall, to enable agile and resilient demand-supply alignment in SCNs operating in the unstable context, we propose a goal-oriented sentient system (GOSS) that can orient itself, argue its decisions, and legitimize its actions based on dynamic targets and sentient capabilities.

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Modeling and Simulation of an Agile Assembly Center in a Physical Internet inspired Manufacturing System

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Abstract: Globalization, high competitiveness, and highly customized products are factors that increase the complexity of product development and production systems. Such complexity makes conventional mathematical or analytical models unsuitable for properly analyzing such systems, for which simulation emerges as an alternative for evaluating, designing, improving, and operating complex systems. This paper focuses on the design, modeling, and simulation of an agile assembly center (AAC) that produces durable big-sized products with the capacity of serving several projects and clients concurrently leveraging Physical Internet (PI) concepts while embedding the decision-making agents' intelligence. This work is the cornerstone for implementing a digital twin of an AAC that will help make operational, tactical, and strategic decisions towards improving the performance of PI inspired assembly facilities.

Keywords: Physical Internet, Manufacturing, Modeling, Simulation, Logistics Systems

Conference Topic(s): Business models & use cases; material handling; Modularization; manufacturing networks; PI modelling and simulation.

Physical Internet Roadmap: Select the most relevant area(s) for your paper: ☒ *PI Nodes,* ☐ *PI Networks,* ☐ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

1 Introduction

Globalization, high competitiveness, and highly customized products are factors that increase the complexity of product development and production systems (Ong et al., 2008). Such complexity makes conventional mathematical or analytical models unsuitable for properly analyzing such systems, for which simulation emerges as an alternative for evaluating, designing, improving, and operating complex systems (Law, 1991; Mourtzis, 2020).

One of the biggest challenges is to properly design, optimize and manage complex logistics systems at a large scale, for which Physical Internet (PI) offers a novel approach towards an order-of-magnitude improvement in efficiency and sustainability. The PI was first described by Montreuil (2011) as an innovative vision for the future of logistics where goods and materials are packaged and transported in standard containers, much like the Internet transmits data in standardized packets (Ballot et al., 2013).

For improving the performance of logistics systems, the Physical Internet concept is materialized through a multi-tier hyperconnected logistics web such as that presented by Campos et al. (2021). These types of networks can be comprised of production, storage, assembly, and transportation nodes, in which the last node in the network is conveniently located close to the end consumer. In this paper we focus, in the context of hyperconnected supply chain networks, on the design and performance assessment of that last node in the context of manufacturing. For this, the concept of agile assembly centers (AACs) is presented,

as a manufacturing facility that can be open to multiple stakeholders and concurrently serve the needs of several clients for small-series production of complex and large products. Such facilities are often associated with the manufacturing of large durable goods, such as in the specialized vehicle, heavy machinery, integrated automation, energy equipment, and building industries.

Conventionally, production facilities for complex and large durable goods tend to be extensive in area and expensive to build and equip, which entails that the products need to be transported over long distances to the different clients, yielding a higher logistics cost. AACs are meant to be temporary and easy to set up in locations close to the clients, reducing the logistics costs of transporting full assembled final products.

Several studies have been published regarding simulation of conventional assembly facilities for assessing and improving performance of the system as seen in Malega et al. (2020), as well as of specific system elements such as the facility layout (Yang & Lu, 2023), or a given production line with individual stations (Afifi et al., 2016). Most of these papers develop simulations through commercial specialized software, which does not allow for full customization or embedding the intelligence of decision makers properly. This paper extends the scope and upgrades the published approaches and models, focused on the design, modeling, and simulation of an AAC with the capacity of serving several projects and clients concurrently leveraging PI concepts while embedding the decision-making agents' intelligence.

2　PI Inspired Agile Assembly Centers

A typical AAC topology is presented in Figure 1. The process starts when suppliers send kitted components and materials in PI modular containers to the facility. The use of kits in modular containers is key in this context for protecting the integrity of the kits, optimizing the space in both trucks and inventory, facilitating the assembly worker tasks, and enabling reverse logistics which reduce waste induced by kit packaging. The kits are received in the inventory management center, from which they will be distributed over the different centers some time before they are required in the assembly process. One of those centers is the Subassemblies center, in which subassemblies that will be part of other assemblies are produced and distributed. The remaining centers in the facility will be operated as a hybrid between parallel
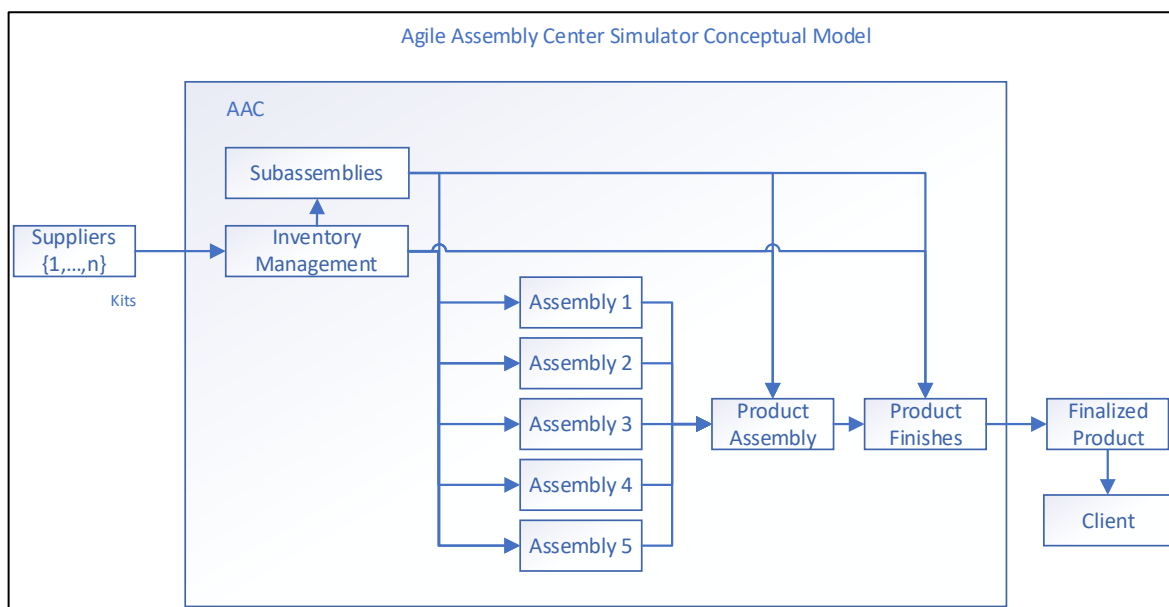

Figure 1. Illustrative Agile Assembly Center process flow diagram

moving lines for the main assemblies, a moving product assembly center where assemblies are used to build the product, plus a stationary center in charge of product finishes.

Several models are required for designing and operating such a facility. As synthesized in Figure 2, the set of models includes the product, assembly process, organization, technology, assembly capacity, assembly operations, logistic process, and logistic operations models, with the simulator as a tool to assess the performance of the system designed.
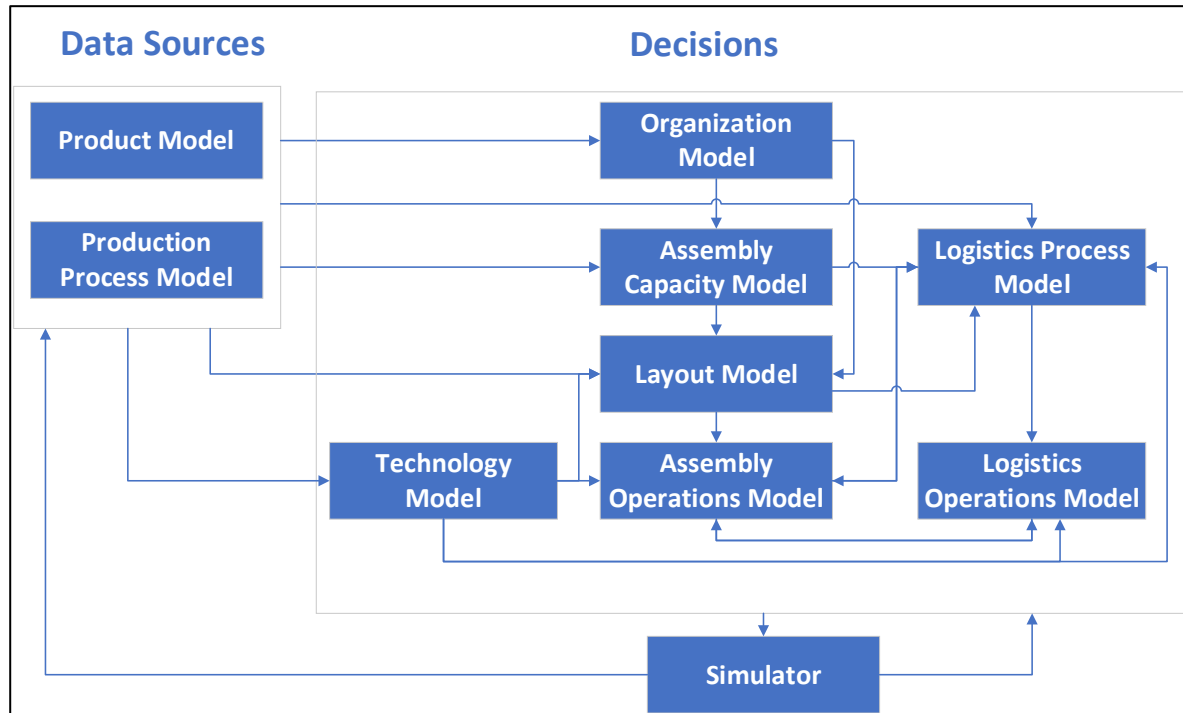

Figure 2. Model structure for designing an Agile Assembly Center

The product model defines the characteristics of the object to be assembled, while the production process model describes the tasks and resources required to assemble the product. The organization model defines the structure of the facility as shown in Figure 1 and the basic operation concepts. The technology model describes the technology available for moving and processing objects. The assembly capacity model corresponds to the line balancing, where the required number of stations is defined. Knowing the number of stations, the layout model can be built, assigning spaces to workstations in the plant floor. Once this process is done, the assembly operations model defines the schedule of the resources required to perform the assembly tasks. Similarly, on the logistics side the logistics process model defines the tasks to be performed to ensure all objects are where needed when needed, and the logistics operations model schedules the resources required for performing the tasks.

3   A high-fidelity simulator of an Agile Assembly Center

In this paper we make a distinction between a simulation model and a simulator. A simulator in this context is a simulation tool capable of modelling different designs, implementations and scenarios of a given system, while a simulation model will refer to a specific instance implemented in the simulator. This distinction is important as for implementing a simulator, the model needs to be parametrized to create various simulation models by varying the parameters without the need to modifying the simulation source code. In the context of complex systems, a simple parameter dashboard is not enough for capturing the dynamics of a full

system implementation, for which external data sources are required. For instance, different operation model instances can be implemented in the simulator by changing input files that contain the workers instructions or the production plan. The AAC simulator uses a mix of two simulation paradigms: agent-based simulation and discrete-event simulation like that presented by McGinnis et al. (2021). Figure 3 shows the agent architecture, where the entities (units of flow), resources and decision-making agent are presented.
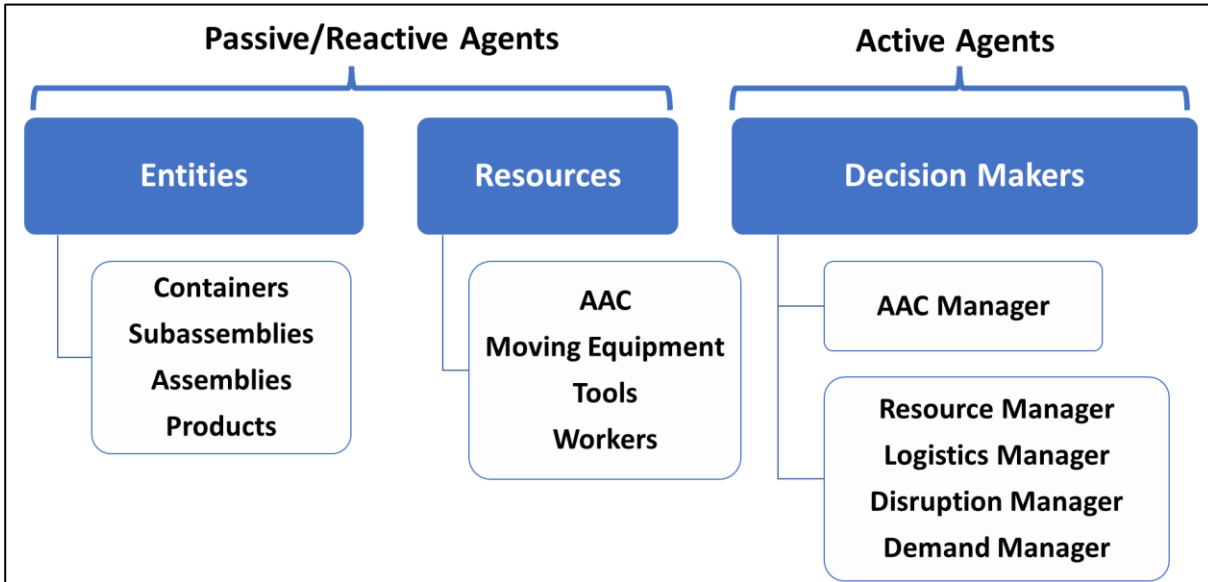

Figure 3. *Illustrative Agile Assembly Center Simulator Agent Architecture*

Similarly, Figure 4 presents the logic and data architecture of the model which uses external data sources that come from the decision models identified in Figure 2 to enable the decision-making agents to manage operations in the AAC. In this implementation, the product, assembly process, organization, technology, assembly capacity, assembly operations, logistic process, and logistic operations models are implemented offline and are an input to the model that is used by the decision-making agents to generate actions and tasks in the model. Although the decision logic might be hard coded in the model, this strategy enables to implement different scenarios with little or no changes in the source code.
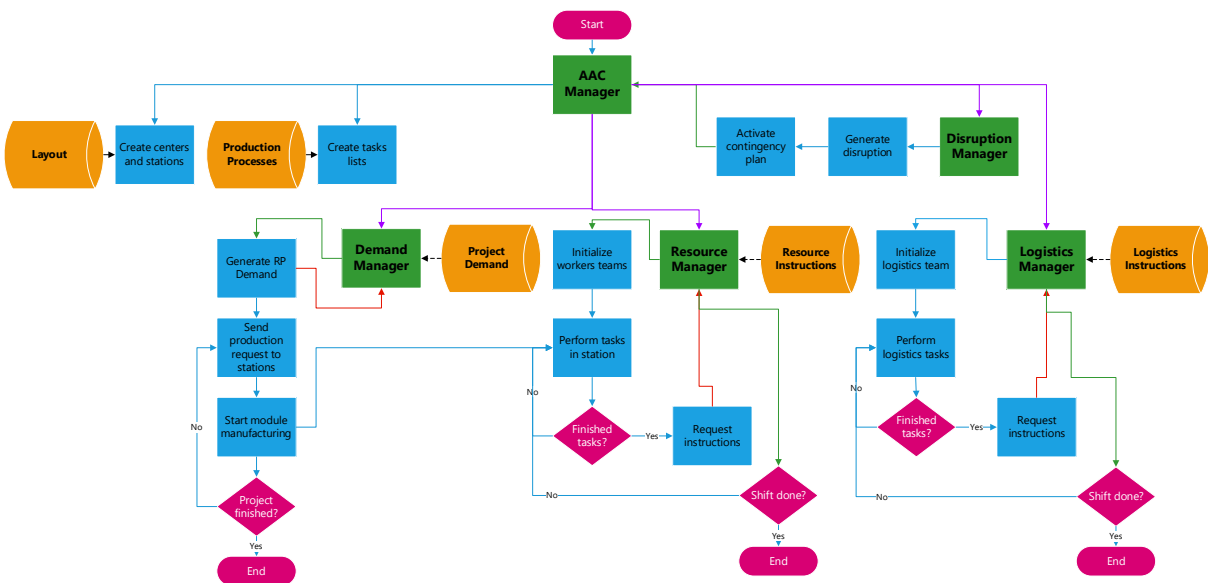

Figure 4. *Agile Assembly Center Simulator Logic Architecture*

Notice the layout, production process, project demand, resource instructions and logistics instructions all come from external data sources, which means the simulator is capable of modeling various instances of an AAC that has a similar operation concept just by changing the data inputs. Various experiments can be made based on this architecture without changing the source code of the model, for instance, different demand scenarios can be tested for a given facility implementation. Regarding the production process, changes in the process can be tested to assess the impact of changes in the product producibility. Additionally, different layouts for the same project can be tested, understanding changes in the layout will affect the assembly operations model and the logistics process and operations models. Another interesting experiment is to test different assembly process and operations models for the same demand and layout, to assess the efficiency of different optimization logic. Similarly, different material handling and logistics logic can be tested towards performance enhancement.

4   Simulation model implementation

The model structure presented in the previous section was implemented in the Anylogic® 8.8.0 simulation software for a large durable products AAC designed for an industry partner. The facility was designed for producing 8 assembled products a day with a takt time of one hour, assuming a single daily shift of 8 hours a day. The AAC consists of 17 centers, with a total of 54 stations distributed between subassembly, assembly, product assembly and product finishing centers, including buffer stations after certain critical stations that are more prone to disruptions. As a takt time driven facility, there is space in each station for storing two takt times worth of kits and/or subassemblies, meaning every takt time one inventory position needs to be replenished by the logistics workers, making sure every kit or subassembly will be ready at the stations two takt times ahead of when the assembly will be performed.

It is of interest for the company running the AAC to implement a pilot in the designed facility for assembling one product as a test. The product selected for the pilot is composed of 9 assemblies, which are assembled into a volumetric product which required finishing work before being ready for shipping. For this purpose, the decision models were run for a scenario producing a single product in the facility and used as input into the simulation model. For this implementation, the simulation model does not consider stochasticity on the processing times, the demand, or disruptions to the facility operations. The objective of this experiment is to validate the production process, making sure the assembly process and operations models are feasible and yield the expected performance.

5   Model Validation

The simulation model was run for 20 working hours considering a deterministic scenario without stochastic processing times or disruptions, enough time for a single product to be assembled. For validating the production process, three procedures were applied: visual verification of resource and product movement, task by task process verification and output statistics analysis. For the visual verification a 3D animation was built in the simulation model as seen in Figure 5, which allows to follow the movement of workers, assemblies, and volumetric product, verifying all objects are moving as intended when intended.

Additionally, each individual task can be revised during run time, as seen in Figure 6. In the figure it can be observed for each task is possible to know the task's general information, duration, resource requirement, start time and current status. For each individual object, the full set of assembly tasks can be individually checked to ensure all processes are being executed correctly. The output statistics analysis also helps to validate these processes overall.
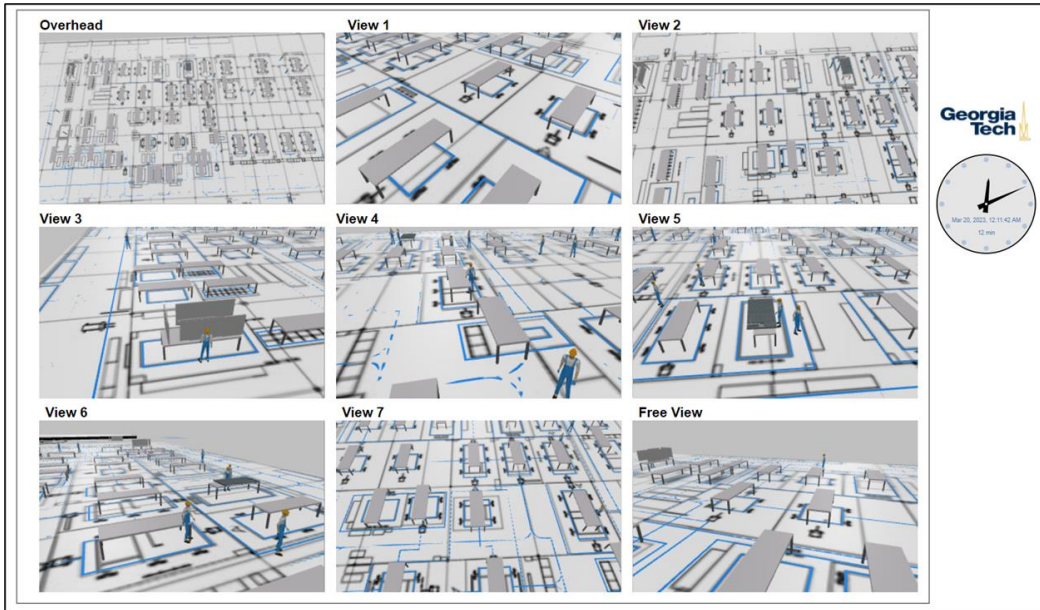
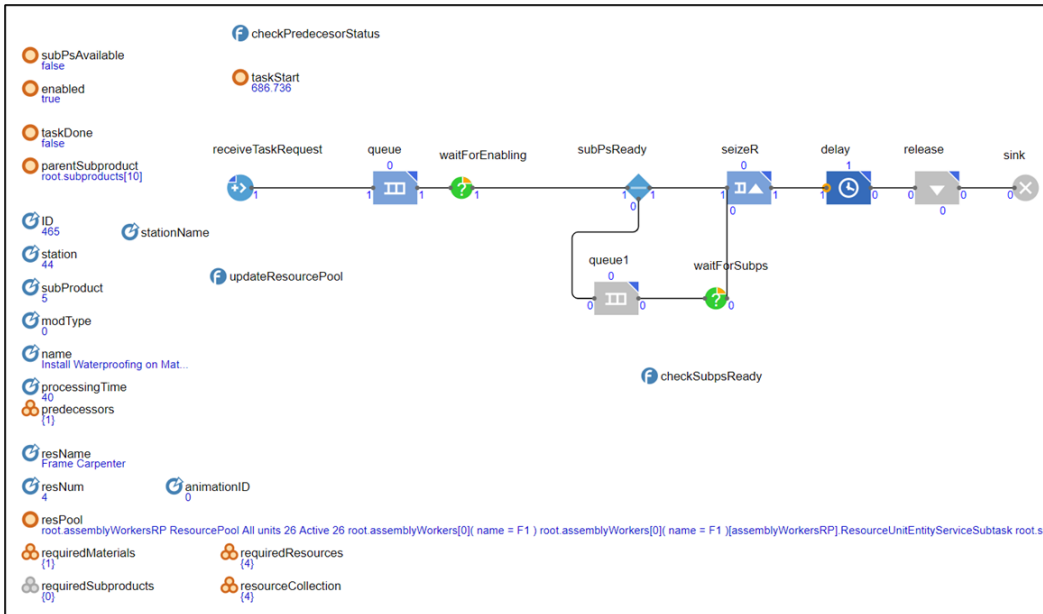*Figure 5. Simulation Model 3D Animation Snapshot*

Figure 6. Individual task status

For the output statistics analysis, two main variables were studied: the labor utilization and the total worker assembly time per subproduct (assemblies, initial product, and finished product). The results of this exercise are synthetized in Table 1 below. From the results it could be verified the labor utilization and work assignment has a perfect match with the production planned, which is expected as this scenario considers no stochasticity. Nevertheless, if any process would not be implemented properly these values would not have a perfect match, thus, this analysis indicates the processing time, precedencies and resource assignment are correctly modeled. Through this analysis, we can conclude the model is valid and therefore ready to test different experimental scenarios.

Table 1. Results of Deterministic Simulation-Based Experimental Feasibility Assessment of Agile Assembly Center Design

KPI	Planned	Simulated
Labor Utilization	17.57%	17.57%
Assembly 1 Worker/Minutes	182.08	182.08
Assembly 2 Worker/Minutes	340.33	340.33
Assembly 3 Worker/Minutes	145.33	145.33
Assembly 4 Worker/Minutes	58.67	58.67
Assembly 5 Worker/Minutes	68.67	68.67
Assembly 6 Worker/Minutes	84.5	84.5
Assembly 7 Worker/Minutes	194	194
Assembly 8 Worker/Minutes	214.33	214.33
Assembly 9 Worker/Minutes	155.33	155.33
Volumetric Product Worker/Minutes	2,002.4	2,002.4
Finished Product Worker/Minutes	350	350

6   Conclusion

The main contribution of this paper consists in presenting the design, architecture, and implementation of a discrete-event agent-based high-fidelity simulator of a complete agile assembly center in the context of hyperconnected supply chain networks. The model built is parametrizable, flexible and reusable, modeled at a fine granularity level, including agents' behavior while emphasizing in the decision-making process, how this affects the systems' performance, and assesses the capability of leveraging PI concepts to deal with the assembly of customized big-sized products. This work is the cornerstone for implementing a digital twin of an AAC that will help make operative, tactical, and strategic decisions towards improving the performance of PI inspired assembly facilities. This paper offers insights into the future of durable big-sized product assembly and the role that the PI could play in shaping this future.

7   Future Work

Now that the simulator has been implemented and tested, the next step is to add stochasticity to the model in terms of processing times, and potential disruptions. In order to add the disruptions, contingency plans need to be in place, such that the decision-making agents can adjust operations to deal with such disruptions. Various additional experiments can be made using the simulator, testing different demand scenarios, production processes, layouts, and optimization logic. This simulator can be used to create a digital twin of a given AAC, but an extension to the model is required where the current state of tasks, resources and objects can be used as an input to start a simulation from any given point in time.

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Physical Internet-driven last mile delivery: Performance requirements across people, process, and technology

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Abstract:

The concept of the physical internet (PI) is changing and reshaping the business environment of logistics along with the cutting-edge technologies and innovations and is rapidly evolving towards last mile delivery (LMD). Implementing new solutions in LMD are particularly essential to meet growing demand, respond to increased operational complexity and enhance efficiency and sustainability. The PI-driven LMD requires new features and capabilities to combat all these challenges. Therefore, there is a need to understand the performance requirements that contextualize the relationships among people, process, and technology (PPT). In this study, a PI-driven LMD framework based on PPT theory is proposed. First, a systematic literature review is conducted to explore the state of the art of academic and practitioner articles and projects on LMD and PI. Then, a thematic analysis is carried out to analyze the requirements of the PI-driven LMD from the perspective of PPT to interpret performance challenges and successes. The main contribution of this study is to investigate the performance related requirements of PI-driven LMD according to PPT perspectives. The findings show that PI-driven LMD improves delivery performance, security, privacy, transparency, and traceability performance as well as customer service performance.

Keywords: *last mile delivery, physical internet, collaboration, hyperconnectivity, technology adoption, performance, logistics operations, city logistics*

Conference Topic(s): *business models & use cases; distributed intelligence last mile & city logistics; omnichannel & e-commerce logistics; PI impacts; technologies for interconnected logistics (5G, 3D printing, Artificial Intelligence, IoT, machine learning, augmented reality, blockchain, cloud computing, digital twins, collaborative decision making).*

Physical Internet Roadmap (<u>Link</u>): *Select the most relevant area for your paper:* ☐ *PI Nodes,* ☒ *PI Networks,* ☒ *System of Logistics Networks,* ☒ *Access and Adoption,* ☐ *Governance.*

1 Introduction

The Physical Internet (PI) is a new logistics paradigm that aims to create a hyperconnected and standardized global logistics network by applying the principles of the digital Internet to physical objects and transportation systems (Montreuil 2013). The PI vision allows for large-scale collaboration among logistics stakeholders, including shippers, carriers, warehouse operators, and retailers through shared assets, information, procedures, and standards, as well as flow alignment (Montreuil, 2011). Due to these characteristics, hyperconnectivity reduces the separation of individual companies and enables them to collaborate more closely in their

delivery operations. Hyperconnectivity helps create a more efficient and resilient logistics network.

Last-mile delivery (LMD) logistics, particularly in urban areas, is often inefficient and costly. It is estimated that up to 40% of the transport costs for a product are incurred in the LMD (Mangano et al., 2021). Additionally, city logistics is responsible for over 20% of urban traffic congestion (World Economic Forum, 2020), which can cause delays and increase the overall cost of delivery. The continued growth of e-commerce has also led to an increase in the number of smaller deliveries being made more frequently to more destinations. These challenges can potentially result in inefficiencies such as idle capacity of assets, poor use of transport mode infrastructure, and inadequate and non-integrated business systems (Plasch et al., 2021). These challenges can be overcome by applying a PI in LMD that supports a structural shift from the current way of operating to an open and shared delivery system.

This study proposes a theory-based framework for PI-driven LMD to investigate the performance requirements of the concept from the viewpoint of people, process, and technology (PPT). The framework aims to provide insights into the challenges and successes of PI-driven LMD and to contextualize the relationships between PPT and their impact on system performance.

The study includes a systematic literature review combined with a thematic analysis to identify the performance requirements of PI-driven LMD. The findings suggest that PI-driven LMD can improve (i) delivery performance through improved delivery speed, increased delivery reliability, cost effective delivery; (ii) security, privacy, transparency, and traceability performance through increased transparency, as well as (iii) customer service performance through increased convenience and increased customer loyalty. PI-driven LMD achieves these goals by providing seamless hyperconnectivity and scalability in the LMD network, standardizing processes, automating tasks, and promoting interoperability. However, such expositions are unsatisfactory from the perspective of PPT and the effect of these aspects on the performance of the PI because there is no systematic study in the literature to explore this context. This is the main aim of this research.

2   Research Background

2.1   Physical Internet

The PI is an ongoing novel approach to performing logistics operations that has been investigated in various studies. This concept fundamentally changes the process of how goods are transported and delivered by creating a global, open, and interconnected logistics system. It is based on the idea of creating a logistics network like the Internet, where goods are transported using standardized containers and protocols, and where logistics providers can collaborate and share resources to increase efficiency and reduce waste. The PI is defined as a "hyperconnected global logistics system enabling seamless open asset sharing and flow consolidation through standardized encapsulation, modularization, protocols and interfaces" (Montreuil, 2015). Although there is no unique definition of hyperconnectivity, it refers generally to intense collaboration through shared assets and information, common standards, procedures, and alignment of flows.

In the current logistics system, data and asset sharing are limited because of the lack of open connections and collaboration among the system actors. Concerning the collaboration in the hyperconnected network setting, various stakeholders can share the same transport network by using standardized transport units and protocols (Ballot et al., 2014). It is important to acknowledge that hyperconnectivity alters the way logistics operations are carried out in

comparison to the current system. Many actors are involved in the PI-enabled hyperconnected logistics networks, and they are not always bound by an agreement based on previous collaboration or performance. The PI operations are unique in that they allow users to connect with others through an open, shared, and transparent network structure. Due to these characteristics, the requirements of the PI and its influence on the overall network performance play an important role in successful PI implementation.

To achieve the vision of the PI, various technologies and innovations are required, such as the development of intelligent transport systems (ITSs), the standardization of container sizes and interfaces, and the use of data analytics and artificial intelligence (AI) to optimize logistics operations.

2.2   PI-driven last mile delivery

By creating a network of interconnected logistics hubs, the PI changes the way goods are transported and delivered, similar to the way the Internet connects computers and servers. The PI concept has the potential to make LMD more efficient and sustainable, where goods are transported from a local hub to the end customer. Last-mile logistics is regarded as the most challenging and expensive part of the logistical system (Brown and Guiffrida, 2014). This involves navigating through congested urban areas, dealing with traffic, and finding appropriate parking. By breaking down traditional barriers between companies and fostering collaboration between logistics providers, the PI could enable seamless and cost-effective delivery of goods in last-mile logistics. For example, the PI could enable a more efficient use of resources, such as vehicles and urban hubs, by sharing them among different logistics providers (Treiblmaier et al., 2020). It could also enable more efficient routing and scheduling of deliveries, based on real-time traffic and demand data (Crainic and Montreuil, 2016). Moreover, the PI concept offers innovative business models towards hyperconnectivity such as crowd-sourced logistics to provide cost-efficient and environmentally friendly LMD alternatives (Rougès and Montreuil, 2014; Raviv and Tenzer, 2018). Overall, the PI vision has the potential to transform the way goods are delivered, making LMD more sustainable, efficient, and cost-effective. However, it is obvious that collaboration between stakeholders is crucial to realize the benefits of the PI.

2.3   PPT Framework

This study is based on PPT theory which consists of people, process, and technology perspectives. The PPT framework considers that people, process, and technology are all important factors in achieving organizational efficiency, and that optimizing the interactions between these three elements can lead to better outcomes in overall system performance (Morgan and Liker, 2020). Employing this perspective, PPT is recognized as a framework aiming to improve the overall organization (Prodan et al., 2015). From the LMD perspective, this framework can improve and optimize logistics operations by defining the value streams of PPT and mapping these by considering system performance.

By understanding how these factors interact, businesses can identify opportunities for improvement and implement strategies that enhance performance and drive success. Balancing between the PPT factors can result in optimal system performance (Morgan and Liker, 2020). The framework proposed in this study is used to reveal the interactions of people, process, and technology to bring better performance outcomes in PI-driven LMD.

3   Methodology

3.1   Systematic Literature Review

A systematic literature review (SLR) was conducted to search the related literature to identify requirements of PI-driven last mile from a people, process, and technology perspective. According to Tranfield et al. (2003), the SLR follows the following protocol.

(i)   Identifying academic databases: The academic research databases were identified:

Databases. Web of Science, Scopus, Science Direct, Springer, IEEE Xplore, Emerald, Sage.

Due to the physical, digital, social, and business nature of last-mile logistics, we also included grey literature (i.e., technical papers, consulting reports, project deliverables and white papers written by practitioners) that can be collected from search engines (e.g., Google) in our search to better capture the state-of-the-art performance indicators.

(ii)   Identifying search string: The databases are searched by using the following search string in title, abstract, and keywords:

Search strings. TITLE-ABS-KEY {("logistics" OR "deliver*" OR "transport*" OR "distribution") AND ("last mile" OR "last-mile" OR "lastmile" OR "parcel") AND ("Physical Internet" OR "collaboration" OR "cooperation" OR "cooperative" OR "collaborative" OR "joint*" OR "interconnect*" OR "hyperconnect*")}. Limit to: Doctype (article, review, grey literature)

Since there is not enough PI research in LMD, we extended the scope of the literature search by integrating collaboration and hyperconnectivity. Based on the search strings used, 58 initial studies were found from identified databases.

(iii)   Screening of the studies: The following inclusion and exclusion criteria were applied. Duplications were removed.

Inclusion criteria: Title, abstract, and keywords shall demonstrate last mile logistics as the clear focus/object of the research. The search has not been limited to specific journals to include all potentially relevant studies. Articles shall be written in English, as English is the dominant language in logistics and supply chain management research. Articles shall be published in peer-reviewed journals. Only peer-reviewed journals as articles and review papers were taken to ensure quality control. Refer to grey literature sources used for related evidence syntheses. Published non-commercial grey literature was searched.

Exclusion criteria: Studies focusing on humanitarian logistics, telecommunications networks, public transportation, crisis management, tourism, and agriculture shall be excluded. This review focuses on the last mile from a business logistics and management perspective.

After applying inclusion/exclusion criteria, 45 studies were selected to review.

(iv)   Selection of primary studies: The authors reviewed the studies according to introductions and conclusions. Then they read the full text of the remaining studies. The studies that are out of scope were excluded from the list. Thus, the primary list of studies was finalized. We found 39 studies to pursue a thematic analysis.

3.2   Thematic Analysis for SLR

Thematic analysis is done to extract the data. In this method, data obtained and refined in the SLR is analyzed to identify, analyze, and report themes (Braun and Clarke, 2006). Thematic analysis focuses on summarizing studies by identifying themes in the literature that are

appropriate for the research. Since this study focuses on the performance requirements of PI-driven LMD, the themes identified should be aligned with the purpose of the study. The steps of thematic analysis method are as follow (Braun and Clarke, 2006):

(i) Familiarize the data: The authors get familiarized with the data by repeated reading of data. This will also help understand the performance requirements of PI-driven LMD.

(ii) Code the data: Initial codes are generated accordingly to answer the research question. For this, this circle is applied: Identify the requirement, identify where this requirement is needed. Categorize the study how the requirement is identified as an empirical or non-empirical. Repeat the steps, until all requirements identified in the literature are mapped.

(iii) Translating the codes into themes: All codes that are identified in the previous step are studied, narrowed down, and categorized.

(iv) Reporting the themes: All codes are mapped. Three different themes were created according to the PPT framework from the analyzed data, and the answers were evaluated to ensure the research gap was answered correctly. The results are presented in the findings section.

4 Findings

In this section, the results of thematic analysis are presented. The refined data is analyzed, and the requirements are identified according to the PPT framework provided in the Appendix. Then, the findings for PI-driven LMD requirements are categorized into three PPT themes. The details of the findings are as follows:

4.1 Person Requirements

For PI-driven LMD, it is important to identify human resources requirements.

• IT and digital skills: A diverse and skilled workforce is required in the PI-driven LMD. The workers must have a strong understanding of new technologies and services such as self-service parcel delivery service, self-service technology, and abilities to use them effectively (Laseinde and Mpofu, 2017; Chen et al., 2018; Yuen et al., 2019).

• Availability of skilled workforce: The future urban logistics systems involve new technologies such as AI enabled robotic delivery systems, where skilled workforce is required to use new systems (Genz and Schnabel, 2021) - not only for truck driving but also for local low-emission vehicles, e-cargo bikes, microhubs and curbside space management. In addition, the local logistics labor cost needs to be considered. Organizations might either face skill gaps already or expect gaps to develop within the next years (McKinsey, 2020).

• Adaptability to change: The workers must be adaptable to more specialized roles and responsibilities aligned with new technology changes and willing to learn new skills as needed (Genz and Schnabel, 2021). This might include training in new technologies, software systems and/or delivery methods for human capacity building, skills acquisition, and human capital building. To do this, there is a need for adequate reskilling services and new foundational education models (McKinsey, 2020).

• Customer-service skills: To ensure a positive customer experience, the workers need to interact effectively with last-mile customers and address their changing demands (flexible delivery time/delivery locations) and meet service expectations (e.g., same-day or on-demand delivery). Specifically, consumer service performance is affected by the features of the delivery service offered by the retailer or logistics service provider. These include but not limited to delivery time (Jara et al., 2018; Milioti et al., 2020), delivery cost (Gatta et al., 2021), reliability (Tang et al., 2021), and trust (Zhou et al., 2020) towards novel delivery services. Moreover, customer satisfaction and previous positive experiences with the use of the same technology

are expected to increase consumers' perceptions and motivation to use the service and eventually improve customer service performance.

- Health, safety, and security training: Workforce working with innovative technologies (e.g., autonomous delivery vehicles, drones, robots) must be trained to meet health, safety, and security requirements. It is essential that the workforce that needs to interact with new technologies and robots is adequately trained, equipped with the necessary tools and resources, and motivated to provide customers with the highest level of service (Janjevic and Winkenbach, 2020). Once LMD becomes familiar with automated delivery technologies, overall health, safety, and security will improve, as digital automation is thought to be safer than human activities (Kern, 2021). Automation of heavy lifting and repetitive tasks and automation of delivery vehicles will improve health and safety conditions, preventing worker injury and safety-related failures (Pauliková et al., 2021).

4.2   Process Requirements

Traditional LMD processes are transitioning to fit the PI-driven LMD business model. The LMD has business-to-business (B2B) and business-to-consumer (B2C) elements. The B2B element is larger than the consumer component in volume of goods, not in volume of delivery. One of the key trends in the LMD is the window for delivery for rapid order fulfillment, as more and more business and individual consumers are demanding improved tracking and quicker deliveries. The restructuring and designing processes aligned with adoption of smart technologies helps provide better customer experience in the PI-driven LMD. The process requirements below were identified concerning the PI-driven LMD.

- Standardized processes and data exchanges: PI-driven LMD offers the possibility of standardized processes, standardized data structures, integrated protocols to simplify the creation and operation of new partners (Montreuil, 2013). Standardization of processes and data exchanges is needed to increase the efficiency of processes and facilitate the consolidation of freight transport. This is also useful for having a neutral driving force to act on the basis of potential platform intelligence (Plasch et al., 2021).
- Real-time tracking and monitoring: The availability of a tracking and tracing feature can affect the reliability and trust towards a LMD service. For instance, the network of mobile parcel lockers can be redesigned in real-time, and the lockers repositioned to best serve the current demand situation (Schwerdfeger and Boysen, 2020; 2022). Additionally, utilising technologies such as GPS tracking and mobile apps can provide real-time updates to monitor and optimize and adjust delivery routes as needed (Laranjeiro et al. 2019). B2B shippers and customers can keep track deliveries via SMS, email notifications and even Google notifications. This can help to reduce delivery times and transportation costs by optimizing the use of available delivery resources.
- Flexible delivery options: Business processes for flexible delivery timing (e.g., scheduled delivery), flexible delivery speed (e.g., same-day delivery), and contactless delivery (no-contact delivery). Successful LMD operations refers to a flexible and dynamic system that can adjust to changing customer demand, traffic patterns, and other related factors that impact the delivery process (Snoeck, 2020). This type of network design can help companies optimize their LMD operations by improving delivery times, reducing transportation costs, and enhancing customer satisfaction. To develop an adaptive network design in LMD, companies can use different methods and techniques to analyse customer behavior and identify the areas with the highest demand for deliveries. This can help companies to adjust their network design in real-time, based on changes in demand patterns and other factors. For example, changing demand patterns can affect the locations of mobile parcel lockers in an area. Another key component of the PI-driven LMD operations is the use of multiple delivery channels, including

traditional delivery methods, such as trucks and vans, as well as alternative delivery methods, such as drones, droids, delivery robots and autonomous vehicles (Arishi et al., 2022; Yuan and Herve, 2022). By diversifying delivery channels, companies can improve their flexibility and responsiveness to changing customer needs, traffic patterns, and other factors that impact the delivery process.

- Adopting new delivery services: As the PI vision is considered an opportunity to interconnect people's mobility and freight logistics (Crainic and Montreuil, 2016), multiple last mile logistics services have been introduced recently aiming to improve the mobility of physical entities (Montreuil et al., 2013). While these services aim to connect passengers with freight movements in last mile logistics, they also lead to changes in consumers' decision-making processes. Rougès and Montreuil (2014) highlight several possibilities for making use of crowdsourced LMD and its advantages in the context of hyperconnected last mile logistics. Studies are showing a promising link between PI and interconnected crowdshipping (Rougès and Montreuil, 2014). Another delivery model for pickup is parcel lockers (Buldeo Rai et al., 2019). This service enables consumers to participate in the LMD operation by picking up their merchandise from a specific point. In the literature, parcel lockers are also referred to as delivery or pickup boxes, smart lockers, locker banks, and automated parcel lockers. Considering that the location of the lockers is one of the most important aspects of their use (Deutsch and Golany, 2018), there is an increasing trend towards lockers being located in dense urban areas, train stations, and other high traffic areas (Poulter, 2014). Smart and/or modular lockers have been examined in the context of complex urban fulfilment flows and it has been determined that they that can diminish logistics flows through consolidation (Pan et al., 2021). Mobile parcel lockers, like mobile microhubs, allow the location of the parcel locker to be flexibly changed during the day. This capability improves accessibility for customers who also have changing delivery requirements and locations. Mobile parcel lockers can be moved with a driver (fix or swap) or autonomously by being mounted on or loaded into vehicles (Schwerdfeger and Boysen, 2022). In the PI context, connecting these innovative services in a network becomes one of the possible research directions to explore how the performance of the LMD operations can be enhanced.

4.3 Technology Requirements

Technology plays a significant role in the performance of PI-driven LMD. This is due to the requirements of seamless connection among different technologies and services in the PI (Leung et al., 2022). Technology related requirements can be categorized into following four categories:

- Automatization: Due to the properties of the PI, hyperconnectivity provides large collaboration among firms (Ballot et al., 2021). This immense collaboration and standardization will also require automatization of last-mile logistics services such as handling, routing, and storage (Montreuil et al., 2010; Tran-Dang and Kim, 2018; Pan et al., 2021).
- Robotization: Robotization becomes another important aspect of the PI vision. Autonomous and self-organizing logistics systems can function as enablers of the PI implementation (Pan et al., 2021). ITSs (Crainic and Montreuil, 2016), robots (Montreuil et al., 2015) and automated guided vehicles (Pan et al., 2021) are some of the topics which have been discussed in the PI domain.
- Optimization: Most of the literature concerning PI enabled hyperconnected logistics systems focuses on the economic, environmental, and societal impacts of this paradigm, calculating these by applying either optimization models or simulation studies (Treiblmaier et al., 2020). Lowering the transportation cost and reducing the negative impacts of last-mile deliveries are two important aspects found in optimization studies (Ji et al., 2019; Crainic et al.,

2020). The possible impact of hyperconnectivity is studied in several research directions. Banyai (2018), for instance, uses heuristic optimization to explore the effect of hyperconnectivity on energy consumption. The study reveals varied energy savings depending on the optimization constraints. Finally, the research shows that collaboration among logistics service providers has the potential to reduce energy use. Another study focuses on modular production in the PI context (Fergani et al., 2020). By applying mixed-integer linear programming, the authors show computational performance of the developed model. The research provides evidence that PI has the potential to deal with economic and environmental drawbacks of the production process by enabling modular production in open facilities.

- Digitalization: Digitalization and corresponding digital technologies are invading all aspects of the logistics chain. AI and big data optimization and planning systems, the Internet of Things for enabling ITSs, automated storage and retrieval systems are all potential elements of a future based urban logistics system. The individuals who operate these systems will no longer be hired because of their ability to handle the manual tasks of unloading, putting away, picking, and loading boxes. These tasks will be performed in an automated manner using robots or similar automated mechanisms. The individuals working in these highly automated systems will need to be capable of handling and controlling their automated partners and performing maintenance functions to ensure that the automation is able to provide the on-demand services that customers will require (Walwei, 2016; Konle-Seidl and Danesi, 2022).

5   Discussion

PPT is a useful framework to achieve optimal system performance outcomes through people, process, and technology innovations. The analyzed requirements of PI-driven LMD from the PPT perspective result in improved performance outcomes namely improved delivery speed, improved delivery reliability, increased transparency, cost effective delivery, increased convenience, increased customer loyalty. Figure 1 shows the proposed PI-driven LMD performance model according to PPT theory.
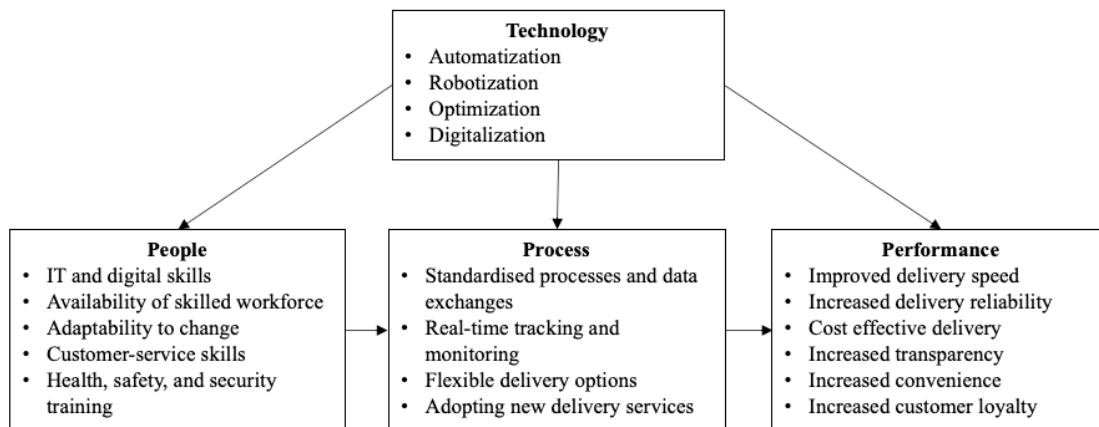

Figure 1 Theory-based PI-driven LMD performance model according to PPT

Based on both observations and qualitative data, the following performance outcomes are identified, and propositions can be proposed:

- Improved delivery speed: PI-driven LMD enables shorter travel routes and better geographical coverage through people, process, and technology innovations to increase operational efficiency, reduce complexity so that to improve delivery performance.

- Increased delivery reliability: People are prone to errors, including manual errors, judgement errors, and knowledge errors during the collection process. However, the use of innovative technologies such as smart lockers and improved processes can maintain a high level of technical delivery reliability which can positively influence functional benefit and provide error-free service performance.
- Cost effective delivery: the use of low- or zero-emission vehicles such as electric vans, e-cargo bikes, autonomous vehicles (road-robots, drones, droits) reduce greenhouse gas emissions and meet net-zero goals and achieves cost effective delivery performance standards.

P1: Developing a dedicated PI-driven LMD strategy will improve delivery performance.

- Increased transparency: PI-driven LMD enables higher transparency and traceability of information, improve governance standards, and engender trust across stakeholders through people, process, and technology innovations to increase value chain efficiency and improve information flow between different entities in supply chain.

P2: Adopting adequate technological solutions will improve security, privacy, transparency, and traceability performance.

- Increased convenience: PI-driven LMD offers flexible delivery options including delivery to a specific location, such as a workplace or a locker, or delivery at a specific time. Offering such delivery options through people, process, and technology innovations can improve customer satisfaction and reduce the number of missed deliveries, leading to a more efficient and effective LMD system.
- Increased customer loyalty: In highly competitive LMD markets, great attention is paid to customer satisfaction in the service sector and improving service quality and maintaining customer loyalty through people, process, and technology innovations.

P3: A well designed responsive customer support in the PI-driven LMD will improve customer service performance.

6 Conclusion

The present study makes a significant contribution to identifying the performance requirements of a PI-driven LMD according to people, process, and technology, that drives stakeholders (e.g., LSPs, shippers) to be involved in a PI network. The requirements according to PPT were investigated and determined through the SLR combined with a thematic analysis. Then, the determined requirements were used to develop theory-based PI-driven LMD performance model, where the three propositions were proposed with several performance outcomes. This study has a limitation, as it is solely based on available literature to understand the current conditions of PI-driven LMD. In the future, an empirical study will be conducted with Living Labs (LLs) of European cities as open innovation ecosystems in real-life environments to reflect the future performance requirements of PI-driven LMD.

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APPENDIX: Thematic Analysis for identification of requirements according to the PPT framework

Category	Category Features	Requirements Identified	Resources
Person	Distribution/warehouse center manager, dispatchers, drivers/deliverers, IT personal	Technological expertise, digital skills, technology acceptance,	Laseinde & Mpofu (2017); Chen et al. (2018); Yuen et al. (2019)
	Skill gap, digital divide	Skilled human power	McKinsey (2020); Genz & Schnabel (2021)

	Adequate reskilling services and new foundational education models; investment in human intellectual capacity	Change management, skills acquisition, human capacity/capital building,	Laseinde & Mpofu (2017); McKinsey (2020); Genz & Schnabel (2021)
	Positive customer experience, on-demand delivery requests	Customer-service skills	Jara et al. (2018); Milioti et al. (2020); Zhou et al. (2020); Gatta et al. (2021); Tang et al. (2021)
	Human-robot interactions, elimination of activities in a hazardous work environment	Health, safety, and security training	Janjevic & Winkenbach (2020); Pauliková et al. (2021); Kern (2021)
Process	Standardized processes and structured data exchanges	Standardized processes and data exchanges	Montreuil, (2013); Plasch et al. (2021)
	GPS tracking, mobile apps, RFID tags, sensors	Real-time tracking and monitoring	Laranjeiro et al. (2019); Schwerdfeger & Boysen (2020, 2022)
	Flexible timing, scheduling, on-demand services, contactless delivery	Flexible delivery options	Snoeck (2020); Arishi et al. (2022); Yuan and Herve (2022)
	Service design for B2B and B2C LMD processes. There are typically five B2C LMD processes: Online shopping, packing process, delivery process, pickup process, return process	Adopting new delivery services	Huang et al. (2009); Montreuil et al. (2013); Rougès & Montreuil (2014); Crainic & Montreuil (2016); Deutsch & Golany (2018); Buldeo Rai et al. (2019); Schwerdfeger & Boysen (2022); Pan et al. (2021)
Technology	Automated routing, storage, and routing	Automatization Self-service technology	Montreuil et al. (2010); Tran-Dang & Kim (2018); Chen et al. (2018); Pan et al. (2021)
	Innovative LMD services such as sidewalk robots, drones, droits, and smart lockers	Robotization	Montreuil et al. (2015); Crainic & Montreuil (2016); Pan et al. (2021)
	Delivery route optimization, cost minimization, minimization of negative environmental effects, profit maximization, energy consumption, stationary/mobile facility location optimization, low- or zero-emission vehicle integration	Optimized vehicle routing, shorter trip detour and better geographical coverage	Bányai (2018); Ji et al. (2019); Treiblmaier et al. (2020); Crainic et al. (2020); Fergani et al. (2020); Ghaderi et al. (2022)
	Mobile applications and digital platforms	Digitalization	Walwei (2016); Konle-Seidly & Danesi (2022)

Robust logistics service network design for perishable products with uncertainty on transportation time

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Keywords: Multi-modal transportation, robust optimization, budget of uncertainty, perishable products, transportation time uncertainty

Conference Topic(s): interconnected freight transport; logistics and supply networks; PI implementation; PI modelling and simulation.

Physical Internet Roadmap (Link): Select the most relevant area(s) for your paper: ☐ *PI Nodes,* ☒ *PI Networks,* ☐ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

Contribution abstract

Disruptions in logistics, including local disruptions (technical issues, out-of-service warehouse, etc.) or mega-disruptions (pandemic, wars, earthquakes, etc.), have dramatically raised industrial practitioners' concern to the shipment delay which damages the logistics service quality. The problem is particularly sensitive to perishable products, e.g. fresh produce, vaccine, medicine, which are usually of short shelf life. It is significant to respect the shelf life since their value (or functionality) deteriorates remarkably with time. Delayed (or uncertain) logistics services can lead to deteriorating commodity quality even waste. Therefore, shippers of perishable products pursue robust solutions on product distribution to guarantee the service quality, including the freshness and on-time delivery under the uncertainty of transportation time.

This work from the shippers' perspectives investigates logistics service network design problem (LSNDP) under uncertainty. Traditional LSNDP aims to achieve the best tradeoffs between service quality and operational costs at the tactical planning level (Crainic, 2000). Based on that, this work integrates service selection with traffic distribution under a multi-modal transportation network with uncertain transportation time, where multi-modal transport services are combined together during transportation, i.e. maritime, air, railway and road way. However, the design of service timetable and frequency is not considered as we focus on route and service selection.

This work also aims to contribute to Physical Internet (PI), a new logistics paradigm suggesting global, open and interconnected logistics systems. Under a such paradigm which is fundamentally different to the current practices, it is possible to dynamically organize the logistics service even in the presence of disruptions. Previous works have shown that it may enable more flexibility, agility and delivery options to mitigate disruptions (Yang et al., 2017). This work investigates how PI can enhance LSNDP under uncertainty of transportation time.

Stochastic programming and robust optimization are the two common paradigms applied in the literature to deal within logistics uncertainty. Stochastic programming assumes that uncertainty can be described by exact probability distribution. Robust optimization, by contrast, assumes that uncertainty cannot be described explicitly by a such distribution, but only subject to a certain rang of deviation from the nominal value. In such setting, robust optimization is a paradigm studied for finding feasible and robust solution for all cases of the uncertainty, in other words, via using a *min-max* objective against the *worst-case*.

This work adopts robust optimization for several reasons. Firstly, in the presence of mega-disruptions or unpredicted disruptions, it is hard to catch the probability distribution information or the impacts which are required by stochastic programming. Secondly, due to the short and strict shelf life, and high sensitivity to lead-time, perishable product shippers have relatively lower tolerance to shipment delay and consequently incline towards conservative solutions on transportation service selection to realize the best tradeoff between costs and service quality. Given that, we apply classic robust optimization with budget-of-uncertainty proposed by (Bertsimas & Sim, 2003), which can control the conservative level of solutions. We assume that shippers know the information on the nominal value and the maximum deviation range of transit time (including transshipment time at hub and transportation time to the next hub) of each service on each arc called service-arc. The uncertainty of transit time is modeled as a deviation degree from the nominal value. The worst-case of uncertainty is modeled as the longest transportation time of each order. To control the conservatism level of the solution, a budget-of-uncertainty, pre-determined by decision-makers, is enforced on the total deviation degree of transit time on all service-arcs.

To find out the robust solutions, a Mixed Integer Linear Programming (MILP) model is proposed to minimize the total costs for shippers, which include transportation cost, transshipment cost, deteriorating cost and early or late delivery cost, with budget-of-uncertainty constraints. At this stage, numerical studies with fictive datasets have been conducted to validate the model, solved by CPLEX solver run on MATLAB. The first numerical results show that the developed model may deliver robust solutions on route and transportation service selection that satisfy all constraints (in particular all products must be delivered before the expiration date) while minimizing the total costs. Sensitivity analysis is carried out on the setting of budget-of-uncertainty, the degree of uncertainty, and shelf life of products, to investigate the tradeoffs between total costs and service quality. The next steps will focus on the real-life case data collection and tailed algorithm design. Managerial insights from the results on real cases will be provided to the industrial practitioners.

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Autonomous vehicles under all weather conditions: steering towards a harmonised legislative framework enabling real-life deployment

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Abstract: *This paper presents and discusses the current status of testing and operation regulations for automated vehicles (AVs) at EU level. Current legal conditions for on-road testing and operation of autonomous vehicles vary strongly from country to country. This paper will focus on examples of European countries that have taken an advanced stance in the formulation of policies and rules (Austria, Norway, France) and developed national policies which already enable on-road testing and operation. This paper will identify and put forward a set of best practices that will support the review of existing and future legislation as the basis of a harmonized EU legal framework designed to give clear signals to the industry, regulators and the general public. Particular attention will be placed on ensuring that safety performance requirements are met across all Operational Design Domains (ODD). Taking adverse weather conditions into consideration will allow to reflect a more adequate real-life environment for AV operations. Updated regulations must ensure the safety of automated vehicle operations while providing some degree of flexibility, rather than imposing specific restrictions to enable future development and deployment of AVs. The technical work carried out under the EU-funded Horizon-2020 programme and more specifically the AWARD project provides the laying ground for the development of frameworks enabling the safe testing and deployment of autonomous vehicles for logistics operations onto public roads.*

Keywords: *autonomous vehicles, road transport, policy, ADS, testing, real-life deployment, logistics, adverse weather conditions*

Conference Topic(s): *autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms), ports, airports and hubs; technologies for interconnected logistics (Artificial Intelligence, IoT, machine learning, digital twins); vehicles and transshipment technologies.*

Physical Internet Roadmap: ⊠ *System of Logistics Networks,* ⊠ *Governance.*

1 Introduction

Although the development of automated vehicle (AV) technologies has been rapidly progressing over the last years, large-scale deployment of driverless vehicles onto public roads requires a review and update of existing regulations. Authorities have already started adapting their rules to enable the manufacturing, commercialisation and deployment of

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driverless AVs on European roads. At EU level, legislative bodies have already implemented a framework to harmonise the conditions for the type-approval of automated passenger and goods transport vehicles, thereby setting clear indications for the industry, regulators and general public. European legislative bodies have set uniform safety standards across borders for type-approval of Automated Driving Systems (ADS), albeit the operating conditions for on-road testing and deployment of AVs vary at member-state level.

This paper will examine policies in selected countries across the EU, enabling both on-road testing and deployment of AVs, while focusing on the best practices. Legal framework at EU-level, and more specifically the Automated Driving System (ADS) act (EU 2022/1426), national legislation for France, Norway and Austria will be presented. The goal of this study is to pursue a framework that harmonises and ensures safety performance requirements across all different traffic scenarios and conditions, to accurately reflect real-life deployment conditions which include adverse weather conditions. Updated regulation should ensure the safety of automated vehicle performance while at the same time providing a degree of flexibility that fosters the development of AVs in a safe way.

2   Analysis of selected EU and national regulatory frameworks

2.1   European framework on vehicle type-approval conditions: The ADS act

To ensure the safety of AV technology while facilitating their commercial deployment, the European Union has developed a new regulative framework that ensures uniform safety standards for AV testing and type-approval of the ADS. Entered into force in September 2022, the implementing EU Regulation No. 2022/1426 lays down procedures and technical specifications for the type approval of motor vehicles equipped with ADS. Contrary to the previous regulations, this act specialises in AVs and no longer requires the mandatory use of safety drivers for fully automated vehicles. In addition, the Regulation provides clear guidance for all stakeholders involved in the development and deployment of driverless vehicles, by informing manufacturers on the performance requirements and technical specifications that vehicles must meet, as well as specifying the modalities and competent authorities needed to obtain a compliance certificate. It should also be mentioned, that the regulation is quite open regarding the Operational Design Domain (ODD) that the manufacturer specifies. Additionally, it establishes aggregate safety metrics that will be used to benchmark performance, and ultimately used as a measurement for allowing AV real-world deployment.

This Regulation, also known as ADS Act, currently specifies:

- the information required by the ADS manufacturer to support their request for EU type-approval;
- the performance requirements and technical specifications applicable to ADSs, under a variety of scenarios and operating conditions (OOD) that the vehicle finds itself in;
- the review process to be used by the relevant approval authorities in their assessment of ADS compliance with the applicable technical specifications;
- the review of documentation, tests to be conducted and guidance for approval authorities, when reviewing applications.

The deployment of fully automated vehicles at the European level is currently limited to individually approved routes. The scope of the EU Regulation No. 2022/1426 is in fact limited to specific "use-cases" of fully automated vehicles or dual mode vehicles operating on a predefined route, which may include urban, suburban, motorway or predefined parking facilities environments. The traffic of fully automated vehicles is currently only allowed in

hub-to-hub routes and pre-defined areas (InterRegs, 2022). This regulatory framework will however be crucial to shape the future of AVs across the EU, by gradually opening up the door to permit the European type approval of fully automated vehicles in the years to come. The ADS regulation is in fact part of a broader maturation in Europe's AV regulatory and commercial environment, which provides a harmonised approach while granting an adequate flexibility to enable the development and deployment of AVs (European Commission, 2018).

While the ADS act specifies the framework for the type approval of vehicles at the EU level, national authorities are granted a level of flexibility to guarantee alternative national requirements and permit exceptions for AVs test operations and deployment. Different countries have introduced regulatory measures to support the testing of autonomous vehicles on their roads: While some countries grant authorization on a case-by-case basis, others focus on modifying national laws to facilitate vehicle testing across their territory (Traton, 2022).

2.2 National framework for AV testing and operation: the case of France

The French regulatory framework currently distinguishes between two main schemes to allow automated driving on public roads: the testing framework and the permanent regime.
If those two regimes are different in terms of use-cases (public transport, automotive, logistics), they are only differentiated by their level of automation. This results in three major categories: partially automated (the system is not able to ensure safe maneuvers), highly automated (the system ensures safe maneuvers within its ODD) and totally automated (the system ensures safe maneuvers within its ODD and is subject to remote control).

Within the testing framework, the circulation of a vehicle without permanent action of the driver requires an authorization, even for experimental purposes. Such experiments may concern one or more of the following cases: technical testing and development, performance evaluations in the situation for which the vehicle is intended to be driven and public demonstration. The vehicles involved in the experiment without partial intervention of the driver need to be registered under a specific registration certificate called WW DPTC.

A specific set of conditions may be linked to ensuring the safety authorization during experimentation. The authorization specifies the sections on which the vehicle is allowed to drive in the delegated driving mode as well as the delegated driving functions that can be activated on these sections. Both passenger and goods transport services may be subject to authorization. Vehicles intended for public transportation either of passengers or goods will have to trial on routes which are predefined in the authorization. However, tests of vehicles with delegated driving, which are intended for the public transportation of passengers, will include a trial period without passengers onboard.

Delegated driving vehicles operating under an experimental authorization must be equipped with a recording device to identify the phases of delegated driving. The applicant must also guarantee that the financial and technical capacities are appropriate for the purpose of the experiment. The authorization specifies the starting date and the duration of the experimentation. If the maximum duration of the authorization is two years, it may be extended by renewal of the authorization, depending on the evaluation of the experiment.

Article 125 of the "Plan d'Action pour la Croissance et la Transformation des Entreprises" (PACTE) Act allows for the extension of experimentation, to use-cases where the driver may not be in the vehicle or responsible for all driving tasks. This provides France with a framework for experimentation that covers the highest levels of automation, with an adapted liability regime.
The application file describes the conditions under which the experiment will be carried out. It contains: a technical file of the vehicle(s), an experimentation file as well as a road

manager, the competent traffic police authority, where specific traffic police measures are required and the relevant transport organising authority, if it is a public transport service. Information on authorised experiments is recorded in a national register within the state services which are monitored in compliance with industrial and commercial confidentiality. The dissemination of this information is restricted to the State services that are involved in the steering and evaluation of the experiment.

Once granted an application, a request for an experimentation file must be carried out, which must include:
- Presentation of the context of the experiment (actors involved and their respective roles, the management of the experiment, and the overall context of the experiment)
- Presentation of the experiment (start and end dates, including the blank run if applicable, location, objectives, daily time slots, safety studies carried out, experimental protocols used, and if applicable, the type of transport service experienced)
- Presentation of the modalities of the experiment (the number of vehicles used, the identification number (VIN) of the vehicles used, interactions with other road users, routes taken, the profile of the experimenters and where applicable, the interactions and coordination between the remote supervision and control systems and the existing traffic management and control systems, as well as the communication protocols between the remote driver and any persons on board the vehicle)
- A sub-file on roads containing in particular (a general location plan of the roads used, the list of road sections used characterization of road sections, equipment and signaling required for the experiment, and if necessary, detailed plans showing the integration into the existing system (cross-sections, organization of junctions, signaling, etc.).
- Regulations in force on the roads concerned in terms of traffic and parking regulations;
- A duly completed certificate of financial and technical capacity;
- Any other information that the applicant deems necessary to be made known.

The holder of the authorisation shall submit to the competent ministers a six-monthly follow-up, or quarterly in the case of an experiment involving a vehicle intended for public transport, of the authorised experiment within one month of the end of each six-month period, as well as a final report within one month of the end of the experiment.

Decree No. 2021-873 of June 29th 2021 "Implementing Ordinance No. 2021-443 of 14, April 2021 on the responsibility regime applicable in case of circulation of a vehicle equipped with an automated driving system and its conditions of use", sets the conditions for the deployment of automated vehicles and automated road transport systems on French roads. It covers levels of automation up to fully automated systems, without a driver on board, provided that they are under the supervision of a person in charge of remote intervention and that they are deployed on predefined routes or zones. The decree sets definitions and general safety provisions for these systems, as well as requirements for the driver or the person in charge of remote intervention. In addition, the decree sets conditions under which fully automated systems (including vehicles, roadside or remote equipment and operational procedures) can be put into service, following a specific safety demonstration process. Orders specify procedures for approved qualified bodies and the content of their report on system safety, as well as conditions for the authorization of remote operators, particularly in terms of training.

A number of reference documents (methodological documents or guides) are intended to support stakeholders such as system designers, operators, service organisers, and approved bodies, in the implementation of safety demonstrations.

When the automated driving system is active, the driver is no longer required to be in a state in which they can conveniently and immediately carry out all maneuvers incumbent on them. However, the driver must remain fit in order to respond to requests at all times, comply with the instructions of law enforcement officers and give way to priority vehicles.

Table 1: Overview of provisions depending on the use-case in France

Overview of provisions depending on use-cases		
Use-case	*Case A: On-board driver*	*Case B: Remote intervention*
Partially automated vehicle	To be able to respond to any request for handover To be able to respond to law enforcement orders and facilitate the passage of priority vehicles	**Not allowed**
Highly automated vehicle	To be able to respond to any request to take over (NB: by design = out of scope) Be able to respond to law enforcement orders and facilitate the passage of priority vehicles	**Only within an automated road transport system (ARTS)** System validated by decision of the service organiser, after safety demonstration and opinion of an approved qualified body. Remote operator able to intervene according to the system's conditions of use
Fully automated vehicle	*Not applicable*	

2.3   National framework for AV testing and operation: the case of Norway

Test applications for self-driving vehicles in Norway are governed by the "Lov om utprøving av selvkjørende kjøretøy" (Test of Self-driving Vehicles Act, TSVA), which came into effect on the 1st of January 2018 and is expected to be revised in 2023. The aim of the TSVA is to encourage and formalise the testing of self-driving vehicles by setting a framework centered around traffic safety and privacy. Tests are to be performed in line with the maturity of the technology at hand and should be designed to establish the implications and risks of the use of self-driving vehicles with respect to external factors, namely mobility and traffic development, the environment and traffic safety. Any vehicle that comprises an electronic system capable of automatically controlling the vehicle and the driving thereof and which either operates without a responsible driver or operates with a responsible driver who is not in a traditional driver's seat is considered self-driving. This includes vehicles that allow the electronic driving system to hand over control to a driver.

In order to test self-driving vehicles in Norway, an application for a test permit must be filed with the Road Directorate (RD) of the Norwegian Public Roads Authority (NPRA). The applicant must be a natural or legal person, and the permit is issued for a fixed time period unless circumstances justify an extension. A permission to test a self-driving vehicle is given on the basis of a specific vehicle and its functionalities, a risk analysis of the proposed project, and one or more designated responsible drivers or operators. Should any of these parameters change, for example because the software of the vehicle is updated, the test environment changes, or a new operator is given permission to operate the self-driving vehicle, the RD

must be at least notified. If any safety-relevant aspects of the project are affected, an application for a new permit might be required. Permits may be suspended or revoked if the conditions for the permit are no longer met.

The application for tests under the TSVA must contain: the description of the vehicle and the automatic system, the risk analysis of the proposed project and the responsible driver or operator.

The vehicle to be included in the test should comply with the requirements of the relevant regulations (depending on whether it is a car, vehicle, motorcycle, tractor, etc.), unless an exemption has been agreed upon. In practice, many self-driving vehicles require such an exemption as they lack features considered essential to be compliant with the standard regulations, such as a steering wheel. The regulations also include standard provisions for vehicles operating in the public domain, such as adequate brakes and compliance with EU regulations on Electromagnetic Compatibility (EMC) emissions. Test vehicles should also be registered in accordance with the Road Traffic Act (Lov om vegtrafikk), although this requirement can be waived in certain instances, for example for very limited testing under strictly controlled circumstances. All vehicles must be insured, and proof of insurance must be provided with the application. The vehicle's automatic system, meaning the system that allows the vehicle to be self-driving, is subject to particular scrutiny. Documentation must be provided that details not only a functional description of the automatic system and its capability to safely drive the vehicle, but also with proof that these functions have been adequately tested by a third party. The security of the system, including provisions protecting the system from cyber-attacks must also be documented. This latter aspect is also relevant for General Data Protection Regulation (GDPR) considerations, which the automatic system must be shown to comply with.

The proposed project must be analysed with respect to safety and risks. Both the environment in which the vehicle is to operate in as well as its interactions with said environment must be carefully described, as well as risk and mitigating measures must be explained. The assessment of the project must be complete and illustrative enough for the RD to be able to evaluate whether the proposed project fulfils the TSVA safety requirements. Normally, this means that an applicant will provide a full safety analysis of every feature along a proposed track for the self-driving vehicle including pictures of the route, explanations of the interactions between the vehicle and other traffic participants, as well as a risk matrix evaluating potential risks by severity and frequency. The RD can ask for a risk analysis to be verified by a third party and risk-mitigating measures should be proposed where appropriate. If the RD issues a permit based on the application, these proposed measures must be put in place, documented, and an updated risk analysis must be sent to the RD for their records. If the RD decides to inspect a project, the environment must match the one proposed in the application (including risk-mitigating measures), otherwise the permit will be suspended or revoked.

Regarding the responsible driver or operator, a distinction must be made between the safety responsible for the project and the responsible drivers or operators. The safety responsible assumes legal safety for the pilot and must ensure that the pilot is executed under the circumstances for which the permit is given. A responsible driver is an operator of the self-driving vehicle whose responsibility is to monitor the vehicle (either while in the vehicle or remotely). All operators must be named and identified in the application, and must provide the documentation for the qualifications of the operator to assume responsibility for the vehicle. These qualifications usually include at least a driving license for the vehicle category

that the self-driving vehicle falls under (car, minibus, bus…) and a training certificate on the use of the automatic system.

The relationship between the responsible driver and the self-driving vehicle must be made clear in the documentation supporting the application. For example, routines should be described that remedy emergency situations, such as means for an operator to remove the vehicle from the flow of traffic in the event that the automated system becomes unresponsive. The operator's level of involvement during normal operations should be made clear, as well as the circumstances under which they are expected to take action.

Finally, all permits are given on condition that any significant events during the project, particularly any incidents are shared with the RD and that information from the project is shared. The RD can (and often do) require the applicant to keep a data log with vehicle data that the RD could access if required (in case of incidents), and it is commonly stipulated that data from the end of the set-up period be submitted such that the RD can verify that operations with the self-driving vehicle are running as expected. Furthermore, there is a requirement for all tests that a report should be submitted at the latest 6 months after the end of the project, together with a version of the report that can be made public.

2.4 National framework for AV testing: the case of Austria

In 2016, a dedicated legal framework to enable tests on open roads has been established (AutomatFahrV). At that time, Austria has taken the approach of defining specific use-cases, which included automated minibuses, motorway pilots with automated lane changing and automated military vehicles. There has been a major amendment of the edict in April 2022, as five new use-cases were added. Previously, demands for new use-cases have been collected, including the new use case "Automated vehicle for the transport of goods" which enables the testing of the Hub-to-Hub use-case in the H2020 EU-funded Project AWARD.

This new use-case has been introduced to allow the testing of automated freight transport on public roads. It is primarily suitable for rather short distances, since the speed is limited to 30 km/h for tests with automated vehicles that have not been type-approved beforehand, and 50 km/h for automated vehicles in which the base vehicle has been type-approved before. Regardless, the actual approved operating speed must be based on the results of a detailed route analysis and risk assessment of the route.

This analysis and risk assessment of the route is one of the new requirements that have been introduced by the amendment in 2022. Applicants must analyze every segment of the route based on a provided checklist. If risks are unveiled, appropriate mitigation measures must be defined. Additionally, the training of the safety operator must include the specific characteristics of the route and use-case specific manoeuvres. Table 2 contains an overview of the information needed to be provided by the applicant to obtain a test permit. Testing on public roads is possible for vehicle manufacturers, research institutions, system developers and transport companies.

Table 2: Summary of requirements and necessary information to obtain a test permit in Austria (own representation, AustriaTech 2023)

Filled in application form:	Safety relevant information:
- Contact person - Description of the use-case - Purpose of the test/research questions - Name of operators	- Analysis and risk assessment of the planned route following a given template (including corresponding documentation of risk mitigation measures) - Confirmation of operator training:

• Licence plate number • Confirmation of third-party liability motor insurer • Duration of tests • Planned route or area • Evidence of having informed the state governor and the road administration • Approval from the driver/operator to perform data recording • Accident data recorder • Description of necessary infrastructure adaptations • Additional questions	o Test driver certificate (or similar) – focussing on driver skills o Training/introduction covering the vehicle specifications, route specifications, use-case specific manoeuvres. etc. • Description of how the necessary manoeuvres have been tested beforehand on a proving ground and in simulation • Description of manual override of the system • Description of manual deactivation of the system • Description of a risk analysis for the whole test and if mitigation measures have been taken; including description of method used

The regulation does not foresee to impose additional restrictions regarding time of operation, weather conditions or similar conditions. The safety validation is based on a self-assessment by the applicant. The applicant needs to describe the results of the safety validation for the overall test case and more specifically for the intended route, which includes documenting the corresponding risk mitigation measures.

As specified in §1 Abs 6 of AutomatFahrV, test reports must be submitted at the end of the test period. These reports are publicly available on the website of the Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology. Critical situations and/or accidents that occurred during the test drives must be reported immediately.

Currently, testing permits can only be issued if they are covered by one of the pre-defined use-cases. If this is not the case, the ordinance has to be amended, which requires time. In most use-cases, testing is only allowed with a safety driver inside the vehicle. The safety driver must be able to intervene and override the system at any time. The legislation for testing of fully automated vehicles without safety driver in the vehicle (remote operation) is currently under development in Austria (BMK, 2022).

3   Conclusions

The legislative framework is usually following technological developments and the European Union is working on setting the rules for a safe and successful deployment of AVs at two levels: EU wide and at Member State level. A different distinction divides legislation into testing and real-world deployment. Testing of AVs is applicable to all the countries studied in this paper (mainly at use-case level accompanied by an application for testing to be submitted to the relevant authorities) while real-world deployment is still limited. Testing of AVs at use-case level on predefined routes is possible in the countries mentioned in this research paper under specific conditions.

EU legislation aims to set out the type-approval rules for AVs in regards to their automated driving system (ADS). The objective at EU-level is to create a harmonised pathway for fully automated vehicles to be deployed on public roads across European Member States. While the implemented harmonised approach for the type-approval of AVs across Europe through the ADS act is critical to set uniform safety standards, it is also crucial to provide adequate flexibility to the rapidly evolving AV technological and industrial landscape. The EU sets policy benchmarks, in which Member States have the leverage to formulate regulations

independently without threat of sanction therefore setting structures for cooperation and learning among national policymakers (Hansson, 2020).

This allows for the development and implementation of a wide range of policy strategies on a national level. While some grant authorization for testing on a case-by-case basis like in Austria, others already have a national regulation including a permanent regime, like in France. Comparing regulations is important not only for policymakers but also for engineers who need to understand the implications of regulations for design requirements (Lee & Hess, 2020). While each Member State implements specific strategies to set requirements for AV testing and deployment permits, some common requirements have been set across borders, notably in terms of safety and traffic requirements.

Developing an automated driving system (ADS) remains a highly-resource intensive endeavor, requiring extensive technical and specialised expertise (Hogan Lovells, 2021). The steps taken by national authorities to develop the legal basis for the approval of ISO/SAE Level 4 driving automation, and fully automated vehicles in the most advanced cases, enable to further build upon the existing regulatory concepts and prepare the market for the safe deployment of AVs.

Acknowledgment

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Hyperconnected Urban Synchromodality:
Synergies between Freight and People Mobility

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Abstract: *This paper investigates the opportunity to exploit an on-demand freight transshipment service in urban areas. This contribution attempts at first to focus on the feasibility to connect people and freight mobility with a joint usage of transportation options. It builds on the hyperconnectivity principles enabled by the Physical Internet (PI) manifesto for city logistics. To this end, this paper proposes an effective solution approach for optimizing multimodal on-demand transshipment. The approach considers multiple mobility options such as on-demand delivery services, cargo bikes, tramways, and buses to transship goods from an urban logistic hub to another. The hyperconnected synchromodal mobility solution is proposed as an alternative option to classical pickup and delivery-based transportation. The proposal is first characterized in link with the interconnectivity needs and then its operability is modeled as a new transportation approach. The proposed solution aims to increase the sustainability of cities by reducing congestion levels, the impact of logistics moves, as well as carbon emissions in urban areas. An illustrative case is provided to demonstrate how the novel hyperconnected synchromodal transportation system could operate, and to provide an evaluation of the economic and sustainability benefits of such system in an urban context.*

Keywords: *Hyperconnected City Logistics, Synchromodality, Physical Internet, Parcel Distribution, Sustainable Mobility*

Conference Topics: *Distributed intelligence, last mile & city logistics.*

Physical Internet Roadmap (*[Link]*): *Select the most relevant area for your paper:* ☐ *PI Nodes,* ☐ *PI Networks,* ☒ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

1   Introduction

Urban population is steadily growing, as demonstrated by the World Business Council for Sustainable Development predicting that by 2025 more than 4.4 billion of people will be living in urban areas. New mega cities are appearing in many countries, especially in Latin America and Asia, which will rise to over 85% the world population living in cities by 2050. The raise of e-commerce proportion in deliveries and the mass customization trend in retailing are responsible for lower volumes per shipment and higher number of shipments. These urban shipments are continuously confronted to an increased service level now expressed in hours to deliver rather than in days. Transportation of goods in urban areas represents an important proportion of the total moves on a daily basis within cities.

From the residents' perspective, the main moves consist of transporting goods supplied from groceries or retail stores, and on moving out to nearby pickup points to collect online ordered products. From the private logistics companies' perspective, the main moves are the well-known last-mile deliveries that are nowadays more and more under pressure induced by the higher requirements of the online retailing system. With the surge in small-package delivery services, these actors represent a vital link between the globally dispersed suppliers and the city residents with a challenge for their efficiency, service level, ecological footprint, and social impact on the city.

The concept of Physical Internet (PI), (Montreuil, 2011), was proposed as a novel and open framework in order to connect within the same system humans, objects, networks, and the main stakeholders (cities, logistics operators, couriers, postal services, retailers). A more distributed and sustainable logistic system could be reached enabling the easy access of goods. Within the PI vision, goods are moved, handled, and stored via a logistic web that corresponds to an open network of logistic networks. The implementation of the PI framework enables to move toward a more interconnected and decentralized transportation service where goods are encapsulated in smart easy-to-handle and modular PI-containers. Within urban areas, interconnectivity is to be strongly enhanced thanks to the usage of a large multi-tier set of logistic hubs and the usage of several transportation options to ensure safe, efficient, and fast transshipment moves between all the origin-destination pairs. Based on all these features, the introduction of the Hyperconnected City Logistics (HCL), (Crainic and Montreuil, 2016), enables a more efficient and sustainable way to handle and transport goods. HCL presents an approach to shift from disconnected dedicated transportation systems to a connected decentralized and highly collaborative transportation and logistics system emphasizing the use of the available spaces and existing infrastructure.

At the city level, the urban infrastructures that provide and operate interconnected sustainable modes rely on public transport resources dedicated to people mobility (buses, tramways, rapid transit systems). With the objective of reducing the impact of freight transport and logistics on the urban fabric, many recent papers stressed the interest in interconnecting people and freight mobility. In the existent literature on city logistics, the solutions presented focus on the integration of freight into a single passenger network. Many of these innovative logistic practices mixing freight and passengers are implemented in the form of pilots and are focused on a single public transportation mode, but few concrete solutions remain. According to a multimodal approach, synergies between freight and passengers based on the sharing of vehicles and public transport infrastructures requires consideration of the notions of hyperconnectivity and synchromodality.

This research paper first focuses on the feasibility of goods transshipment with a joint usage of public mobility and freight urban vehicles. Within an urban area, interconnectivity would be strongly enhanced thanks to the usage of a high number of multimodal transit hubs, which are locations where several transportation modes crossover. Interconnectivity would also be leveraged by the usage of several transportation options to ensure efficient and fast transshipment moves, synchromodality, between all the origin-destination pairs of the multimodal transit hubs network. Accordingly, this paper proposes a model-based decision support system to transship goods in an urban area based on the joint use of public transport mode (tramways and buses) and on-demand mode (cargo bikes and taxis). The paper uses a case to illustrate a mobility solution based on modular containerization (PI-containers). This case is built within an urban area where a set of predefined itineraries are designed to run different type of vehicles and multiple transportation modes. Finally, this paper demonstrates the benefits from creating synergies between freight and people mobility in urban areas from economic, ecologic, and societal perspectives.

2   Literature review

The literature dedicated to city logistics has proposed several innovative practices with the aim to improve the unsustainable situation currently operated by freight mobility at road traffic level. City logistics emphasizes the need for an optimized consolidation of loads from different shippers and carriers based on the coordination of freight transportation activities (Crainic 2008; Toh et al., 2009; Anand et al., 2012; Cleophas et al., 2019). Tactical planning models (Crainic et al., 2009) and operational transportation models (Crainic et al., 2004; Hemmelmayr et al., 2012; Crainic et al., 2015; Nguyen et al., 2017) have been proposed to cope with a number of real urban contexts. In these latter works, the two-tier modeling framework proposed for city logistics underlines the important role of peri-urban structural resources to connect distribution operations to urban areas. The expansion to multi-tier distribution systems is rapidly facing limitations when companies act solely, due to the heavy investment costs in durable facilities. Faced with a highly competitive context, urban deliveries must be redesigned to find the appropriate level of economic efficiency while integrating environmental and societal perspectives. In parallel, city logistics activities are subject to the regulations implemented by local authorities to minimize negative impacts (Savelsbergh and Van Woensel, 2016). The systemic view of city operations points out the crucial need for collaborative and sharing-based practices. City Logistics research and practice have shown that enhancing only traffic and parking regulations is no longer efficient to deal with all urban issues (de Jong et al., 2015) and that a more global vision on people mobility and goods delivery is desired in terms of sharing transportation networks, vehicles and routes.

The Physical Internet initiative enabled the emergence of the Hyperconnected City Logistics (HCL) for designing urban logistics and transportation systems that are significantly more efficient and sustainable (Crainic and Montreuil, 2016). In the PI framework, goods are encapsulated in standard, modular, smart, and reusable PI-containers, routed across open distribution networks. HCL is based on the key concept of interconnectivity, in order to shift to an open system engaging a multitude of diverse actors and emphasizing the interconnected utilization of existing urban logistics facilities and usable spaces. It enables leveraging on-demand paired transportation requests including transshipment, cross docking logistic operations as well as multiple transportation tools and options.

Several facts underlined the failure of current transportation companies to provide efficient distribution networks at the urban level (Crainic, 2008; Montreuil, 2011). Many researchers and practitioners have investigated innovative solutions with the consideration of shared vehicles between persons and goods as well as shared cargo bikes (Gruber et al., 2014) or freight rapid transit system (Fatnassi et al., 2015). Innovative mobility business models materialized in the last years finding a way to use alternative energy vehicles during slow periods outside rush hours (Hildermeier and Villareal, 2014). Several studies and literature reviews were published in order to present the potential benefits of the use of multimodal transportation system in urban areas (Kumar et al., 2016 ; Cochrane et al., 2017; Cleophas et al., 2019; Mourad et al., 2019; Cavallaro and Nocera, 2022).

Reducing the environmental impact of freight transport activities in urban areas is one of the primary concerns for more virtuous mobility, often approached through encouraging modal shift from road to other more environmentally friendly modes of transport. The concept of synchromodality, whose various foundations are discussed in many recent publications such as (Dong et al., 2018), (Ambra et al., 2019) and (Lemmens et al., 2019), allows standardized containers to switch between different modes of transport, dynamically adapting the routes according to planning approaches particularly based on real-time information. Faced with this search for flexibility, the number of transport modes directly available in a city impacts the possibilities for modal shift. Many research works propose approaches based on the design of interconnected networks, but there is no approach to evaluate the economic, environmental and societal performance of urban distribution based on multimodal

mobility using several public transport modes. In order to characterize the concept of urban synchromodality the following section is devoted to defining its underlying assumptions.

3   Multimodal on-demand transshipment problem

The modeling approach relies on multiple transportation options, time windows and distance constraints. These features give rise to a multimodal on-demand transshipment problem. However, only a few studies expressed these opportunities and attempted to model this specific on-demand transportation problem. Here, different types of vehicles with their own characteristics are being used for specific time windows at a daily basis. Each itinerary is dedicated to a specific transportation mode between different pairs of multimodal transit hub locations. Then, the proposed decision support system uses jointly several mobility options to serve a set of goods delivery requests. Several insights are derived from this illustrative case on the benefits of hyperconnectivity in ensuring an adequate delivery service, alternatively to dedicated on-demand vehicles. Also, the role of synchromodality is underlined in reducing the waiting time and parcels footprint at the urban level.

The model considers each PI-container as an independent traveler over the network aiming to reach its destination node before a deadline, by means of choosing several pairs of vehicles and multimodal transit nodes. Depending on the selected vehicle option and the arrival time to a node, a PI-container might need to spend some time in that multimodal transit node to get the next selected trip. Although the PI-containers are travelling independently from each other, they share capacity on the same selected trips and in the same visiting nodes. As the ultimate goal is to arrive with the least possible delay, the model tracks the timing of each PI-container's moves in the network. If the available urban mobility options or the operating couriers do not reach the expected service level (no late delivery), the use of on-demand vehicles which might speed up the moves is allowed yet penalized due to their unfavorable impacts. In the model is considered a single-size PI-container.

The problem is defined for a planning horizon broken into time intervals (large periods) to capture the deviations arising from the congestion and demand levels. The planning horizon is also broken into decision periods (small periods) to capture the problem dynamics, to update the parameters and to re-optimize the problem. In addition, there are scheduled moves on the public network over the whole horizon. For example, the defined time settings for a 6am-6pm horizon with 4 large periods, 12 small periods and several scheduled moves are shown in Figure 1.
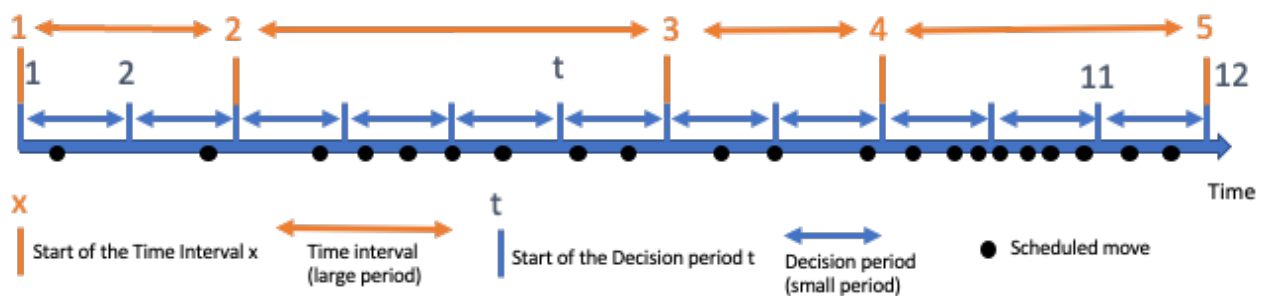

Figure 1: Time settings

There is one local hub, acting as the origin of arriving PI-containers and accessible for all transport modes. There are several access hubs dispersed in different zones of the city that can receive and dispatch PI-containers. This network design approach is based on the concepts of multi-plane meshed networks interconnecting hubs introduced in Montreuil et al., 2018. Access hubs are connected to one/several other access hubs by one/several transportation modes depending on the zone and accessibility of each arc by each transport mode. Each access hub can be the destination of an arriving of PI-container expressed by a capacity for reception and dispatching activities during each period

that can be defined the same as either the traffic-level time intervals or the decision periods. The capacity limit should be defined relative to the length of each period, otherwise it can impose unnecessary inflexibility in routing optionality. Depending on the length of each period, this capacity parameter implies the maximum availability of operational resources (workforce or chargeable equipment for unloading and loading operations) and space in the load/unload and holding area.
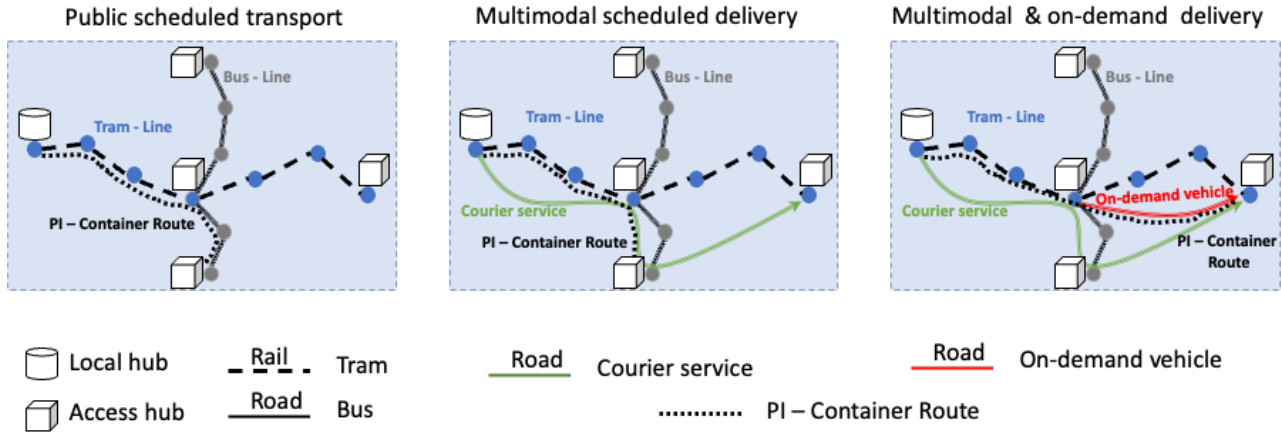

Figure 2: Multimodal good transportation system within Physical Internet context

The travel time on each arc depends on the transportation mode speed and the period' congestion factor, specified at the beginning of the large periods. Each of the public transportation modes has scheduled departures from the respective access hubs to respective destinations over the planning horizon. The courier service is another scheduled transport option with fixed and known itineraries (with scheduled departure from respective access hub). Each vehicle in the scheduled transport option (public or private) has a remaining capacity parameter which should be considered while assigning the PI-containers. On-demand vehicles can travel on some of the arcs depending on the zone of the arc's ends, the decision period and the on-demand transport option. As public transport and courier options have a fixed reachable network, their accessibility matrix is large-period independent and is defined separately.

Unlike the previous modes, there are no scheduled moves for on-demand vehicles. But assigning a PI-container to an on-demand vehicle to move on an arc on the network incorporates an uncertainty in the arrival of the on-demand vehicle. This arrival uncertainty may differ for each on-demand vehicle option (such as cargo bike versus taxi) in each access hub for each large period of the day. In a one-size PI-container setting and assuming that each request corresponds to a single PI-container, the arriving on-demand vehicle always has sufficient capacity. Calling an on-demand vehicle enforces an empty move for that vehicle to reach the respective access hub. Therefore, a fixed cost for each utilization of an on-demand vehicle is considered.

PI-containers start at the local hub and need to be delivered to an access hub destination. It is possible to choose a mixture of transportation nodes and intermediate access hubs to connect the arriving PI-containers to their destinations. Each PI-container has a soft deadline for its delivery to the destination access hub. Violation of this deadline incorporates a penalty cost, which might differ from one PI-container to another depending on the length of the delay. The following components should be considered in the objective function to minimize the impact of PI-containers' journey in the time and space of urban transport network space:

- Penalty cost for deviating from delivery deadlines;
- Fixed cost for calling on-demand vehicles (for their empty moves);
- Total arc-dependent travel costs incurred by choosing on-demand vehicles (includes the cost of undesired environmental consequences, like a CO_2 tax).

4   Illustrative example

To illustrate the solution approach proposed based on PI-container mobility, this section considers a typical urban context related to Bordeaux, a mid-size city in France. Different types of mobility options with their own characteristics are being used for specific time windows on a daily basis. The use case is built within an urban area where a set of predefined itineraries are designed to run vehicles of different types and multiple transportation modes. Each itinerary is dedicated to a specific transportation mode between different pairs of access hubs. The distance matrix for the illustrative example was generated based on the hypercentre of the city of Bordeaux. The network is composed of two types of nodes serving as PI-container transshipment and temporary storage locations. A local hub is located at the Bordeaux train station, it represents the starting point of the PI-containers and is characterized by a large capacity in terms of storage, speed of transshipment and connectivity with the public transport modes. In addition, the network is made up of 12 loading/unloading points which are access hubs corresponding, in terms of public transport, to stops on the routes and in some cases to interconnection points between the different modes. One of the characteristics of the access hubs is that they provide transshipment spaces with relatively small storage capacity corresponding to temporary waiting areas.

At the level of the selected urban area, Figure 3 presents the location of the transshipment nodes, the lines of the two public transport modes considered (bus and tram) as well as the spatial location of demand points that come from the survey on urban freight transport in the city of Bordeaux (French Mobility, 2015). The connections between the nodes of the network correspond to the routes taken by the different public transport modes using two types of infrastructure: rail for the tram and road for the bus.
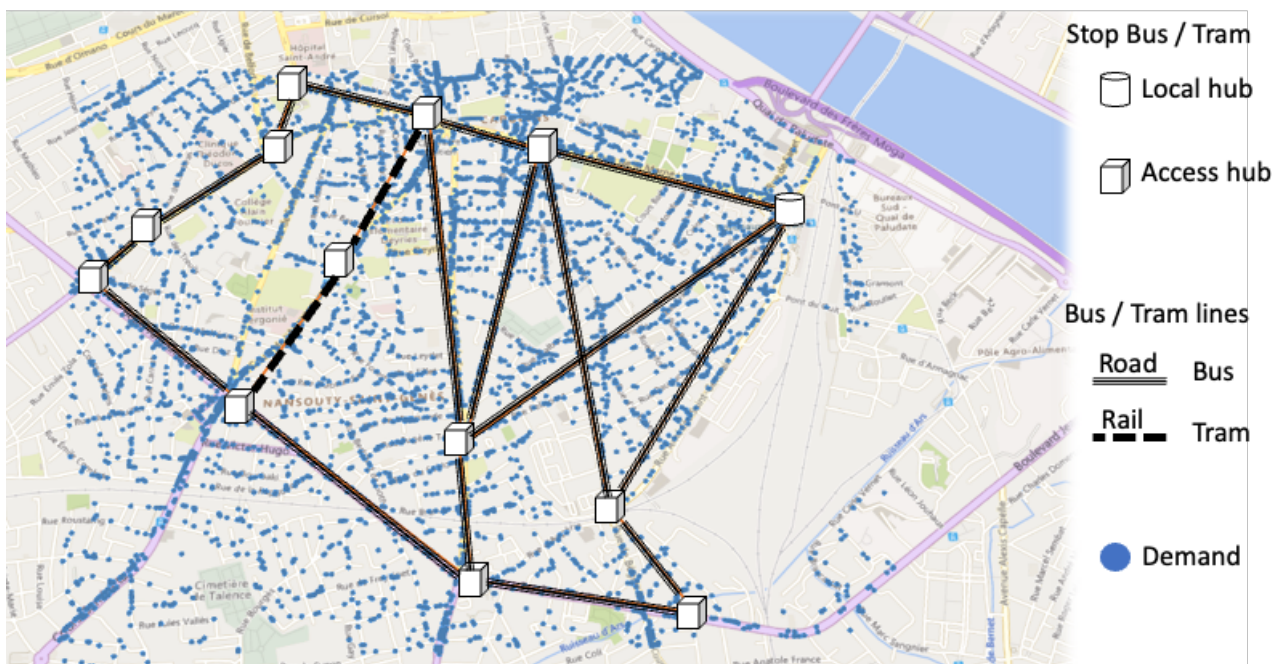

Figure 3: Spatial pattern of freight movements in Bordeaux hypercentre (one week)

The illustrative case is hereafter used to demonstrate how a multi-modes transportation system could operate, and to provide an assessment of the economic and sustainability benefits of such system in an urban context. The following section presents the results for different levels of demand, different time settings and different PI-container mobility options.

5   Preliminary results

This section investigates the performance of alternative configurations of multimodal on-demand delivery service exploiting several mobility options in satisfying a set of PI-container delivery demands. The performance assessment procedure considers the different characteristics of the problem in order to conciliate economic, ecological, and societal objectives. To this end, the following two subsections present different mobility network configurations over different time horizons and demand levels.

5.1   Scheduled multimodal delivery service

In this first investigated mobility network configuration, eight nodes are considered: 7 access hubs and 1 local hub. For the transport options, only scheduled public and private routes are exploited to connect the nodes. For public transport there are tram and bus lines and a courier service to the private sector, as shown in Figure 4. On a time-window of 3 hours divided into three periods of 1 hour, 14 scheduled departures are planned, as illustrated with the table in Figure 4.
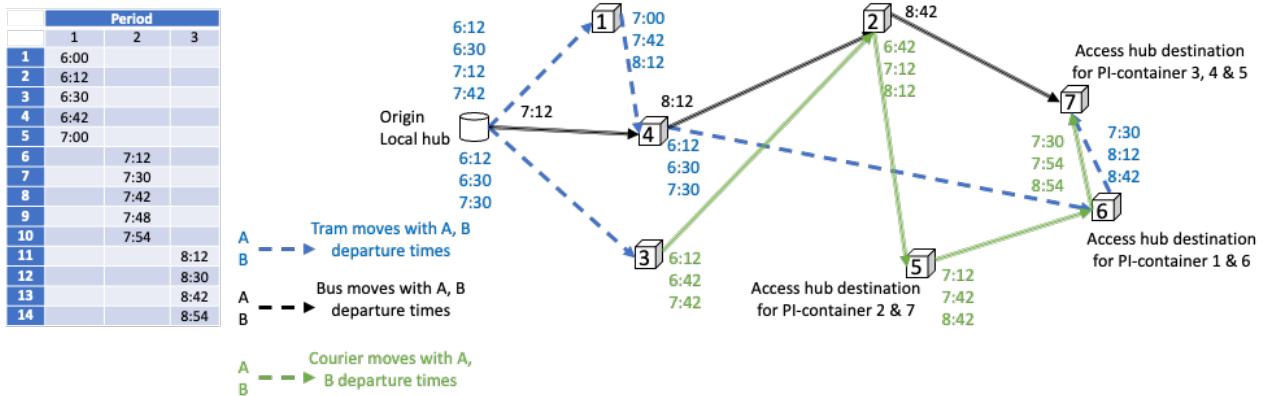

Figure 4: Timetables and multimodal network

The first results obtained are based on the delivery of 7 PI-containers considering the following assumptions: i) at each period the routes, the timetables and the travel times are known, ii) capacities are available on each route, iii) no constraints on congestion levels, transfer, and storage capacities in the access hubs, and iv) all containers are at the local hub at time zero. As presented at the table level in Figure 5, this first step made it possible to validate the solution approach by obtaining for each PI-container a route allowing to reduce unnecessary moves and the total waiting time from the PI-containers to the destination access hub. In the example, PI-containers 1 and 7 arrive at their final destination with a delay of 24 minutes and 36 minutes.
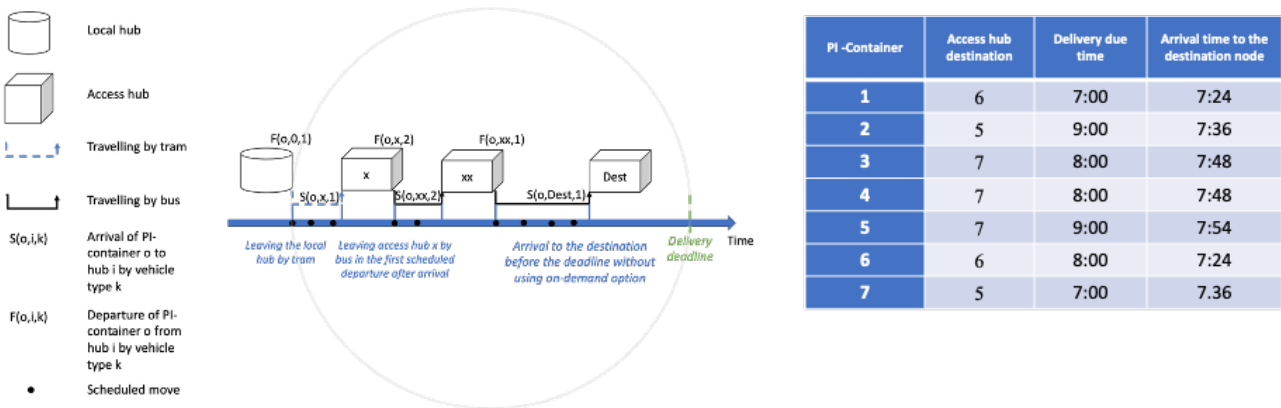

Figure 5: Example of delivery plan

5.2 Multimodal on-demand delivery service versus routing

In this second configuration of the mobility network, thirteen nodes are considered: 12 access hubs and 1 local hub. For the transport options, public scheduled lines and on-demand modes are exploited to interconnect the access hubs. The selected public transport network consists of one tram line and six bus lines. Over a 2-hour time window between 7 PM and 9 PM, 113 departures on public transport lines are planned. In terms of on-demand transport, two options are retained: taxi and cargo bike. Each of these options incorporates additional characteristics to measure the impact of the on-demand transport in the urban space (number of added vehicles to the city traffic flow, occupied city parking space per unit of time, etc.). For taxis, some parameters are added to consider the ecological impact (fuel consumption and CO_2 emission rate). Due to the different parameters for the multiple transportation options, the proposed problem involves finding a route for each PI-container, composed by a set of travel moves and transits. To this end, an analysis based on the delivery times of 30 PI-containers is proposed in Figure 6. The aim is to compare a modelling and optimization-based approach for the multimodal on-demand transshipment problem (Multimodal & on-demand) with an exact approach with CPLEX for solving Vehicle Routing Problem (VRP).

The two tested delivery modes incorporate the following assumptions: i) at each period the routes, the timetables, and the travel times are known; ii) the capacities are available on each route; iii) no constraints on congestion levels, transfer and storage capacities in the access hubs; iv) all containers are at the local hub at time zero; v) the loading/unloading time for one PI-container is 180 seconds; and vi) unlimited availability of on-demand resources. The results presented in Figure 6 make it possible to specify for each PI-container the local hub of departure (Origin), the access hub of arrival (Destination), the expected delivery time taking as start time 7PM (Delivery time expressed in minutes and seconds), and the arrival time taking as start time 7PM (Arrival time expressed in minutes and seconds) according to the two delivery modes. The VRP approach proposes a solution with a distribution of the 30 PI-containers in two trucks. Truck 1 will handle the delivery of 17 PI-containers and truck 2 will deliver 13 PI-containers, for a total distance traveled of 13.04 km.

Truck n°1

			Due date		Actual delivery time — Multimodal & on-demand		Actual delivery time — VRP	
Nb Order	Origin	Destination	min	sec	min	sec	min	sec
1	1	2	119	7140	102,20	6 132	3,28	197
7	1	2	119	7140	102,20	6 132	3,28	197
8	1	2	92	5520	87,20	5 232	3,28	197
16	1	2	75	4500	73,20	4 392	3,28	197
3	1	3	66	3960	62,00	3 720	11,82	709
4	1	4	77	4620	77,00	4 620	21,07	1 264
9	1	4	118	7080	105,80	6 348	21,07	1 264
27	1	4	110	6600	103,00	6 180	21,07	1 264
12	1	5	74	4440	73,20	4 392	29,80	1 788
13	1	5	48	2880	45,20	2 712	29,80	1 788
26	1	5	100	6000	99,50	5 970	29,80	1 788
5	1	9	42	2520	40,20	2 412	71,00	4 260
6	1	9	71	4260	70,50	4 230	71,00	4 260
11	1	9	56	3360	54,20	3 252	71,00	4 260
19	1	8	80	4800	76,50	4 590	80,02	4 801
20	1	8	76	4560	67,50	4 050	80,02	4 801
30	1	8	105	6300	86,50	5 190	80,02	4 801

Truck n°2

			Due date		Actual delivery time — Multimodal & on-demand		Actual delivery time — VRP	
Nb Order	Origin	Destination	min	sec	min	sec	min	sec
17	1	12	83	4980	69,80	4 188	4,58	275
21	1	12	92	5520	89,00	5 340	4,58	275
23	1	12	55	3300	43,20	2 592	4,58	275
14	1	10	64	3840	62,80	3 768	41,80	2 508
28	1	11	97	5820	96,00	5 760	50,05	3 003
15	1	13	87	5220	83,00	4 980	59,83	3 590
18	1	13	71	4260	69,00	4 140	59,83	3 590
25	1	13	88	5280	83,00	4 980	59,83	3 590
29	1	13	105	6300	98,00	5 880	59,83	3 590
2	1	7	54	3240	52,20	3 132	69,37	4 162
24	1	7	86	5160	80,80	4 848	69,37	4 162
10	1	6	78	4680	77,20	4 632	78,00	4 680
22	1	6	76	4560	63,50	3 810	78,00	4 680

Figure 6: Deliveries plans of 30 PI-containers (Multimodal & on-demand versus VRP)

The VRP approach proposes a solution in which the vehicle utilization rate decreases after each visit to the access hubs. As mentioned previously, all PI-containers are available at 7PM, regardless of the expected due dates. This constraint can lead to very long waiting times for the PI-containers once they reach their destination, as is the case for the orders 1 and 7 assigned to Truck 1. Lastly, the travel and unloading operations represent an occupation of urban space, either in terms of traffic or in terms of parking spaces.

In terms of the multimodal and on-demand solution, the results presented in Figure 6 show that each PI-container will have its own route defined according to the actual delivery times. This reduces the waiting time at the access hubs and ensures that the actual delivery time is close to the due date. This removes the constraint associated with the presence of all PI-containers at 7 PM, thus allowing greater flexibility in terms of arrival at the local hub. Of the 30 PI-containers delivered, 29 used only public transport by combining bus and tram lines, and only one PI-container used on-demand transport by cargo bike. The main resulting impacts are based on the reduction of the use of urban space and on the reduction of CO_2 emissions for goods delivery activities.

6 Conclusion

In this paper, a new approach is proposed for freight transshipment in an urban area based on the joint use of on-demand mode and public transport. The modeling approach is based on multiple transportation options, time windows and distance constraints. The solution approach is based on a forward-looking periodic approach that periodically solves the related on-demand multimodal transshipment problem with CPLEX. Based on the case of an urban mobility network in France, we proposed results that confirmed the effectiveness of our proposal in terms of service and sustainability. Several insights are derived from this showcase on the benefit of hyperconnectivity in ensuring an adequate delivery service, alternatively to dedicated on-demand vehicles. Also, the role of synchromodality is underlined in reducing the waiting time and parcels footprint at the urban level. Finally, this work demonstrates the benefits from creating synergies between freight and people mobility in urban areas from the economic, ecologic, and societal perspectives. These results show the feasibility of our proposal, and the performance levers it could bring in the future.

Avenues for further research include extending the model to consider several local hubs, more vehicle types/services in an on-demand mode. Extending the set transport options in the mobility network could also be an interesting avenue: leveraging options for goods transport that currently mainly dedicated to move people, such as automated vehicles (AVs) for on-demand transport requests.

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New business models for last mile delivery in city centres

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Abstract: In urban regions, freight transportation is crucial for replenishing stores and markets' inventories as well as for transporting packages, parcels and goods to citizens' homes. However, urban freight transportation generates a number of negative effects, such as increased air and noise pollution, disturbance of traffic flow, and traffic congestion. We wish to address a particular aspect of today's cities: the commercial traffic which enters cities daily and occupies the public space. We aim to reduce several of the nuisance sources of this activity. By reducing the traffic, we would obtain a lower carbon footprint of the commercial vehicles which come into cities to deliver e-commerce parcels to residents as well as reduced traffic and reduced noise. We present in this paper three possible templates to be implemented in cities which will have both positive attractiveness for logistic service providers, satisfy end-customers and yet reduce traffic and CO2 emission.

Keywords: Last mile delivery, city logistics, business models, regulatory framework, URBANE Project.

Conference Topic(s): business models & use cases; last mile & city logistics; logistics and supply networks; omnichannel & e-commerce logistics;

Physical Internet Roadmap ([Link]): Select the most relevant area for your paper: ☐ PI Nodes, ☐ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.

1 Introduction

The purpose of the URBANE project is to help cities in Europe in increasing social welfare for their residents. To this end we are dependent upon other partners in the project to provide a set of objectives and the Key Performance Indicators (KPIs) which would have to be tracked to monitor the performance of the solutions which we wish to provide. Since such KPIs have not yet been defined, we shall only describe in a general way how the proposed framework, business models, policies, and Incentive schemes would provide some of the necessary impetus to improve such KPIs and succeed in achieving the targets. In urban regions, freight transportation is crucial for replenishing stores and markets' inventories as well as for transporting packages, parcels and goods to citizens' homes. However, urban freight transportation generates a number of negative effects, such as increased air and noise pollution, disturbance of traffic flow, and traffic congestion.

We address the e-commerce generated traffic which enters cities daily and occupies the public space. By reducing the traffic, we would obtain a lower carbon footprint of the commercial vehicles which come into cities to deliver e-commerce parcels to residents as well as reduced traffic and reduced noise.

We must indicate here that the task covered by this report only includes the traffic generated by the delivery of orders placed by residents through phone or e-commerce (ie, the 6% that have

been identified as such in the study on urban logistics in the city of Vienna, 2019, see Figure 1).
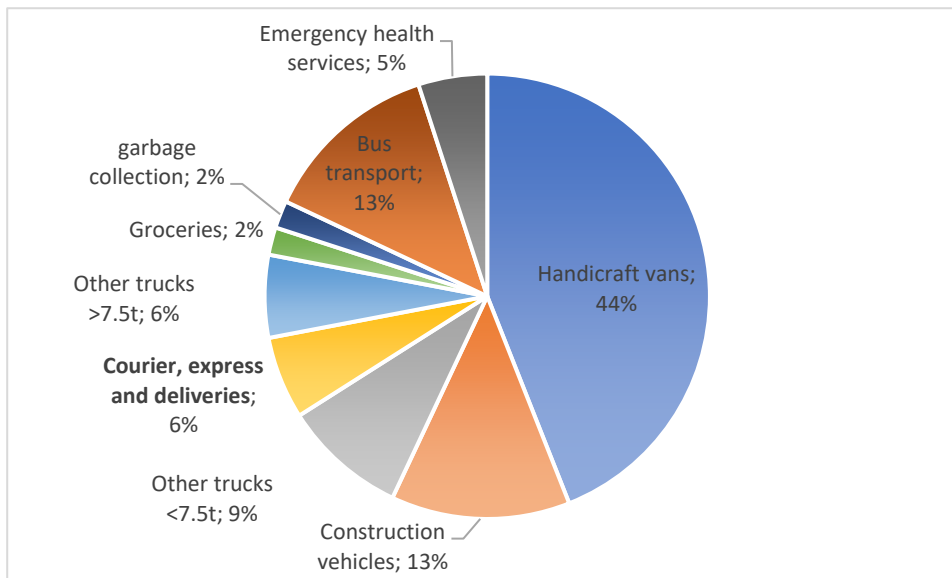

Figure 1: Urban logistics, distribution by type, Vienna 2019 (Mobilität mit Zukunft, VCO)

This means that we do not take into account the traffic due to public services such as waste collection, ambulance or other health services, police, firefighting services. We do not take into account either the traffic due to construction and other building services which have to enter the city to deliver building materials or take out rubble or other building waste. Commercial transportation regarding the replenishment of shops, deliveries from shops to customers or the traffic due to artisans on their regular installation works in the city are not included here either. Finally, we do not consider people mobility services.

In the remainder of this paper, we present the various stakeholders that we have identified and their characteristics in terms of sensitivity to the e-commerce last mile delivery services. We then define the governance and regulatory models which should be set up to frame the way each of the stakeholders would develop their activities before presenting the three operating models that could be set up to for the last mile delivery of goods ordered online in city centres.

2 Stakeholders

We present below those stakeholders and describe how they will interact with each other and with the organizations which will be carrying forward the job of reducing the carbon footprint of the last mile delivery of parcels in city centres when the necessary regulatory framework will have been defined and set up.

2.1 City authorities

City authorities are the de jure representatives of the residents. As such they are responsible for their wellbeing and echo their preoccupations. Over the years city authorities have developed and implemented several types of regulatory frameworks for the usage of public space and roads such as parking space, traffic control, etc. In that capacity some are now trying various policies to reduce the various types of pollution such as noise, fine particles, and CO_2. we will presume that city authorities have the power to define under which conditions parcels can be delivered to residents. That presumption involves political power and a political will to do so.

2.2 Third party logistic service providers (3PL)

The number of 3PLs delivering e-commerce parcels in a city are usually limited in number and remain the same firms over a long period of time. In the project, we expect to observe approximately four to five large 3PLs and a limited number of local operators with fleets of environmentally friendly delivery vehicles such as bikes, cargobikes, electric scooters and the like.

For the major 3PLs such as DHL, Fedex, UPS, DPD, Chronopost, Die Post and other local post parcel delivery providers, the cost of delivering in a city centre with its high density of deliveries means that the cost per drop is low. It is reckoned that 3PL make a profit on deliveries inside cities with dense population but a loss on deliveries to residential and rural addresses. The plan presented here would be to maintain their commercial and logistic presence in the market of city deliveries while controlling or reducing costs. These stakeholders are key to the success of the project.

2.3 Microhub and locker owner-operators

Microhubs are logistics facilities for micro-consolidation, which is the bundling of goods at a location near the final delivery point (e.g. within 1 to 5 km from the final destination)(Janjevic & Ndiaye, 2014).

Microhub operations may use a permanent building or a mobile structure, operate on a permanent or temporary basis, and may be operated by one or more businesses in parallel. In general, though, microhub operations have five common characteristics (Janjevic & Ndiaye, 2014):

•   Intend to reduce the number of vehicle trips in an urban area

•   Focus on the delivery of smaller and lighter loads

•   Allow goods to be transferred to a cleaner mode of transport, such as cycling or walking, for the last mile of delivery

•   Are typically operated by privately owned transportation companies

•   Facilities are located within an urban area near the final delivery point
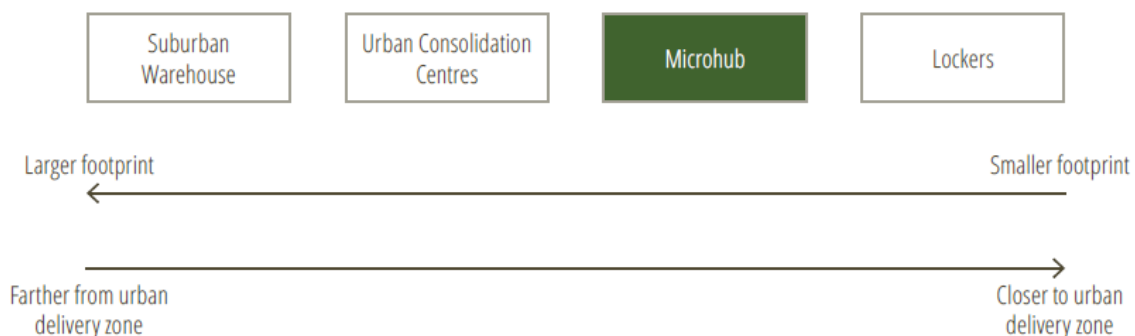

Figure 2: Types of urban logistics spaces (Janjevic & Ndiaye, 2014)

Single-carrier microhubs are typically private-led initiatives. Transport companies can use these microhubs as additional transhipment platforms within their existing and exclusive delivery networks and build them to be either stationary or mobile (Katsela et al., 2022). The position and corresponding authorization by the city authorities must be related to delivery volumes and frequencies. As those change in time, so the lockers and microhubs must be eventually repositioned to different locations.

2.4 Residents

Residents are interested in obtaining their deliveries on time and in full at the desired delivery spot (drop-off point or home). They consider that their welfare is improved if traffic on the streets, pollution, and noise are reduced.

We expect to define within the URBANE project the variables to be monitored which take all these aspects into consideration and establish the corresponding KPIs. This category of stakeholders will not object to the plan we propose given that the outcome will be improved welfare.

2.5 Cargobikes and other small electric vehicle operators

This category of stakeholders includes various types of firms: some large, others small, some privately owned or in partnership with a city. We consider here that their preoccupation is to ensure commercial viability and acceptance by the other stakeholders.

2.6 Parcel exchange platform

This type of stakeholder is necessary in the proposed solutions which are to be contemplated in this report and in the upcoming work in the course of the URBANE project. There already exist a stream of literature on such platforms with some proposing white label ones (Pufahl et al., 2020). This platform would be created jointly with city authorities and 3PL participation to ensure success. Such a platform will provide the following services to the 3PL and to the city.

To the 3PL:

•	On a real-time basis evaluate and present each 3PL with a set of routes combining the available parcels to be delivered or picked up inside the city in such a way as to optimize the number of stops, kilometres, and time of the appropriate delivery vehicle.

•	Present updated quality metrics (on time delivery) for parcels delivered the preceding business day for all parcels offered in the platform. These metrics will be the basis for quality reports for each 3PL about the deliveries performed by the assigned 3PL of the parcels originally entrusted to them. For example, if DHL has 300 parcels to deliver or pick up daily and these are shared between DPD, UPS, FedEx as well as DHL, then DHL will be informed of the quality of the service provided by the others as well as its own vehicles.

•	Define periodically the bonuses and penalties shared out between the 3PL according to their quality of service over the considered period. This will ensure that all 3PL will strive to provide the highest possible service over time.

To the city:

•	Periodic reports about the number of parcels delivered by period and neighbourhood.

•	Periodic reports about the market share of the various 3PL active in the city. These will have to include all 3PL which participate in the parcel exchange platform.

•	Periodic reports about the overall quality of delivery service provided by the 3PL in the platform. These reports might help the city in vetting the 3PL active in the delivery service provided to citizens.

•	Periodic reports about the emissions generated by the traffic of delivery vehicles inside the city as well as an estimate of the traffic generated in terms of road and parking occupancy.

To be able to deliver those services, a number of information systems are required. The type and form of those systems are detailed elsewhere in the project.

Information from the 3PL

- Parcels to be delivered or picked up in real-time by the 3PL with the corresponding logistic information such as origin and destination, size and weight of the parcel, time widow in which the parcel must be delivered or picked up. This information will serve as the basis for the optimization of the PUDO routes which will then be assigned to a particular vehicle.

- Geographic position in real time of the fleet of delivery vehicles operating. In this way the system will assign a PUDO route to the optimally available vehicle in real time.

Information from the microhub operators

- Information about parcels received for each microhub so that they be assigned to a vehicle for delivery in real time.

- Information about parcels returned because of missed deliveries in real time. In this way, a new delivery may be planned in a new time window.

Information from the city:

- Planned works in the city such as road closures, restrictions, parking availabilities etc. This information will be used by the exchange to evaluate the optimal PUDO routes.

- City plan of roads, parking spaces, traffic lights, etc.

Various economic models can be applied. In the following some of the most important by their expected consequences. Others could eventually be implemented.

3 Governance and regulatory models

3.1 City regulatory authority

We describe briefly the framework of rules which the city authorities would set to the 3PLs as well as the locker and microhub operators who which to provide their services to the residents. Such an entity would issue the regulatory framework needed for the operation of 3PL in the city centres. Such a framework would be necessary so as to ensure that all commercial entities which operate in the city be included and that the "playing field" be made level. For example, if a city wishes to reduce the pollution and other sources of Green House Gas (GHG) emissions, then the maximum level of emissions per vehicle/km will have to be provided by type of vehicle. In the same way, some cities prohibit the entrance to city centres at some hours of the day or days in the week. These restrictions should be made mandatory for all operators in the same way. The city regulatory framework should be made visible and its evolution in time (towards stricter limits) be made clear and sufficiently in advance so that the commercial operators have the time to adjust their operations. It appears also evident that some form of consultation and recourse should also be provide so that the necessary debate and information exchange can take place in the best interests of all parties.

3.2 Third party logistic service providers

The 3PLs who wish to participate in the PUDO of parcels in the city would have to adhere to the regulatory framework. This includes all 3PLs whatever their nature, public or private, and whether they operate with their own fleets of vehicles or through third party fleet owners as well as other transport service providers such as cargobike, electric vehicle, delivery robots or bicycle operators.

As participants, 3PLs would have to link up their information services to the parcel exchange platform of the city through the corresponding APIs. They would also agree to participate in

the financial incentive schemes provided by the parcel exchange in such a way that bonuses or penalties could be perceived or paid up. The incentive scheme would involve also sharing some information about previous periods activities and costs. These will be described later.

3.3 Microhub and locker owner operators

These actors own some real estate in the city on which certain infrastructure has been built. They would need to be involved in obtaining some synergy by consolidating flows from distinct 3PLs in a micro-consolidating of parcels in local microhubs. They might be incentivized into setting up hubs or lockers in public places through favourable treatment of permits or even subsidized rent by the city authorities. Sharing of resources is a way of collaboration in last mile delivery. Urban consolidation centres are a typical example of this (Marcucci & Danielis, 2008). A white-label pickup station follows the idea of sharing logistics resources to improve performance and decrease environmental impact. The particularity of a white-label pickup station lies in its openness to all (or at least a group of) parcel delivery companies as delivery point. A white-label pickup station may be operated by a logistics company, any other company or the public sector. Independent of its operator, it potentially offers various benefits (Schodl et al., 2020).

In return for placing such logistic warehousing capacity, the 3PLs would be invoiced according to the usage done. The usage would be calculated as the number of lockers in time or the square meters in time being occupied by parcels or other forms of cargo.

3.4 City residents

The city residents are interested in getting the deliveries of their e-commerce orders on time. They are also highly aware of the traffic, noise, and pollution generated by the 3PLs and other cargobike services. Their behaviour may generate further disturbance and extra costs in terms of the above because of missed deliveries due to absence.

4 Operating models

There are several PPP operating models with varying degrees of participation, from almost total public sector control (i.e. city) to almost total private sector control (i.e. 3PL). Basically, the following forms of PPP operating models can be distinguished:

• The Build-Operate-Transfer (BOT) model assumes that construction and financing are private. After construction, ownership is transferred to the public sector. Operations can then be carried out by the public sector or by a private operator. As a rule, the latter will then be granted an operating license for a limited period.

• Build-Own-Operate-Transfer (BOOT). In contrast to the BOT model, here the private investor temporarily receives the ownership rights, which pass to the public sector at the end of the contract period.

• The Lease-Develop-Operate (LDO) is the form of a leasing contract. The construction, financing and operation are private, but the ownership remains in public hands.

• In Build-Own-Operate and Buy-Own-Operate (BOO), all criteria are organized in the private sector. Since these are public tasks, the state will secure itself via contracts or public regulation.

Table 1: operating model types

Operating Model		Administrative fiat	Provision of Infrastructure	Market regulated
Owner		Public Sector	Public / Private Sectors	Private Sector
Operator	Package Exchange	City	City	Neutral Third Party
	Microhub	City	City	3PL
	Last Mile	City	3PL	3PL
White Label		Yes	Yes/No	No

4.1   Administrative model: administrative fiat

In this model, the city assumes the operation of the package exchange, microhubs and the last mile. It owns the microhub real estate.

4.2   Provision of infrastructure

Here the city assumes the operation of the package exchange and the microhubs. It also owns the microhub real estate. Similarly, as in the first Operating Model, the activity of 3PLs regarding parcel delivery within city limits is restricted due to environmental or transport regulation. However, the last mile is carried out by 3PLs, who either closely cooperate within a white label framework or do not cooperate with each other, being parcels sorted on the basis of the respective 3PL and fed into their respective routes. Here the delivery vehicles (incl. cargo bikes and others) are provided, operated and maintained by the respective 3PL.

4.3   Market regulated

This model describes a variant in which a neutral third party assumes the operation of the package exchange, while 3PLs operate microhubs and last mile deliveries. Ownership of the microhub real estate is in private hands, who rents it to the 3PLs. There is no city environmental or transport regulation. Here the operation of the microhubs and the delivery of parcels within their respective zones of influence are allocated to individual 3PLs. Since this model is not a white label approach, there is only limited cooperation within the 3PLs. The delivery vehicles (incl. cargobikes and others) are provided, operated and maintained by the respective 3PL.

5   Business Models

Here we will only present for the three operating models the key activities, cost structure and revenue sources to conserve space.

Table 2: key activities for each operating model

Key Partner	Administrative fiat	Provision of Infrastructure	Market regulated
City	Regulate parcel deliveries in the inner-city Operate the package	Regulate parcel deliveries in the inner-city	Ensure Neutral Operator and 3PL

	exchange Buy / build and operate microhubs Buy and operate last mile equipment Debit 3PL for parcel deliveries in the inner city	Operate the package exchange Buy / build and operate microhubs Debit 3PL for parcel deliveries in the inner city	performances through service contracts
3PL	Transfer parcel data to package exchange Deliver parcels to microhubs	Transfer parcel data to package exchange Deliver parcels to microhubs Buy and operate last mile equipment	Transfer parcel data to package exchange Deliver parcels to microhubs Rent and operate microhubs Buy and operate last mile equipment
Neutral Operator	None	None	Operate the package exchange
Real Estate Developer	None	None	Buy / build microhubs

Table 3: Cost and revenue sources for the three operating models

Key Partner		Administrative fiat	Provision of Infrastructure	Market regulated
City	**Cost structure**	Investments in microhubs and last mile equipment Costs of operation of microhubs and last mile delivery Costs of operation of package exchange	Investments in microhubs Costs of operation of microhubs Costs of operation of package exchange	Service invoice from the Neutral Operator
	Revenue sources	Service invoice to 3PLs	Service invoice to 3PLs	Service invoice to 3PLs
3PL	**Cost structure**	Reduction of last mile delivery costs Service invoice from the city	Investments in last mile equipment Last mile delivery marginal cost Service invoice from the city	Costs of rental of microhubs Last mile delivery marginal cost Service invoice from the city
	Revenue sources	None	None	None
Neutral Operator	**Cost structure**	None	None	Costs of operation of package exchange
	Revenue sources	None	None	Service invoice to the city

Real Estate Developer	**Cost structure**	None	None	Investment in microhubs
	Revenue sources	None	None	Rental fee from 3PLs

6   Incentive schemes in each operating model

6.1   For administrative fiat

To ensure the success of this model, the city must make participation compulsory. If, as has happened in some cities, the 3PL can withdraw from this operating model, they will do so and that will lead to the failure of the model and a return to the previous undesirable situation. Given the above, the city authorities will need to establish a very strong and clear regulatory and governance framework establishing clearly the roles, expected performance metrics and regulatory regimes for all of the actors involved: the 3PL, parcel exchange platform, and real estate developers of the microhubs.

The 3PL only deliver to the microhubs and no longer have the commercial contact with the end-customer. Given the importance of this continued contact, they are expected to refuse to participate in such an operating model. In this model, the cargobike operators take over that role. It is to be expected that 3PL will resist this change. Only if participation is compulsory under the threat of exclusion from operating in the city will they agree.

As the cargobike operators will deliver, they are entitled to a share of the fee that 3PL receive for the delivery (or collection) from the end-customer. There is a risk that this fee will not be shared as it should be since the city has effectively a monopole on the contracting of the cargobike operator. The neutral operator of the last mile PUDO service inside the city centre limits is a de facto monopolist. As such, she has to report quality of service metrics such as percentage of parcels delivered within the time slot which the end-customer booked. To ensure that the neutral operator does not engage in opportunistic behaviour, proof of delivery (POD) data about the final delivery would be collected and made available to the 3PL whose parcels are thus being manipulated.

6.2   Provision of infrastructure

In this model, the 3PL has to invest in the ecologically friendly transport equipment to deliver themselves the parcels retrieved from the microhubs to the end-customers. In this case, the 3PL do keep the commercial contact with the end-customers. The investments in the microhubs and the package exchange platform have to be borne by the city. The cost of using such infrastructure shall be paid by the 3PL. The necessary incentive to ensure adoption of this model by all 3PL delivering in the city is equivalent to the difference between these costs and those supported by them in the anterior situation. This difference is expected to be negative (ie, the cost will be higher in this operating model because of the cost of investment in the ecologically friendly delivery vehicles, probably electric vehicles). Again, to ensure that all 3PL comply, the city will have to make the subscription to the parcel exchange platform compulsory.

6.3   Market regulated with private operators

The cities will have an important role, we propose that cities must agree to a common set of dispositions which would be adopted across Europe. The logistic service provider is the owner and operator of the fleet of inner-city delivery vehicles (eg, cargobikes, electric delivery vans) will perform PUDO operations along optimized tours provided by the parcel exchange platform. This means perfect coordination through the exchange platform between the three

actors: the 3PL, the microhub and the final delivery service. The parcel exchange service has the duty to transparently inform all parties about the position of parcels, position of delivery vehicles and the messages that need to be transmitted to the right parties. Only if the whole information system including the 3PL, the last-mile delivery vehicles and the end-customers works seamlessly can the value be unlocked.

7 Conclusion and possible evolution between models

As we have seen, all the above operating models have widely different implications for the delivery and collection of parcels in city centre. City authorities have an important role to play. According to their political will and the availability of city officials to take on many duties, they can engage in centralizing the logistics of deliveries or let the market take on that responsibility. What is evident is that if cities intend to follow up on citizens demands on clean air, unclogged roads and high-quality service for last mile delivery, they must take action. This action mostly turns on setting a regulatory framework which will foster the development of electric delivery vehicles in dense city centres. Cities must also help in presenting clear and well-defined rules for the investment in microhubs and lockers. It is the recommendation of this work that beyond the initial investment, cities should not subsidize neither of the delivery or storing services. We could have a city start with a laissez faire policy change as technology evolves and citizens behaviours change. For example, if citizens can be convinced to pick and drop off their internet orders at lockers or specially equipped stores, that in itself might reduce traffic as there would be less PUDO. If electric delivery vehicles become cheaper, there might be more.

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Thrive with standard moving towards the Physical Internet

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Keywords:
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Global Data Standards; Situational Awareness

Conference Topic(s): *interconnected freight transport; distributed intelligence last mile & city logistics; logistics and supply networks; omni-channel & e-commerce logistics; PI fundamentals and constituents; technologies for interconnected logistics (5G, 3D printing, Artificial Intelligence, IoT, machine learning, augmented reality, blockchain, cloud computing, digital twins, collaborative decision making).*

Physical Internet Roadmap *(Link): Select the most relevant area(s) for your paper:* ☐ *PI Nodes,* ☐ *PI Networks,* ☒ *System of Logistics Networks,* ☒ *Access and Adoption,* ☐ *Governance.*

Abstract

Supply Chain stakeholders have struggled for decades to get even the minimum information from transport and logistics networks that they need to manage their Supply Chains in such a way that these stakeholders can meet the expectations of their Customers. Among other needs, the Supply Chain stakeholders need a reliable answer to two very basic questions:

1. ***Where are my Goods?***
   The SC stakeholders (Sellers and Buyers) think in Goods Sold/Purchased.
   All to often the actors in transport and logistics forget that all transport activity is ultimately to Move Goods from where they are to where they should be.

2. ***Are my Goods still in good condition?***
   Once the Goods are at the right location (hopefully at the right time), the Seller/Buyer of the Goods needs these Goods to be in a condition that they can be used for the intended purpose be it used in manufacturing or consumption by humans or animals.

Knowing the answers to these questions more or less in real-time will create the situational awareness about the Goods and the associated Trade Transactions, which in turn will assist the Supply Chain stakeholders to take the most appropriate actions to address an exceptional situation with the goal to ensure as good an experience for their Customer as possible.

Introduction

Supply Chain stakeholders have struggled for decades to get even the minimum information from transport and logistics networks that they need to manage their Supply Chains in such a way that these stakeholders can meet the expectations of their Customers. Among other needs, the Supply Chain stakeholders need a reliable and timely answer to two very basic questions:

- *Where are my Goods?*
- *Are my Goods still in good condition?*

Knowing the answers to these questions more or less in real-time will create the situational awareness about the Goods and the associated Trade Transactions, which in turn will assist the Supply Chain stakeholders to take the most appropriate actions to address an exceptional situation with the goal to ensure as good an experience for their Customer as possible.

It is important to note that these questions are far more about the effectiveness of the Supply Chain (and supporting T&L) than they are about efficiencies (even though the data needed will also enable many efficiency improvements).

The Physical Internet (like the Internet itself) ***must*** help the users of the Physical Internet to be both more efficient **and** more effective (improve Customer experience through more resilience, reliability, predictability, communications).

Key challenges for the actors in T&L to be able to respond to the two questions above included lack of standards, disconnected standards or even conflicting standards. However,

There is now a range of standards from various standardisation bodies that are quite well aligned and may therefore be combined to ensure the flow of data that can respond to the two questions mentioned above.

We will briefly present various standards from UN/CEFACT, GS1 and ISO as well as event and event data standards. We will also cover the work of the International Taskforce Port Call Optimization (ITPCO) and how that is being incorporated in standards and other documents of the IMO, IHO, ISO and other organisations that Maritime Transport relies on.

More importantly, we will indicate how these standards interoperate to solve issues that have plagued Transport and Logistics networks for a very long time. Using the relevant standards in the most appropriate combinations will enable the Supply Chain stakeholders and the operators in Transport and Logistics to collaborate and exchange the information required to be able to respond to the two questions at last.

Most of the standards we will present are targeted mostly at "unitised" cargo (transported in any kind of "packaging" or "container" a.k.a. "transport units"). Therefore, the standards we will present and how they interoperate will be of interest to all supply chain stakeholders (large or small) who manage the transportation of their goods in discrete, identifiable transport units. That said, other standards cover all types of cargo including bulk products (grains, oil&gas, ores, chemicals, etcetera). Bulk transportation (goods that are **not** transported in transport units but rather directly in transport means such as tankers, rail wagons, barges and so on) presents challenges that one generally does not encounter in the context of unitised cargo.

In short, we want to present the recently released standards for improved exchange of information among stakeholders in Trade and Transport and Logistics, and *how these standards interoperate and reinforce each other in delivering much improved supply chain visibility, situational awareness and collaborative decision making.*

1 Foundational principles for interoperable standards in Supply Chains and Transport and Logistics

Although it would seem all to obvious, the following principles are all too often overlooked by stakeholders engaged in supply chain and transport and logistics activities:

- **ALL transportation starts with the SALE of GOODS**
  If there were no Sellers and Buyers that agreed that the Seller would (at some agreed pricing) provide the Buyer with an agreed set of products, at an agreed location, at an agreed time and in an agreed condition, then there would also not be any need for transportation of those goods.

- **ALL transportation is ultimately paid for by the Beneficial Cargo Owner (BCO).**
  The Seller or the Buyer. Today, the number of shipments crossing country borders directly related to a Consumer is more then twenty (20) **times** higher than the traditional large shipments between "large" organisations.
  Waste in transport and logistics operations causing higher costs
  translates into higher product prices for all of us.

- **Cargo does not move unless data moves** [1]
  As the article on the "Insider Thoughts" pages of the ICC explains, there is an ever increasing need for information to be made available to stakeholders involved in the journey of Goods from Seller to Buyer to ensure those goods (shipments) can be transported at all. Regulatory requirements as well as Customer/Consumer demand all require much more data to be available than ever before. So much so, that the traditional ways of paper-based provision of information are no longer able to support all of these requirements.

> The most basic conclusion from these foundational principles is that all information to be made available across the supply chain and related transport and logistics **must** be linked to the transaction (SALE of GOODS) that triggered the entire process in the first place.

Because most (nearly all) standardisation efforts have been conducted in various (narrow) silos within the wider area of supply chain and transport and logistics, many standards have been developed without taking into account the need to always be able to link back to the original Sale of Goods transaction. UN/CEFACT called this the Gap/Disconnect between the Trade and Transport domains. In turn that Disconnect makes it difficult for practitioners in the field of supply chain and transport and logistics to "patch together" the often significant number of standards to achieve some level of consistent support for their daily operations.

2 Standardisation efforts moving in the right direction

Fortunately, over the past decade, several standardisation initiatives have realised the need to look at the development of standards in a more holistic fashion and started to fix the Disconnect.

Probably one of the first to do so is the [International Taskforce Port Call Optimization](#) (ITPCO)[2] that started its efforts almost ten years ago. It is now one of the most influential groups for development of standards related to the maritime mode of transport. See figures 1 and 2 below.
Because maritime transport takes care of over two thirds of all cargo carried over any distance anywhere in the world we will cover that mode of transport in a bit more detail than others.

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1   https://icc.academy/cargo-data-supply-chains/
2   See flyer: https://portcalloptimization.org/images/Flyer%20ITPCO%2020221220%20(1).pdf

Figure 1: ITPCO participation

Figure 2: ITPCO Endorsers

Right from the start, ITPCO adopted a roadmap for development of standard. See figure 3 below.

Figure 3: ITPCO Agenda / Roadmap

Note-1: The 8-step approach also includes that the standards developed will find wide-spread adoption and implementation (where applicable).

Note-2: The roadmap shown here is applicable to all standards development efforts. Just replace "port calls" with the name of the process to be improved.

ITPCO also did **not** want to reinvent any wheels. Therefore, the efforts build on standards already available (consolidating and harmonising along the way) and then anchoring that in robust global standardisation organisations (like IHO, ISO and IMO as most appropriate for maritime). Other standardisation organisations like UN/CEFACT, GS1 and may also be included as appropriate.
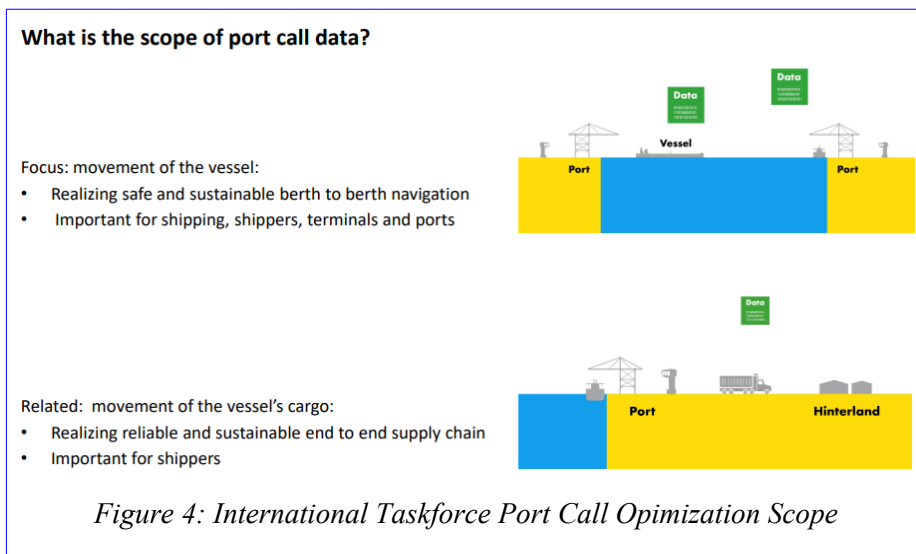
Figure 4: International Taskforce Port Call Opimization Scope

ITPCO also recognised right from the start that although ITPCO was a group that could have operated in a silo, maritime and ports operations have to be an **integral** part of the end-to-end supply chain. The slide in figure 4 is taken from ITPCO Agenda presentation[3].

From this slide, it will be clear that the focus of

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3   https://portcalloptimization.org/images/Agenda%20230118.pdf#page=5

ITPCO is on the vessel and operations, events, communications, etc and standards related to the vessel.

These maritime and port standards support two major initiatives in the maritime and ports environment: Port Call Optimization and Just-in-Time Arrival. Both of these are instrumental to improve the performance of Maritime and Ports operations in terms of efficiency, effectiveness and sustainability (see also section 4). The illustration below positions these initiatives.

The ITPCO standardisation results are adopted in several foundational documents of the IHO, IMO and ISO.

E.g., The ISO 28005-series provides the technical specifications to support the maritime community. Work is on-going in ISO TC8 (Ships and Maritime technology) to enhance the ISO 28005-series with the results of global collaboration within the maritime and ports industry to develop standards that are well aligned with the wider supply chain standards.
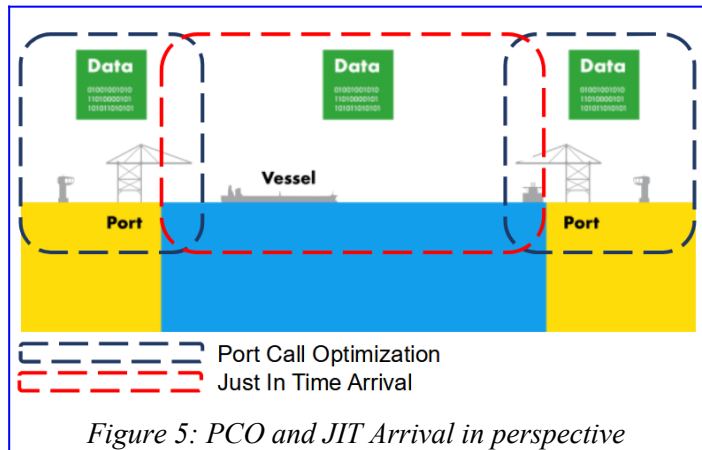
Figure 5: PCO and JIT Arrival in perspective

A key component in these efforts is unambiguous definitions for exactly when an Event is considered to have occurred. E.g., What does "Vessel arrived at berth" mean? Is it when the vessel has started manoeuvring to come alongside, when the first line is ashore, when the last line is secured, when gangway is safely down or yet another trigger point. There may be several hours between the occurrence of these trigger points. Unambiguous definitions have been agreed and documented in ISO 28005; work is ongoing to add more - also related to landside Events up to and including transfer of cargo between port facilities (e.g., terminals) and connecting landside modes of transport.

*Similar confusion about the exact trigger points for events
also exist in all other modes of transport and all over the supply chain.*

The ITPCO agenda above, clearly starts with understanding the business process and the slide above indicates that it is also important to understand how this all fits into the "bigger picture". Again, the slide is merely included as an example of positioning the specific standardisation effort within the business process itself and the relationships with adjacent business processes. Similar positioning slides can be created for standardisation efforts anywhere in the supply chain.

UN/CEFACT also started to adopt that more holistic approach to fix the Disconnect between Trade and Transport mentioned above.

One of the first examples of that are the efforts related to the so-called "Smart Containers". The smart containers are any kind of packaging that is equipped with IoT (Internet of Things) devices that can communicate with the world outside the "container". The Smart Containers efforts first delivered a White Paper. This White Paper lists some 20 Use Cases that occur in different places in the life cycle of a smart container as it travels/circulates through the supply chain.[4]

The Business Requirements Specification[5] (the official UN/CEFACT standard) elaborates on these Use Cases and adds a few more. Many of the Use Cases rely on information provided by sensors connected to the IoT devices. These sensors provide the basic information that can help the stakeholders involved to determine whether the goods transported in the smart container are still in "good condition", so they may still be used when those goods arrived at their destination.

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4   https://unece.org/DAM/cefact/GuidanceMaterials/WhitePapers/WP-SmartContainers_Eng.pdf#page=9

5   https://unece.org/fileadmin/DAM/cefact/brs/BRS-SmartContainer_v1.0.pdf

More importantly, the BRS clearly places the Use Cases in the business context of Shipments Transported from Seller to Buyer[6]. See figure 6.

Even though there is currently only a very small percentage (well below 5%) of all intermodal containers equipped with IoT devices (even less when looking at other kinds of containers), there are initiatives also from major industry actors that will increase that percentage. E.g., Hapag-Lloyd have stated they will equip **all** intermodal containers that they use with IoT devices (enabling tracking in real-time).

That said, this UN/CEFACT standard for developing smart container solutions will assist all stakeholders involved in the transportation of the smart container and the goods transported in it in achieving much better interoperability and as a result

Figure 6: Typical multi-segment logistic network

better situational awareness related to where there cargo is and also in what condition there cargo may be.

3 Standardisation for end-to-end transportation traceability

In September 2022, UN/CEFACT adopted a new standard that can act as a framework within which many other standards related to visibility and tracking and tracing of products, shipments and consignments can be understood and where feasible aligned and harmonised.

This is the Business Requirements Specification (BRS)
"Integrated Track and Trace for Multi-Modal Transportation"[7]

This standard aims to help stakeholders to always be able to easily answer their main question:
"Where are the Goods at any time?"

The scope is also very clearly defined as
*"Logistic services related to the **transportation of traded goods** between **Seller** and **Buyer**"*
This explicitly includes all modes of transport that may be needed to execute that transportation.
The diagram below depicts that idea in a "basic" fashion. Actual transport and logistics network are often significantly more complex.
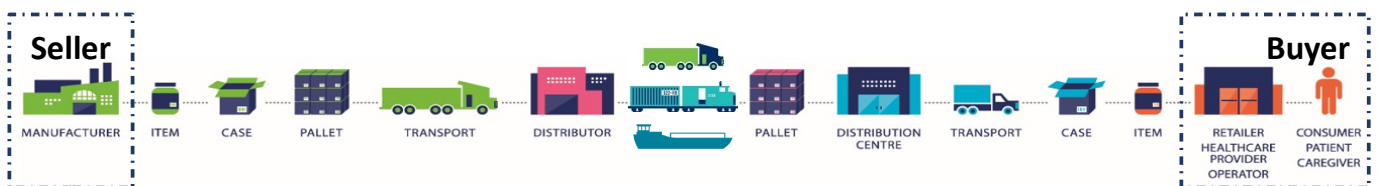

Figure 7: Multi-Modal transport from Seller to Buyer

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6   https://unece.org/fileadmin/DAM/cefact/brs/BRS-SmartContainer_v1.0.pdf#page=10
7   https://unece.org/sites/default/files/2022-09/BRS-IntegratedTrackandTraceforMulti-ModalTransportationv0.1-Final.pdf

This BRS proposes an approach that will enable tracking and tracing of products and transport assets (transport means and transport equipment) and information sharing about events in a standardised electronic format. Following that approach groups of stakeholders will be able to implement a common well-understood tracking and tracing solution for any and **all traded and identified items**, which includes transport equipment and transport means even when empty.

Within this context it is important we highlight some essential concepts:

1. The standard expects that goods, objects and entities are uniquely identified within the end-to-end process.

2. UN/CEFACT (and other standardisation organisations) recognise that in end-to-end supply chains actors generally operate (mostly) in either the TRADE domain or the TRANSPORT domain. The actors in one domain tend not to know much about how things work in the other domain (and what identifiers they use). This is the Disconnect also mentioned above. To know where goods are it is imperative that the two domains will be linked as part of the daily operational activities that are part of figure 7. That means that the identifiers used in each step of the process must be linked to identifiers used in a previous process step.

3. Terms and definitions used by actors (such as shipment and consignment) have **different** meanings for different actors across the two domains. UN/CEFACT (and other organisations like GS1) provide an unambiguous library of terms and definitions[8] that may be used across the domains. Without a common language across actors, it is next to impossible to achieve good situational awareness to manage the flow of goods well.

Related to bullet 2, the BRS covers events and linking the related identifiers for a range of events (Process steps):
1. Packing
2. Consolidation
3. Combining consignments
4. Loading consignment onto transport means
5. Unloading consignments from transport means
6. De-consolidating consignments
7. Shipment splitting event

In each of these steps, identifiers for shipments, products (trade items), transport units, consignments, transport equipment, transport means etcetera may be established, recorded and shared with parties involved.

Related to bullet 1, figure 8[9], provides an insight into the need for unambiguous global data standard identifiers to enable situational awareness. Each object and entity in the transportation network from Seller (e.g., Manufacturer) to Buyer (e.g., Retailer or Consumer) needs to be identified unambiguously in order to be able to share information related to them among the parties involved in the network. To then be able to use that shared information, it is necessary that the unambiguous identifiers can also be automatically read (captured) from physical objects so that an operator/device can effortlessly and quickly get to the information he/she/it needs to correctly process the object at hand.

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8   UN/CEFACT Core Components Library, GS1 Web Vocabulary and others
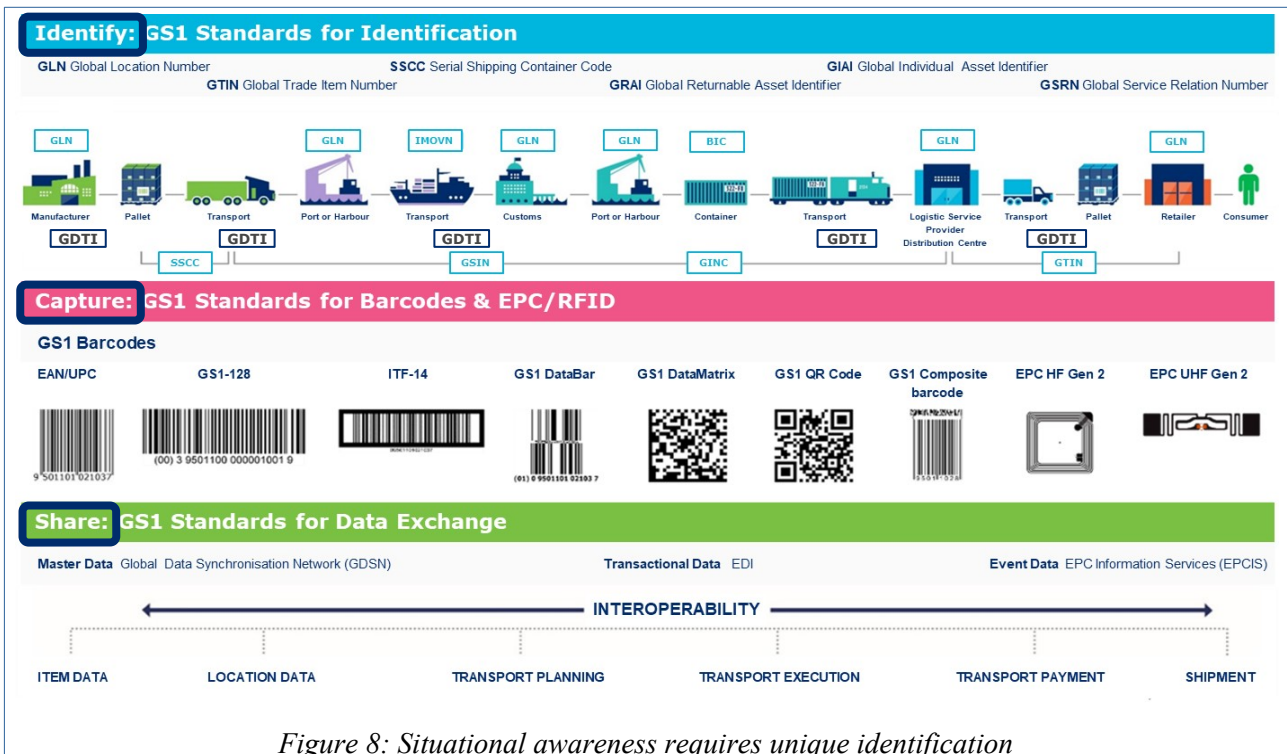9   Source GS1; Also showing non-GS1 identifiers such as IMO Vessel Number and BIC container code

Figure 8: Situational awareness requires unique identification

Figure 9[10] "maps" various standardisation initiatives within the TRANSPORT domain that we briefly covered above.
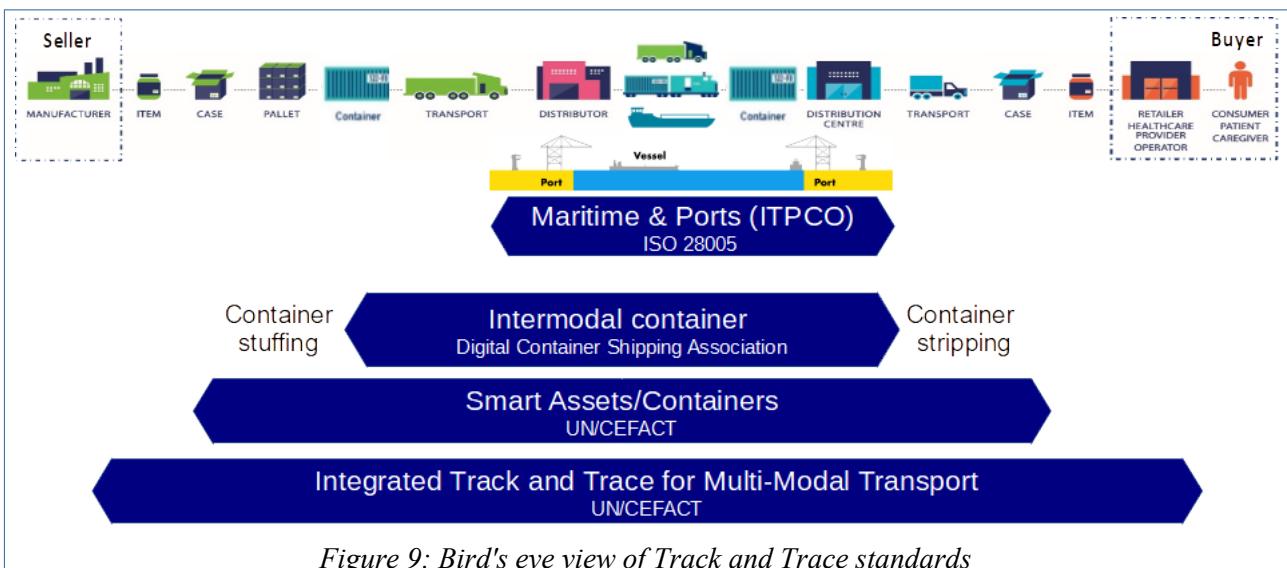

Figure 9: Bird's eye view of Track and Trace standards

Across the top, we see the transport network between Seller and Buyer. The navy-blue arrows indicate how far across the standards "extend" across the transport network between Seller and Buyer. Although the DCSA efforts have not been covered above, they are included in the diagram because the DCSA efforts are being followed closely by many organisations. In this context it is important to note that the DCSA efforts look at all intermodal container related processes but only between the cut-off points of stuffing the container and stripping it. These two activities may occur at various locations/stages in the transport network. It will often happen in a facility within the port[11] (the stripping in the figure). However, they may also happen in locations (far) away from the

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10 Courtesy of FixLog Consulting; https://fixlog.consulting

11 Using the port as example only; similar activities may occur related to rail, inland waterways etc.

port (the stuffing in the figure occurs in one of those locations). In principle, the Seller may already stuff the container.

The two UN/CEFACT arrows at the bottom of the figure, indicate that they extend over (much) more of the transport network. There is an important distinction between the "Integrated Track and Trace" standard and the others in the figure. The other standards (currently) do **not** concern themselves with the Goods/Cargo being transported; instead they focus on tracking and tracing of the various assets. Assuming you also know what Goods are in/on which assets, you may also know "*Where are the Goods?*". The UN/CEFACT Track and Trace standard on the other hand, aims to enable that the links between the Goods and Assets are always created such that stakeholders involved in the supply chain may always know their goods are, in effect "fixing the Disconnect".

It should be noted here that these standardisation initiatives have laid a solid foundation, but there is still significant further effort required. However, with this framework all further efforts may position themselves in their "proper" place. As a result, they may align their efforts with the work that has already been done ensuring interoperability among the results of all those efforts. The positioning will also (significantly) help to explain to the stakeholders what sets of standards will be relevant to the challenges they are addressing and why.

4   Standardisation for end-to-end Product Transparency

All transportation is driven by stakeholders acting in a Value Chain that may be very complex, spanning the world, involving many different stages and processes and many transformations of materials and goods before the final product is sold to the ultimate buyer. The figure below[12] gives an impression of the Value Chain for products (textiles) created from cotton.
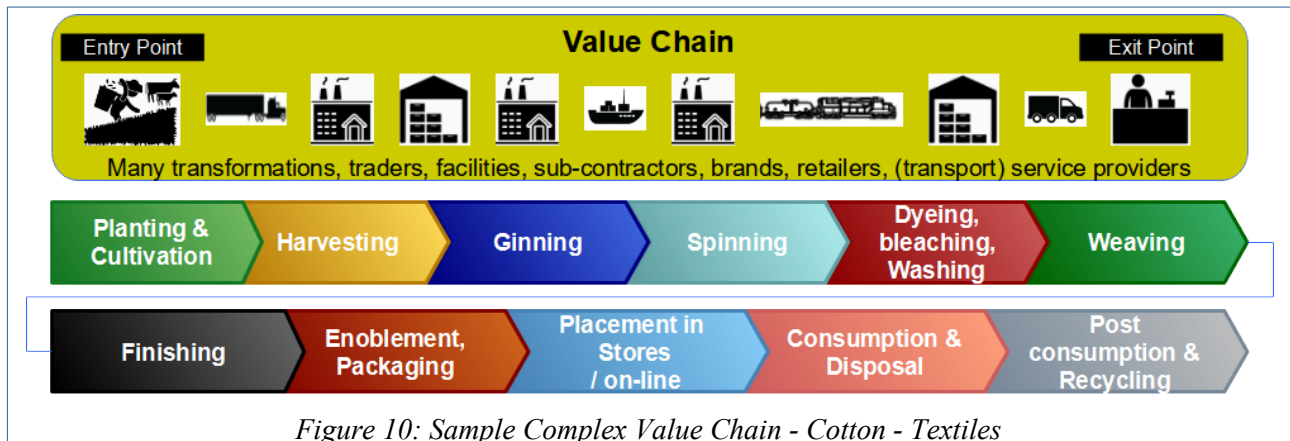

Figure 10: Sample Complex Value Chain - Cotton - Textiles

Figure 10 shows several facilities for processing materials and goods as well as facilities for storing them. In between those, there is always also some kind of transportation (also indicated). We need to stress here that this figure is still a (considerable) simplification of the actual Value Chain.

Next to ten main steps up to Consumption & Disposal, you will also see a stage for what should happen with the product after that. In many countries around the world, regulators are getting more serious about the United Nations Sustainable Development Goals (UNSDG); see also[13]. An ever increasing number of regulations has been put in place or will (likely) be put in place in the next few years to ensure products coming out of complex value chains help to achieve some of those UNSDG or at least do not hamper achieving those goals.

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12 Image courtesy of FixLog Consulting; https://fixlog.consulting

13 https://unctad.org/news/transport-newsletter-article-no-101-un-cefact-track-and-trace-publication

Another term/abbreviation often used in this context is ESG (Environmental, Social and Governance). The European Union especially has high ambitions. The *"Ecodesign for Sustainable Products Regulation"* is the cornerstone of the Commission's approach to more environmentally sustainable and circular products. An important element of these ambitions is the creation of so-called *"Digital Product Passports"* (DPP). These DPP will include data that will need to come from all over the Value Chain for the particular product (batch).

Various UN/CEFACT deliverables aim to provide visibility of the ESG conditions under which products (especially raw materials) were made, and where they were made e.g., working conditions, use of chemicals. Among the UN/CEFACT products is the *"Sustainable textile and leather traceability and transparency project"*.
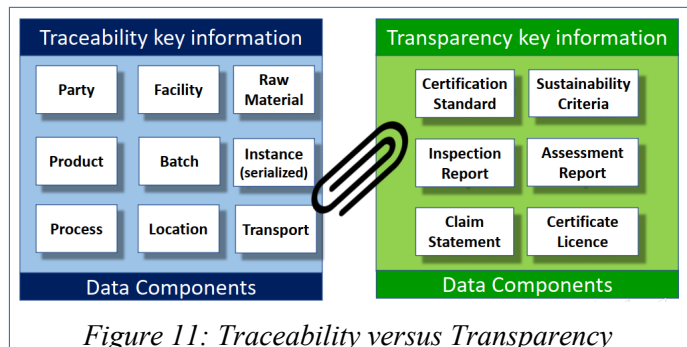
Figure 11: Traceability versus Transparency

The figure above illustrates that next to the data associated with "traditional" traceability, it will be necessary to also have evidence "Transparency Key Information" linked to the traceability data regarding the validity of the traceability data. This is not entirely new and UN/CEFACT has
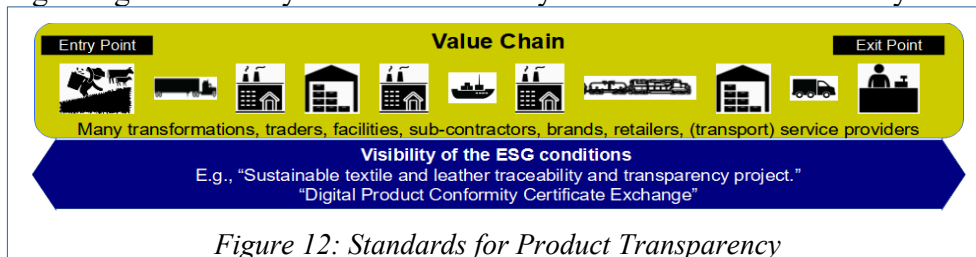
Figure 12: Standards for Product Transparency

recently published a White Paper *"Digital Product Conformity Certificate Exchange"* that describes how the links between the Traceability and Transparency information may be established and used across the Value Chain.

5 In Conclusion

There are many standards that can support track and trace. In fact there are so many that many actors in the supply chain get confused about which ones may be useful for them. Furthermore, many standards have been developed with a siloed view on a particular area of the transport networks between Seller and Buyer.

Fortunately, over the past decade, more and more standards are being developed with a more holistic view of the supply chain and the transport networks between Seller and Buyer. This has now resulted in a

> **set of standards that can be deployed in unison in interoperable ways and serve as the basis for even further (in-depth) coverage of various process in supply chains.**

We also have a framework within which further standardisation efforts may be positioned to ensure early alignment and interoperability as well as clear messaging towards users of standards developed. There is also the emerging area of standards related to Product Transparency, which is needed to support achievement of UNSDG and ESG goals and regulations.

Here too, a framework for the development of interoperable standards is beginning to appear that will help stakeholders in (complex) Value Chains to meet the future needs related to capturing and reporting on Product Transparency Information.

Evaluation of PI boxes for last mile delivery

M. Reinthaler, P. König and M. Steinbauer

IPIC 2023

9th International
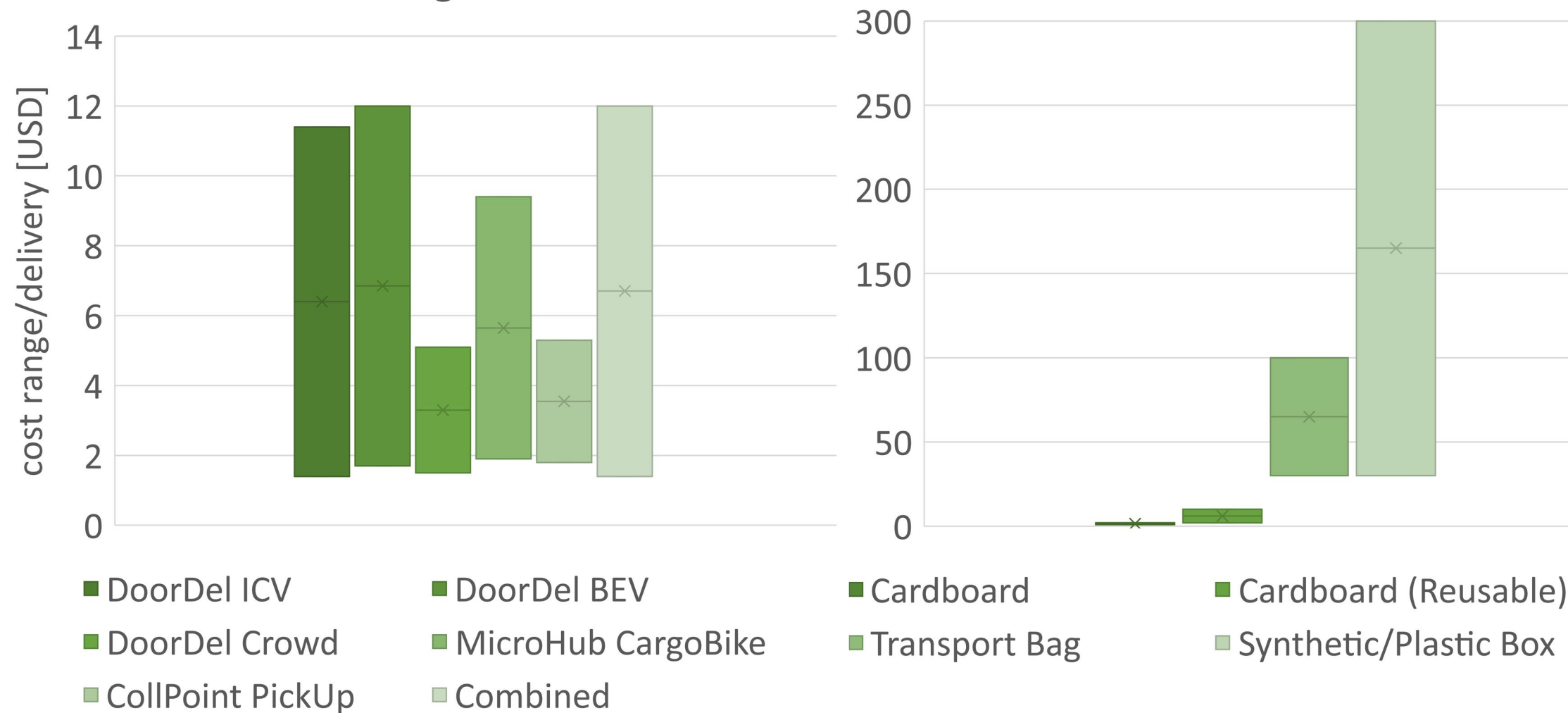Physical Internet Conference
June 13-15, 2023
Athens, Greece

PhysICAL

Introduction

The last mile is the most time consuming and cost intensive part of delivery processes. The handover of consignments to the customer, the associated multiple delivery attempts, unsecured depositing of consignments and the increasing problems with returns and packaging material require new approaches and solutions in the last mile.

Previous work has shown the cost range of different delivery strategies for the last mile segment, were the door delivery (DoorDel) was listed as the significantly most expensive method.

Furthermore, alternatives to the classic cardboard packaging are required in order to reduce packaging waste and to enable the reuse of packaging material. In contrast to reusable cardboard boxes, many more cycles can be fulfilled with transport bags and synthetic boxes.

cost range/delivery of last-mile strategies[1]

number of cycles for box materials

Legend:
- DoorDel ICV
- DoorDel BEV
- Cardboard
- Cardboard (Reusable)
- DoorDel Crowd
- MicroHub CargoBike
- Transport Bag
- Synthetic/Plastic Box
- CollPoint PickUp
- Combined

[1]A. Pahwa, M. Jaller, A cost-based comparative analysis of different last-mile strategies for e-commerce delivery, Transp. Research Part E, Vol 164, 2022, https://doi.org/10.1016/j.tre.2022.102783.

Objectives

The PhysICAL project is focusing on PI concepts, such as the use of PI boxes. PI Boxes were identified according to appropriate features and integrated into a real-life last mile scenario, tested and evaluated. The pilot cases are in the area of:

- **eCommerce**: including packaging and consolidation
- **Pharma logistics**: including B2B and B2C services
- **Wholesale**: consolidated delivery of materials to construction sites

The evaluation of the tests will be done by further specifying the feature matrix and the suitability for application scenarios, as well as according to the criteria of sustainability, including economic, ecological, social aspects.

Methodology

Since each application scenario has its specific requirements and framework conditions, the identification of suitable PI boxes is essential. The relevant feature elements for were elaborated to identify the characteristics and performance of PI boxes. The elements were organized in categories to assess the properties of e.g. the materials and sensor technology as well as the handling and expected cycles of PI boxes that are currently available or under development. The assessment is based on the estimation of the suitability of the box in the respective category on a scale from 0 (not at all suitable) to 10 points (very suitable).

At the same time, this evaluation was also applied from the perspective of the use cases in order to describe the requirements of the features of the PI Box. This methodology results in a feature matrix that evaluates and connects both perspectives (requirements of the use case) and properties of the box on the same scale.

Results

As a result of the study the relevant feature elements for PI Boxes were identified and grouped in categories, as shown in the graph. This specifies the assessment metric that was used to assess the suitability of boxes and requirements of use cases from the perspective of the involved actors.

Legend:
- eCommerce
- Pharma logistics
- Wholesale
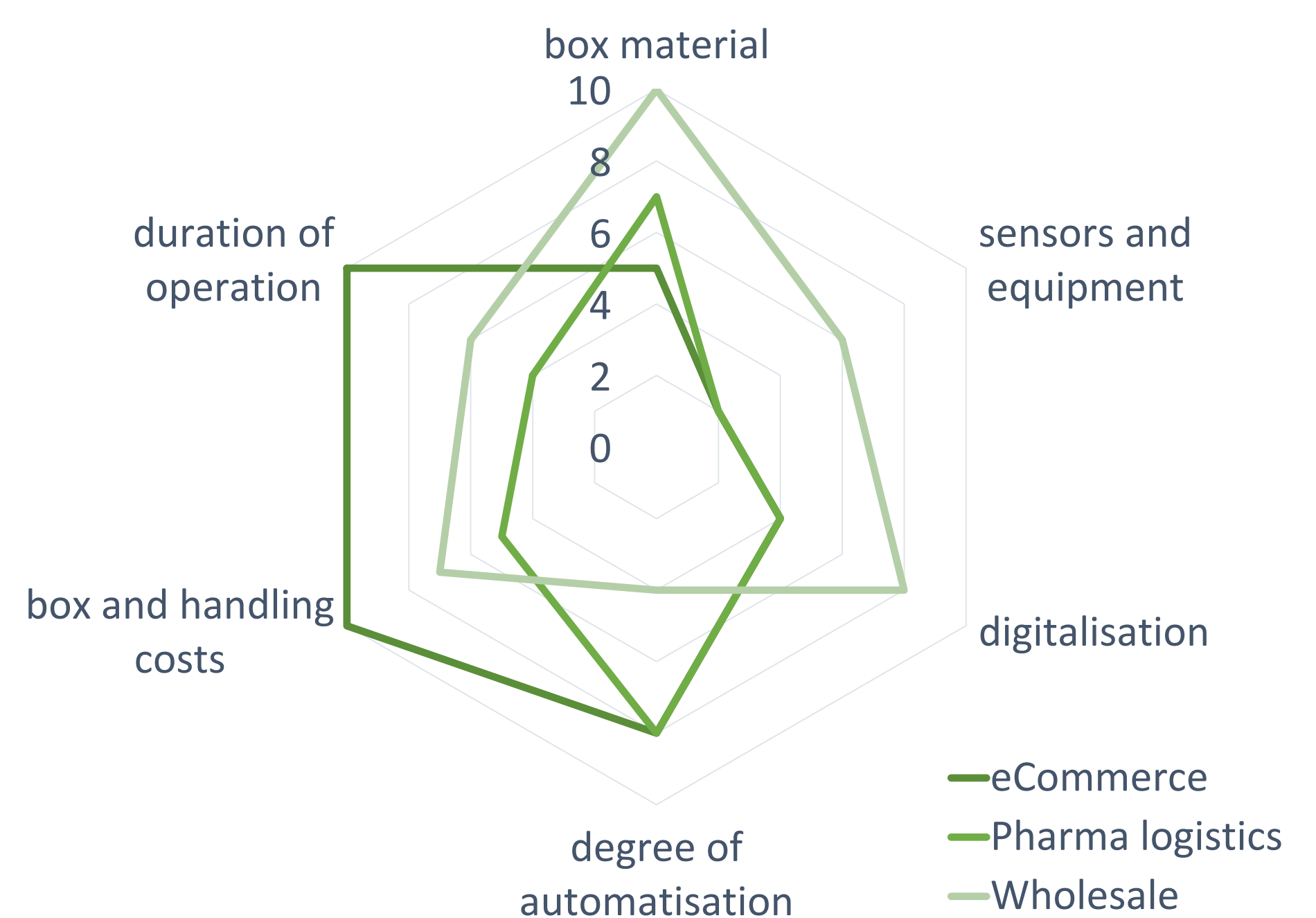
The PI Boxes and the suitability identified from this process will be integrated into a real-life last mile scenario, tested and evaluated. The evaluation of the tests will be done by further specifying the feature matrix and the suitability for application scenarios, as well as according to the criteria of sustainability, including economic, ecological, social aspects.

Acknowledgements

Conference Sponsor-Logo Area

The Concept of Dynamic Smart Contracts to Enable Automated Payments in the PI

Malte Spanuth, Rod Franklin

IPIC 2023

9th International Physical Internet Conference
June 13-15, 2023
Athens, Greece
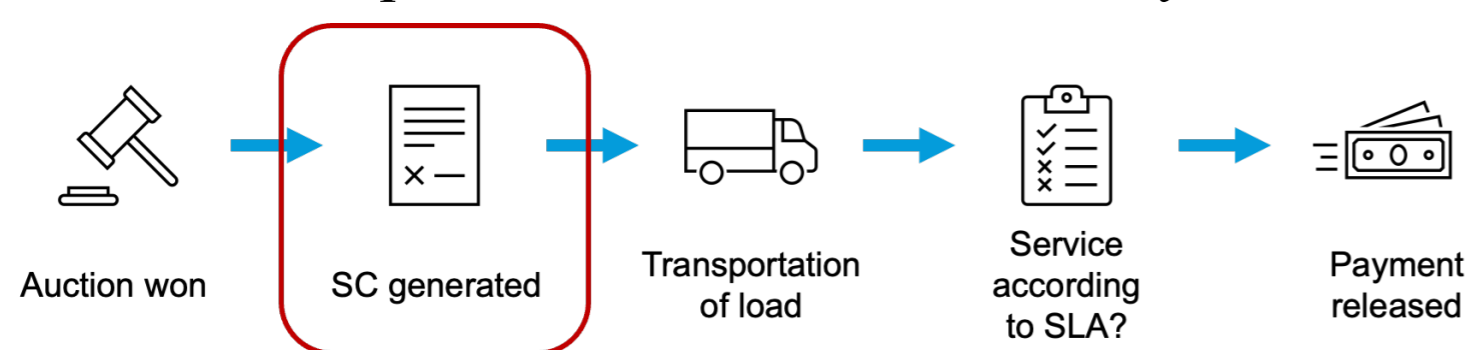
KLU
KÜHNE LOGISTICS UNIVERSITY

Problem & Motivation

One area of research that has not been extensively studied in the Physical Internet (PI) domain concerns how stakeholders receive payments for the services they have provided. While a payment mechanism is required for any transaction that occurs in the movement of a shipment from origin to destination (e.g., loading, unloading, load assembly, storage, etc.) we focus in this research on one type of transaction - the auctioning of a load to a carrier and the carrier's movement of that load from one node to another node. Due to its decentralized architecture, blockchain (BC) represents a promising technology for handling this process. Thereby, smart contracts (SC) are stored on the BC. Once a previously defined event occurs, the SCs are automatically executed and release the payment. The SCs must be generated as soon as the winner of an auction has been determined and it is thus clear which carrier will transport the packet from the current to the next node. Due to the large number of different components of the auctions (including, e.g., certain country-specific regulations or handling requirements), standardized SCs cannot be created. They must be adapted each time to the parts specified in the auction. Performing this process manually would be inefficient and not feasible in the long run.
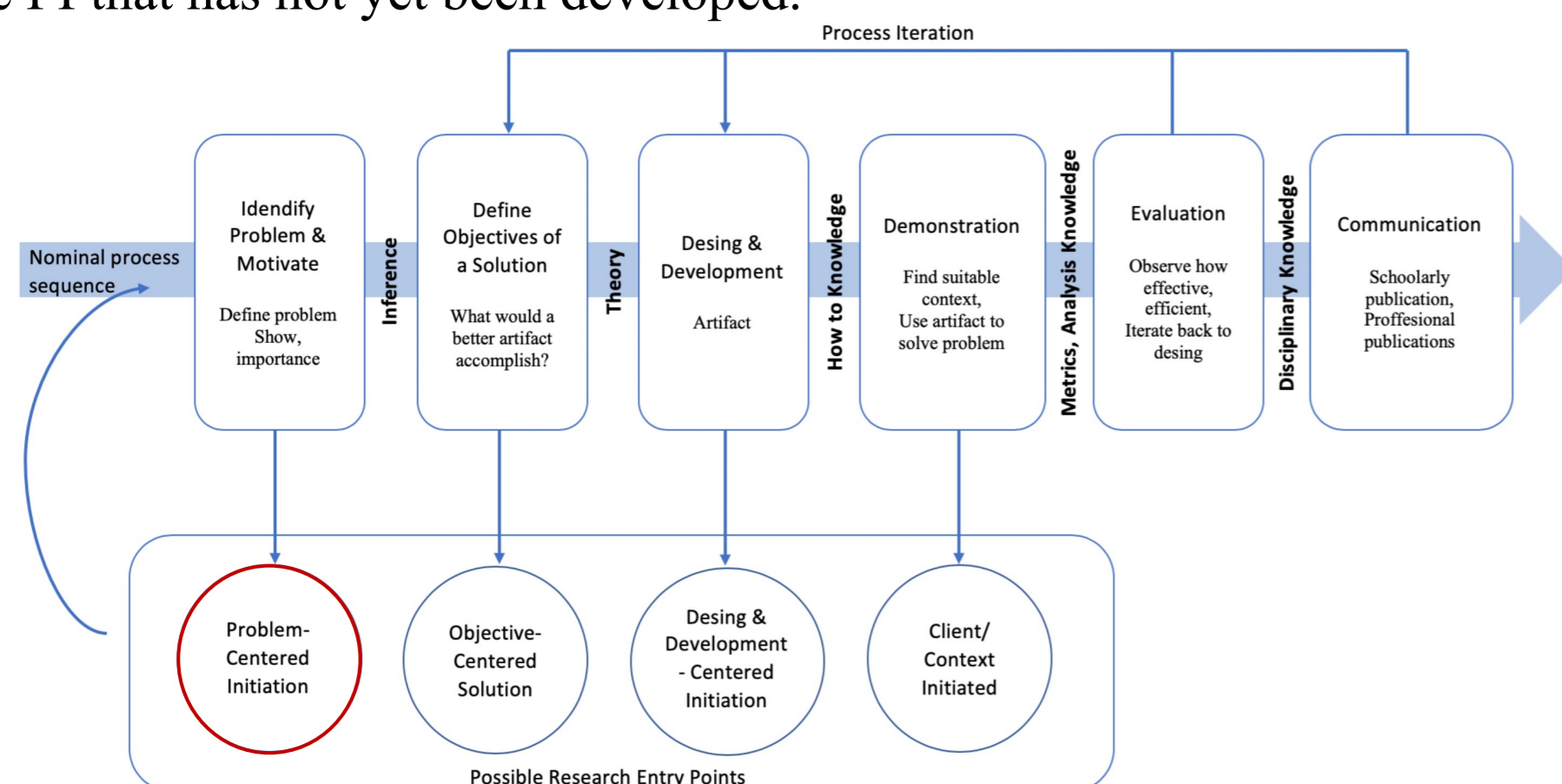
Objectives

The aim of our research is to develop a frame SC model that can be implemented and used in the PI. As data security is a major concern to the stakeholders the SCs will be deployed on a private permissioned blockchain using Hyperledger Fabric. On the one hand, this has the advantage that only the parties involved in the process have access to the transaction data and, on the other hand, due to an other consensus mechanism more transactions can be realized than with public permissionless blockchains such as Ethereum. This is an important factor for the scalability of the solution.

Auction won → SC generated → Transportation of load → Service according to SLA? → Payment released
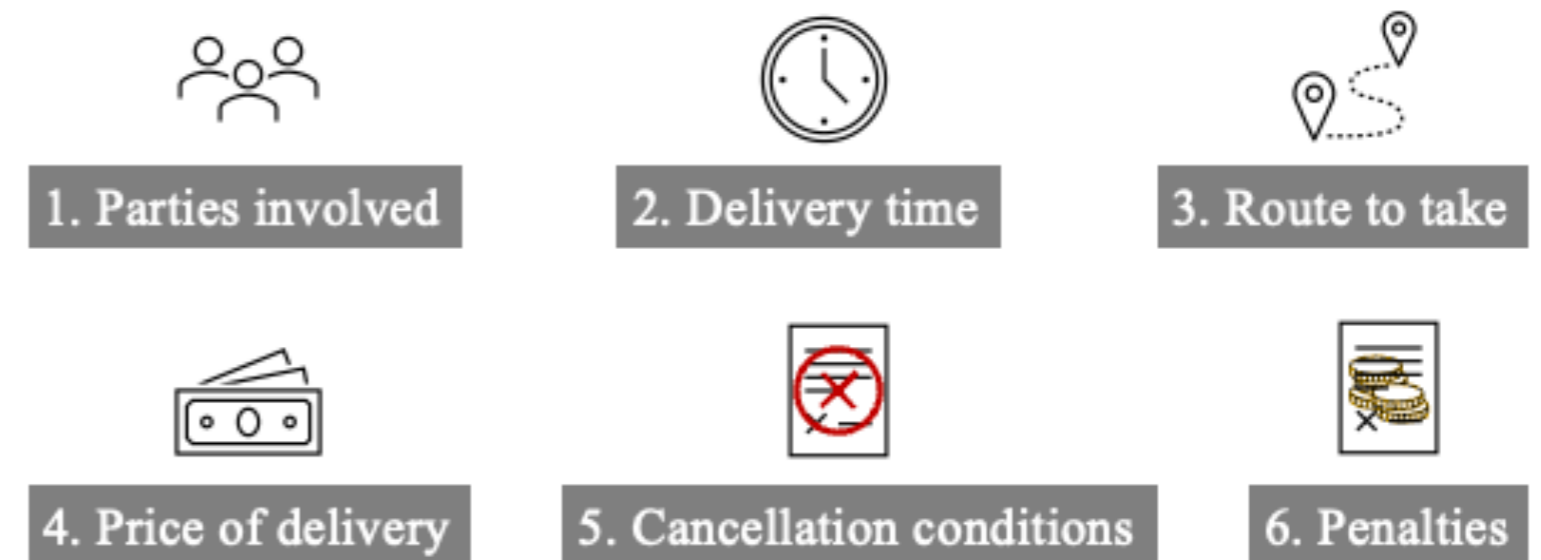
Methodology

Design Science Research (DSR) is a well established methodology within the Information Systems research area for creating artefacts and thus will be used for our study [1]. Peffers et al. (2007) developed a process for conducting DSR which we follow [2]. We are tackling a problem-centered initiation, as our research started with the need for a payment scheme for the PI that has not yet been developed.

Process Iteration

Nominal process sequence

Identify Problem & Motivate
Define problem
Show, importance

Inference

Define Objectives of a Solution
What would a better artifact accomplish?

Theory

Desing & Development
Artifact

How to Knowledge

Demonstration
Find suitable context,
Use artifact to solve problem

Metrics, Analysis Knowledge

Evaluation
Observe how effective, efficient, Iterate back to desing

Disciplinary Knowledge

Communication
Scholarly publication, Proffesional publications

Problem-Centered Initiation
Objective-Centered Solution
Desing & Development - Centered Initiation
Client/ Context Initiated

Possible Research Entry Points

[1] Gregor S, Hevner AR (2013) Positioning and Presenting Design Science Research for Maximum Impact. MIS Quarterly 37(2):337–55.
[2] Peffers, K., Tuunanen, T., Rothenberger, M. A., & Chatterjee, S. (2007). A design science research methodology for information systems research. Journal of management information systems, 24(3), 45-77.
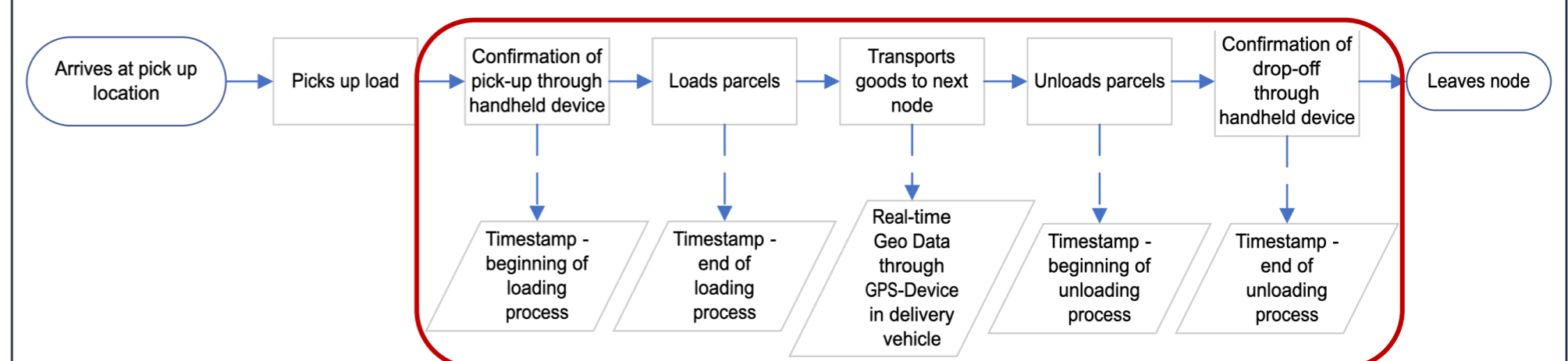
Design & Development

1. Analysis of SLAs & Contracts

1. Parties involved
2. Delivery time
3. Route to take
4. Price of delivery
5. Cancellation conditions
6. Penalties

After the components of SLAs in the transport sector have been identified in an initial literature analysis, these results must be reviewed and supplemented in a second step together with practitioners. Based on the feedback, the individual components are sorted into groups, which later form the individual components of the frame contract model.

2. Documentation of Delivery Process

In a second step, the events that trigger the SCs must be identified. For this purpose, the delivery process with the points at which data is generated is illustrated.

Arrives at pick up location → Picks up load → Confirmation of pick-up through handheld device → Loads parcels → Transports goods to next node → Unloads parcels → Confirmation of drop-off through handheld device → Leaves node

Timestamp - beginning of loading process | Timestamp - end of loading process | Real-time Geo Data through GPS-Device in delivery vehicle | Timestamp - beginning of unloading process | Timestamp - end of unloading process

3. Development of Pseudo Code & Frame Contract

To achieve acceptance of the stakeholders and to enable a larger group to review the contract and make suggestions for improvement, a frame contract model and a pseudo code will be developed. The results that will be revised with practitioners will serve as the basis for the creation of the code with Golang.

4. Creation of Code and Implementation on BC

In this phase, the pseudo code is converted into an actual code using Golang. The SC will be stored and tested on a private permissioned blockchain in Hyperledger Fabric after completion. Once it works in the test environment, it will be tested in a real-life scenario in the next step.

Demonstration & Evaluation

Demonstration

In the fourth step of Peffers et al. (2007) DSR process, the artefact, in our case our frame SC model, is demonstrated and tested in real-life scenario. Thus, we will deploy the SC on the BC in a living lab within the URBANE project. Due to the close cooperation with the living labs, they offer the optimal environment for a first demonstration and provide insights into whether the artefact needs to be revised.

Evaluation

Based on the results of the demonstration, the frame contract model must be evaluated if it meets the objective and enables efficient payments in the PI.

Conference Sponsor-Logo Area

Behavioral Modelling of Public Transport Passengers Participating in Last-Mile Freight Delivery

Seyed Sina Mohri, Neema Nassir, Russell Thompson, Patricia Lavieri
University of Melbourne

Abstract

An emerging stream of Crowd-Shipping (CS) solutions focuses on existing momentum in Public Transportation (PT) to ship viable delivery packages by PT passengers. Few studies have explored the package delivery acceptance behavior of passengers engaged in PT-based CS initiatives while passengers' behavioral intention to participate (i.e., engage) is not studied. It is requisite that newly introduced CS platforms explore their potential crowdshippers' behavior on intention to participate and set efficient marketing strategies. Given a survey data collected from 2208 PT passengers in Sydney metropolitan area, this study explores the intention of PT passengers as crowd-shippers to participate in PT-based CS initiatives, as well as prohibiting factors in way of participation.

Introduction

This study contributes to the literature on CS with PT passengers by estimating the probability of intention to participate using a binomial logit model developed using survey data collected from the Sydney metropolitan area in 2022. Results of the model can estimate the initial attractiveness of the initiative for PT passengers and be used in approximating the expected number of registered crowd-shippers. The data collected also includes the reasons for passengers rejecting the initiative, collected through an open-ended question in the survey.

Methodology

In order to model the intention of PT passengers to participate in the PT-based CS initiative, this research relies on discrete choice models based on random utility maximization (Train, 2009).
Using an inductive thematic analysis, 917 reasons (text responses) for not participating are scrutinized, and the prohibiting factors are identified and categorized. Considering demographic and socio-economic characteristics of the respondents, the study reveals to what degree passengers with different characteristics are sensitive to prohibiting factors.

Discussion

This research provides several practical insights that can assist in successfully defining, launching, and advertising a new PT-based CS initiative. As a key finding, it is observed that women, full-time employees, elderly, retirees, and low-income PT passengers hardly participate, while the youth, individuals with a positive attitude towards sustainable freight initiatives, and those who experienced working with parcel lockers would participate with a higher probability. Moreover, it is observed that factors relating to time availability/flexibility and physical health condition of passengers are much more important than the compensation level for passengers to accept to participate in PT-based CS initiatives.
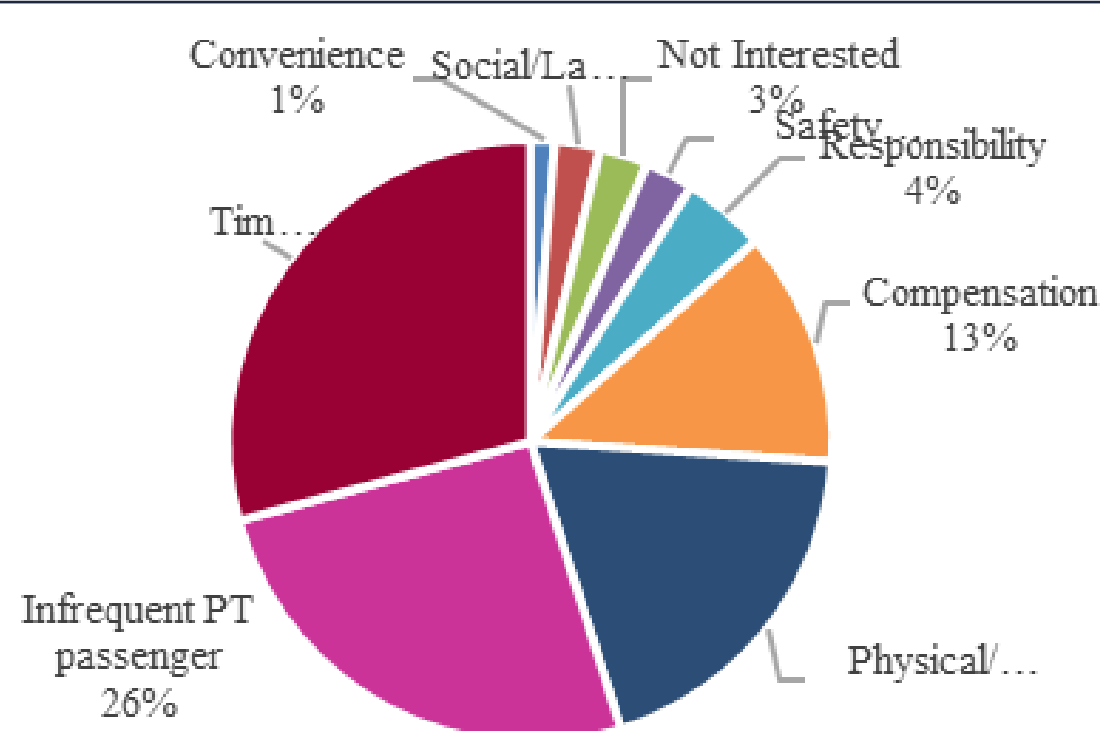
Variable name (units)	Units	Parameters estimated	Z (P>|Z|)	95% confidence interval
Female (yes:1, no:0)	1,0	-0.418**	-4.28 (0.000)	-0.610 to -0.227
Young adults (yes:1, no:0)	1,0	0.268**	2.60 (0.027)	0.066 to 0.470
Senior adults (yes:1, no:0)	1,0	-0.403**	-2.27 (0.030)	-0.751 to -0.055
High-income (yes:1, no:0)	1,0	-0.347**	-2.62 (0.014)	-0.607 to -0.870
Full-time employee (yes:1, no:0)	1,0	-0.230**	-1.89 (0.037)	-0.469 to 0.008
Retired (yes:1, no:0)	1,0	-0.527**	-2.71 (0.030)	-0.907 to -0.146
Large household size (yes:1, no:0)	1,0	0.165	1.67 (0.137)	-0.290 to 0.360
PT trip frequency per month	Continuous	-0.012**	-3.20 (0.000)	-0.201 to -0.004
Sustainable role (yes:1, no:0)	1,0	0.537**	3.95 (0.000)	0.270 to 0.804
Locker preference (yes:1, no:0)	1,0	0.793**	6.80 (0.000)	0.565 to 1.021
Locker experience (yes:1, no:0)	1,0	0.514**	4.41 (0.000)	0.286 to 0.742
Medium-volume delivery (yes:1, no:0)	1,0	-0.990**	-5.71 (0.000)	-1.328 to -0.650
High-volume delivery (yes:1, no:0)	1,0	-1.007**	-5.55 (0.002)	-1.363 to -0.652
Constant		0.486*0	2.03 (0.082)	0.016 to 0.956
Model fit statistics				
Number of observations	1589			
Log-likelihood at zero betas	-1623.37			
Log-likelihood at convergence	-1283.91			
Pseudo R^2	0.234			

Variable definition:
Female: Women
Young adults: Individuals aged less than 40
Middle-aged adults: Individuals aged between 40 to 60
Senior adults: Individuals aged more than 60
Low income: Individuals with an income less than 30k AUD per year
Medium income: Individuals with an income between 30k AUD to 90k AUD per year
High income: Individuals with an income more than 90k AUD per year
Full-time employee: Individuals working full time
Part-time employee: Individuals working part time
Unemployed: Unemployed individuals
Retired: Individuals who are retired
Disable: Individuals with disability
Small household size: Individuals living in households with maximum 2 members
Medium household size: Individuals living in households with 3 or 4 members
Large household size: Individuals living in households more than 4 members
PT trip frequency per month: An average number of PT trips per month
Sustainable role: Individuals supporting sustainable urban freight initiatives
Locker preference: Individuals not having an opposition to contact with parcel locker facilities
Locker experience: Individuals having has working experience with parcel lockers
Low-volume delivery: Individuals having less than 5 deliveries per year
Medium-volume delivery: Individuals having between 5 to 20 deliveries per year
High-volume delivery: Individuals having more than 20 deliveries per year
Apartment dwellers: Individuals living in an apartment
House residents: Individuals living in a house

Managerial findings

Providing a large and balanced supply (i.e., crowdshippers) with demand (i.e., delivery tasks) in CS systems is of utmost importance, particularly in the initial phases of launching CS initiatives. If an oversupply or overdemand situation exists, a deadweight loss will occur which leads to market inefficiency. This study can help CS managers keep the demand and supply balanced. For example, once a surge demand situation is present, CS managers can focus on attracting PT passengers who participate with a higher probability by taking an optimal advertising strategy. For instance, young male passengers with high PT trip frequency and having experience in contacting parcel lockers can be prioritized for labor absorption. Once, CS managers decide to expand their market share and the rate of labor observation is declining, they can shift from generalized to personalized marketing strategies.

Future research

We recommend future studies extend this research by exploring the intention of other potential crowds to participate in CS initiatives in different scopes such as occasional drivers, cyclists, and passengers of ride-sourcing or ride-sharing systems. Specifically for launching PT-based CS initiatives, PT passengers' intention to participate can be modeled by advanced discrete choice models such as mixed or latent-class discrete choice methods. Moreover, exploring prohibiting factors for participation in the initiative can be collected through interview-based surveys rather than online surveys with open-ended questions. Therefore, the possibility of building richer models based on grounded theory would be attainable.

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PI-Transporter Requirements as an Enabler for the Implementation of the Road-Based Physical Internet (RBPI)

Steffen Kaup[1], André Ludwig[2] and Bogdan Franczyk[1,3]

Aim and objectives

The contribution of this research poster to the Physical Internet (PI) is to present PI-Transporter functionality that enables vehicles to take part in the road-based Physical Internet (RBPI). The requirements are derived from detailed protocol analyses and applied to road-based PI-Transporters [1, 3]. This ranges from remote access to the cargo space of PI-Transporters, cargo securing through an adaptive 3D surface cargo space interior, an automated vacant cargo space detection, up to a standardized interface for V2X communication in order to negotiate freight forwarding within the road-based vehicle network.

Cargo Space Observation

The objective of the Cargo Space Observation is to track and trace freight components and to identify vacant cargo space capacity. The two approaches are applicable as separate systems or in conjunction via:

- AUTO-ID methods (e.g. RFID, NFC, QR-Barcodes)
- Sensors for automated detection of transported freight as a basis for identifying remaining cargo space capacities (e.g. optical or ultrasonic systems).

For communication, In-Vehicle-Network technologies like WiFi, Bluetooth, Zigbee, or LoRaWAN might be used for both methods.

V2X Communication Interface

The V2X Communication Interface ensures interoperability of road-based PI-Transporters, both directly with each other and/or via a cloud connection [2]. Vacant cargo space capacities and the planned routes of the PI-Transporters are exchanged 'anonymously' with each other by means of identity management. This allows the negotiation of rendezvous between PI-Transporters for the exchange of freight or freight components. Alternatively, this negotiation can be performed by software representatives of PI-Transporters on a virtual marketplace.

Human Machine Interface

Displaying of relevant information, e.g. rendezvous-points, in case of manual operation.

Cargo Space Access

Authorization for cargo space access to PI-Transporters is the result of the negotiation process of either PI-Transporters or their digital representatives on a virtual traffic marketplace [3]. This allows for a seamless interaction for transport chain involved parties in order to exchange freight or freight components between PI-Transporters.

Optional: Driver Assistance

Detection of road conditions, e.g. potholes and icy roads, to better predict arrival times of PI-Transporters.

(5G)

V2X Communication Interface

Cargo Space Observation/ In-Vehicle-Network

PI-Container

Tailgate
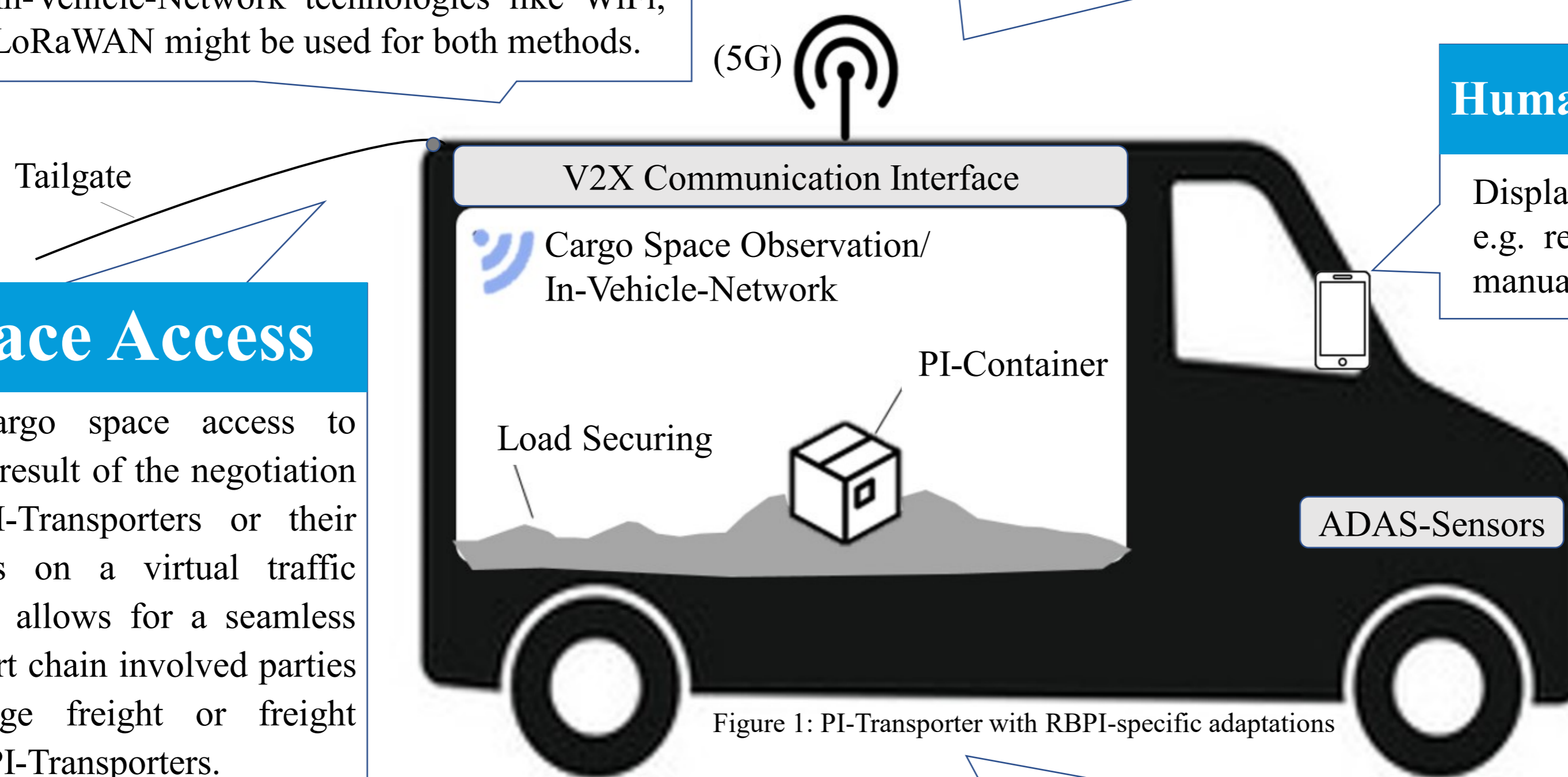
Load Securing

ADAS-Sensors

Figure 1: PI-Transporter with RBPI-specific adaptations

Optional: Automated Load Securing

An automated shape shifting interior can make a significant contribution to protect load from slipping or damage during the ride within PI-Transporters [4]. This becomes possible through an adaptive 3D surface cargo space interior. Electrically controllable piezoresistive elongation elements (Figure 2a) are arranged in the form of a matrix.
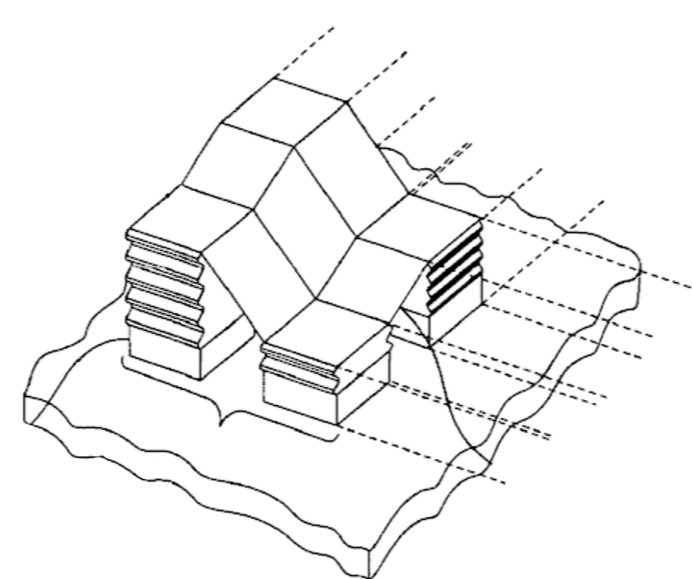

Figure 2a: Elongation elements

This actuator matrix of elongation elements provides load restraint by form closure with a freight component corresponding surface buildup (Figure 2b). The retention force of the matrix is determined by the used expansion material and the applied voltage on the corresponding elements. (Figure 2b, factor x).
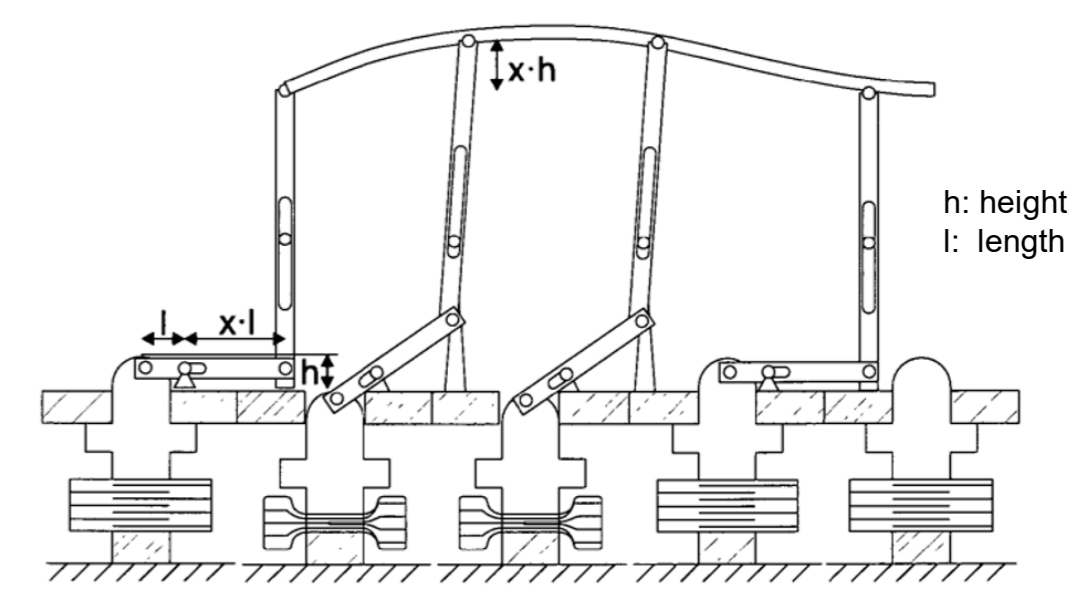

h: height
l: length

Figure 2b: Shape shifting surface buildup

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Synchromodal transport re-planning using Agent-Based Modelling

Shafagh Alaei*, Javier Durán-Micco, Cathy Macharis

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Introduction

Synchromodal Transport (ST) is an evolution of multimodal transport, where involves the **flexible** planning of transport processes and the ability to switch in **real-time** between modes of transport based on the the available resources, imposing complexity to the planning process. It offers **integrated**, **optimal**, and **sustainable** logistics solution.
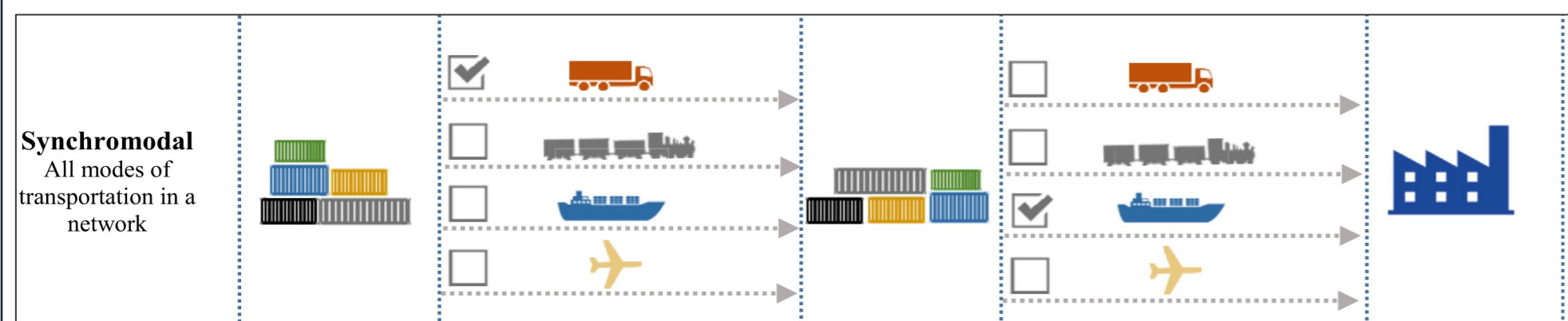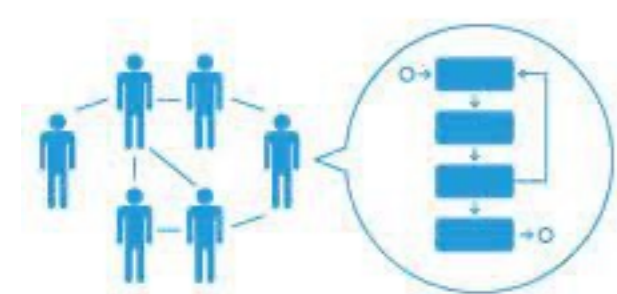

Fig1: A representation of ST [1]

Methodology

Agent-Based Simulation

- To study multiple actors' behaviour;
- Their interconnectivity and interactions.

Scope: Regional-level network;
Decision horizon: Short-term;
Prespective: Logisitcs service providers' (LSPs');
Logistics operations: Centralized and decentralized;
Goal: to transport orders to their destinations within the time window, while minimizing the costs and emmisions.

Simulation model

The model represents the operation of several LSPs, interacting to meet the transport requests. The model is a combination of short and long- haul transport. Roads, rails, and IWW are the available modes. Trucks are flexible, but trains and barges follow fixed schedules. Orders arrive **stochastically** in the system.

The **objective function** is:
➔ to minimize the costs (delays, transport, transhipment);
➔ to minimize the climate change impact (CO_2 emmissions cost).

An experiment is conducted in the Benelux (Belgium, Netherlands, Luxemburg) region (Fig2).

The model considers **disruptions** in the network, which results in modifications in the travel plans according to the **LSPs strategies toward the disruptions:**

(1) Conventional routing (**business as usual scenario**);
(2) Flexible re-routing (**synchromodal scenario**).

Three types of relations/collaborations between LSPs are also studied: **competitive**, **collaborative**, **centralized**.
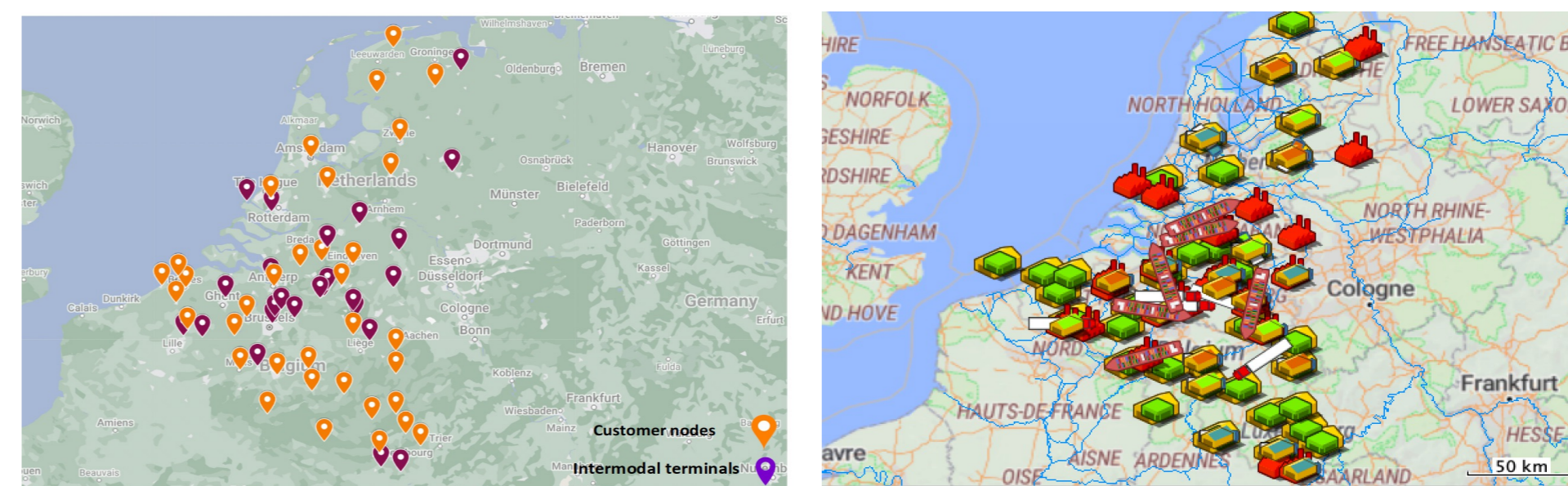

Fig2: geographic scope of the experiment

Experimental results

➔ Multiple replications conducted **to reduce the impact of stochasticty** (in demand and disruptions);
➔ Number of replications decided by the software (Anylogic) based on normal disribution and at 90% confidence- level (of total cost expression);
➔ Anylogic stopped after 6 replications.

	Bussiness-as-usual	Synchromodal	
Total cost (€)	1.299.307	1.102.783	**-15%**
Monetary costs (€)	1.478.731	1.221.333	**-17%**
Emission cost (€)	880.651	826.164	**- 6%**
Orders transported multimodal (%)	34	44	**+29%**
Late deliveries	24	9	**-62%**
Capcaity utilization (%)	20	36	**+80%**

Promising outcomes

- ST planning is more **cost and environmentally efficient** than conventional planning methods;
- ST increases **flexibility** and **reliability** of the system, as the probability of **delivering orders on time** is considerably higher than business as usual scenarios;
- In synchromodal transport, the level of **capacity utilization** is greater.
- A **centralized approach**, yields in several advantages; increased efficiency, capacity utilization, as well as cost reduction.

Reference:
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Automating Capacity Pre-Booking at Physical Internet Warehouse Nodes

Zavitsas K., Kouloumbis M., Sen J.M., Ramirez M.

OUTBOUND CAPACITY CHALLENGE

The Physical Internet envisages the automation of the capacity booking process through the introduction of smart contracts. This requires the use of predictive models to determine what is a reasonable quantity to book, which are not well integrated into the decision making process. Currently, most warehouse operators book capacity only one day ahead when more concrete bookings' data are available. The paper proposes the integration of a pre-booking decision support tool to enhance the implementation of the predictive model outputs into smart contracts.

Each delivery route is assumed to have a pricing structure that spans from ten days ahead to the day of delivery and contains early booking and cancellation fees. The aim of the tool is, considering the prediction quantity and pricing structure to determine an optimal strategy for issuing smart contract orders.

SOLUTION ALGORITHM

The algorithm builds on inventory management theory and utilises Monte Carlo simulation to determine an optimal strategy for issuing smart contract orders. A pricing structure is assumed with small discounts for early bookings and cancellations.

The mean and standard deviation are extracted from the predictive model, and converted to confidence intervals. For a 10-day planning horizon capacity booking alterations are allowed 10, 3 and 0 days ahead of delivery.
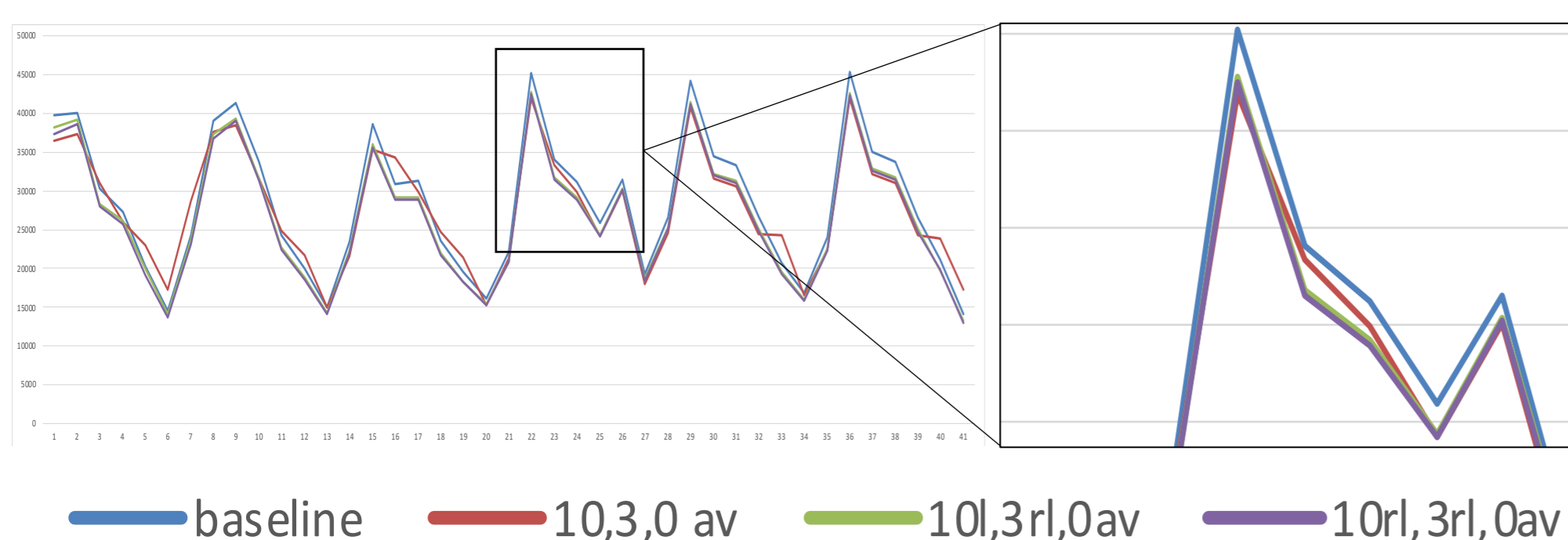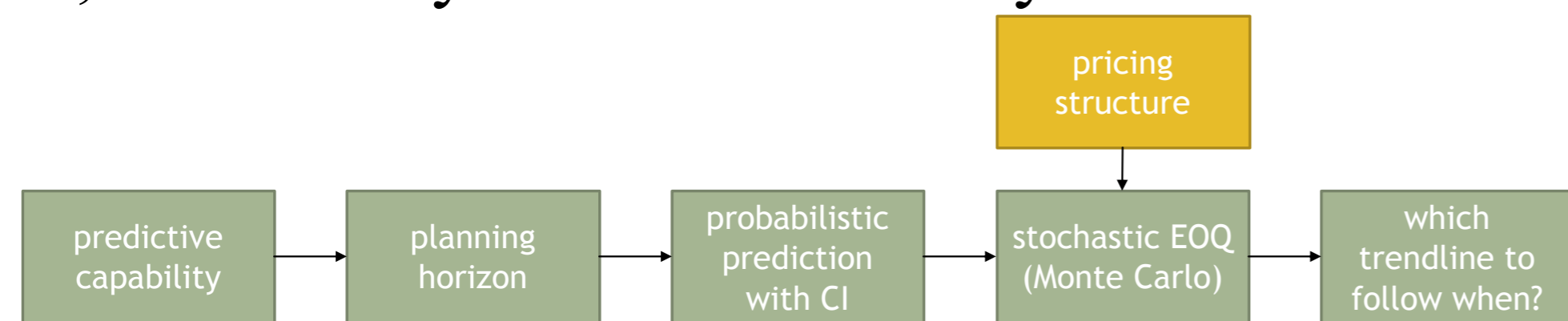
Scenario	Cost savings (%)
baseline	0
red	2.54
green	5.35
purple	6.39
perfect	8.63

PERFORMANCE

The algorithm produces **reliable** and **cost-efficient** capacity booking actions that consistently outperform current practice.

To validate results a DHL route from Madrid to Barcelona is considered. Two years of historical data were used to train an ARIMA predictive model for a planning horizon for 40-days. Furthermore, a capacity booking cost and cancellation fee structure are assumed.

Smart contract actions are compared for the following strategies over the 40-day planning horizon:

- **baseline scenario (blue)**: book all capacity on the day of delivery.
- **red scenario**: book predicated capacity 10-days ahead of delivery. If necessary make adjustments 3-days ahead.
- **green scenario**: book 95% (low) confidence interval 10-days ahead. If necessary make adjustments based on "stochastic order quantity" 3-days ahead.
- **purple scenario**: book the "stochastic order quantity" 10-days ahead. If necessary make adjustments 3-days ahead.
- **perfect scenario**: assumes perfect prediction and booking correct capacity 10-days ahead

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How to monitor the social and public impact of the Physical Internet

Giuseppina Schiavone, PhD[1]

[1]Sustainability Advanced Analytics Consultancy

INTRODUCTION

Social and public impact plays a relevant role in successful **Governance, Access and Adoption of the Physical Internet (PI)** as defined in the ALICE Roadmap. Processes for continuous detection, tracking and monitoring of **environmental-social-governance (ESG) aspects** able to capture the benefits of incremental solutions' deployment for the PI require gathering, processing and modeling of **complex data.**

OBJECTIVES

A generic dashboard for at-a-glance comparison of companies' ESG-related impact as emerging from unstructured publicly available data. The dashboard addresses and it is not limited to, small-to-medium (SME) logistics businesses and aims at **increasing impact's awareness, stimulating transparency and data sharing, with implications for measuring and monitoring the social and public impact of the PI.**

METHODOLOGY

<u>Data Gathering</u>: Google Maps Reviews / Ratings, first possible source of publicly available data, were obtained via responsible scraping (search within 50km radius around major Dutch cities: Rotterdam, Breda, Eindhoven). Companies' sizes gathered from graydongo.nl, adoption of environmental/social policies from companies' websites and social media presence from Facebook.

<u>Data Processing and Modeling</u>: filtering out of companies without reviews, application of NLP (Natural Language Processing) to analyze review, descriptive statistics, annotation of reviews per sentiment polarity and reviewer profile, evaluation of a pre-trained model of sentiment analysis, selection of a companies' subset (criteria: SME, reviews>20, unique location), identification of the logistics lexicon from the most frequent words (appearing >100 times)

<u>Preliminary Impact metrics</u>:
- Number of reviews, Reviews' rating, Reviews' sentiment polarity
- Social media presence
- Adoption of Environmental and/or Social policies

RESULTS: TOP OF MIND DASHBOARD

SENTIMENT MAP OF LOGISTICS SERVICES – **PI ACCESS**

INDUSTRY RATING AND SENTIMENT ARE DRIVEN BY CLIENTS

RATING IS INDEPENDENT FROM COMPANIES' POLICIES AND SOCIAL MEDIA PRESENCE - **PI GOVERNANCE**

NUMBER OF COMPANIES WITH REVIEWS GROWS OVER TIME – **PI ADOPTION**

DERIVED LOGISTICS LEXICON IN RELATION TO …

SENTIMENT POLARITY

ENVIRONMENTAL / SOCIAL POLICIES

COMPANY TYPE

WORDSCLOUD

The Google search, conducted in September 2022, resulted in a total of 391 businesses (48% having reviews, 57% having rating) in 73 cities, 7908 stars, 3395 reviews (85% English translated), spanning throughout a period of 11 years. Only companies having reviews were considered (N=187), of these, 60% were identified as trucking companies, the remaining as offering other logistics services; 30% were located in Tilburg, Eindhoven, Rotterdam, Breda. The number of companies with reviews grew over time peaking during the COVID-19 pandemic. Google Maps Reviews were generally positive for this industry. 60% of the selected companies adopting social policies also adopts environmental policies. The derived logistics lexicon mostly captured clients' appreciation rather than employees' satisfaction.

IMPLICATIONS & FUTURE WORK

Google Maps Review helped capturing general and company-specific trends in customers' satisfaction. Monitoring wider public and social impact requires the integration of other data sources in relation to environment, employees, inhabitants (to get for example insights into road and workplace safety, emission, noise, energy and resource use, biodiversity, equality, labor conditions).

Next steps will focus on **(i) stakeholders' validation (companies, consumers, workforce, policy makers), (ii) gathering/processing/modeling of new data sources, (iii) deployment of stakeholder-specific dashboard(s) through the network for the PI developers and coordinators.**

We will evaluate how such a dashboard can stimulate transparency and data sharing among the players of the PI.

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Synchromodal transport: How are the benefits of collaboration distributed?

Javier Durán-Micco*, Shafagh Alaei, Cathy Macharis

Synchromodal transport

Synchromodal transport aims for **more sustainable supply chains** through more flexible operations and horizontal collaboration. However, one of the key challenges to implement it is the lack of trust and fear of losing competitiveness from potential participants.

We propose a simulation model that represent a multimodal logistic network, to estimate the benefits generated by synchromodal transport and how these are distributed among logistic service providers.

Simulation model
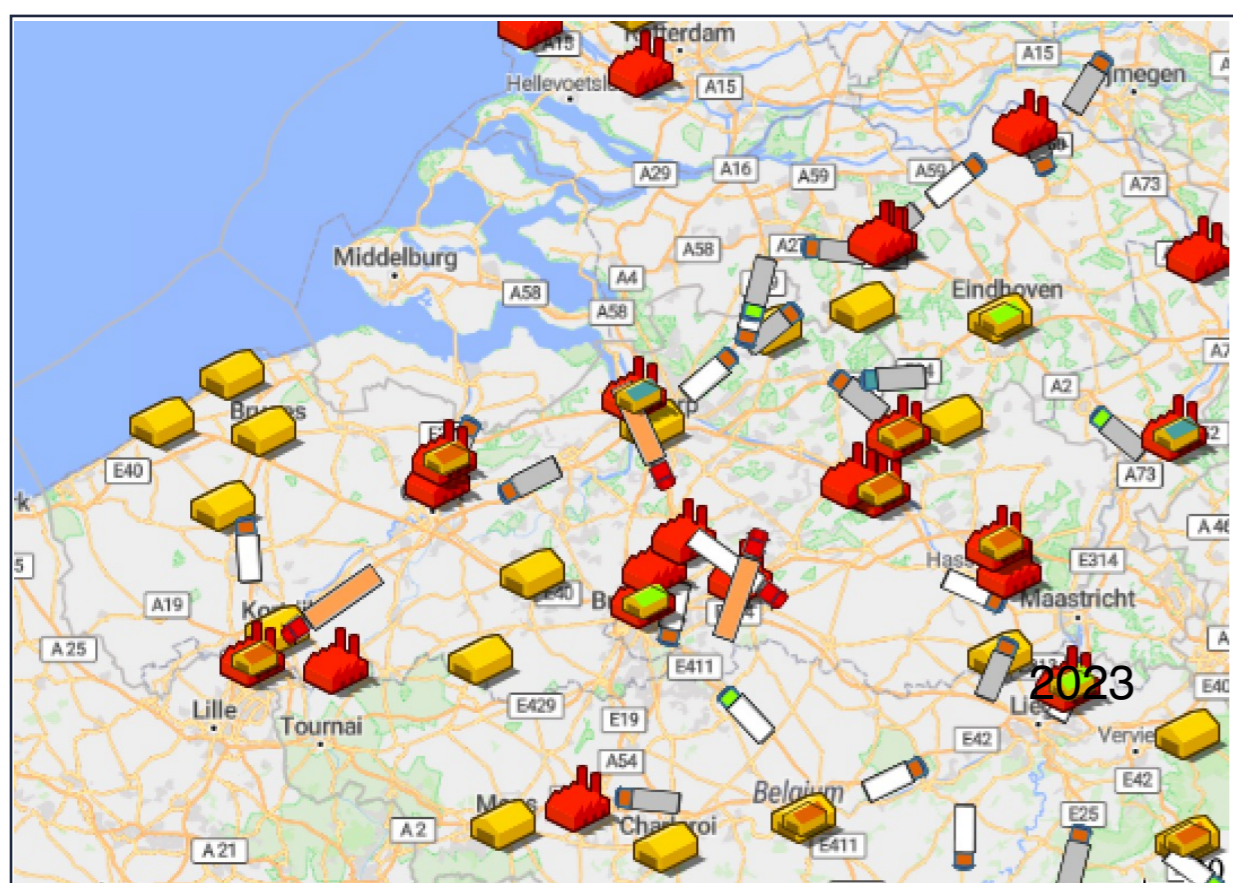
An **agent-based simulation** model is proposed to represent a multimodal logistic network in which different logistic service providers (LSPs) interact to satisfy transport requests. When a request enters the system, LSPs make offers depending on their own resources (trucks and train slots) and the cheapest option is selected.

The model represents trucks, trains and containers in a **GIS environment**, so LSPs consider real-time information when making their offers.

Experimental results

Two aspects are considered to define 4 scenarios:

- **Collaboration level:** Competitive (business-as-usual) or Collaborative (sharing resources).
- **LSP relative size:** Balanced or Unbalanced.

The results with 3 LSPs show:

- Collaboration generate **lower costs and emissions** for the whole system.
- In the **balanced** scenario gains are **equally distributed**, but that is not the case in the **unbalanced** scenario, where the larger player gains more and smaller players even experience losses.
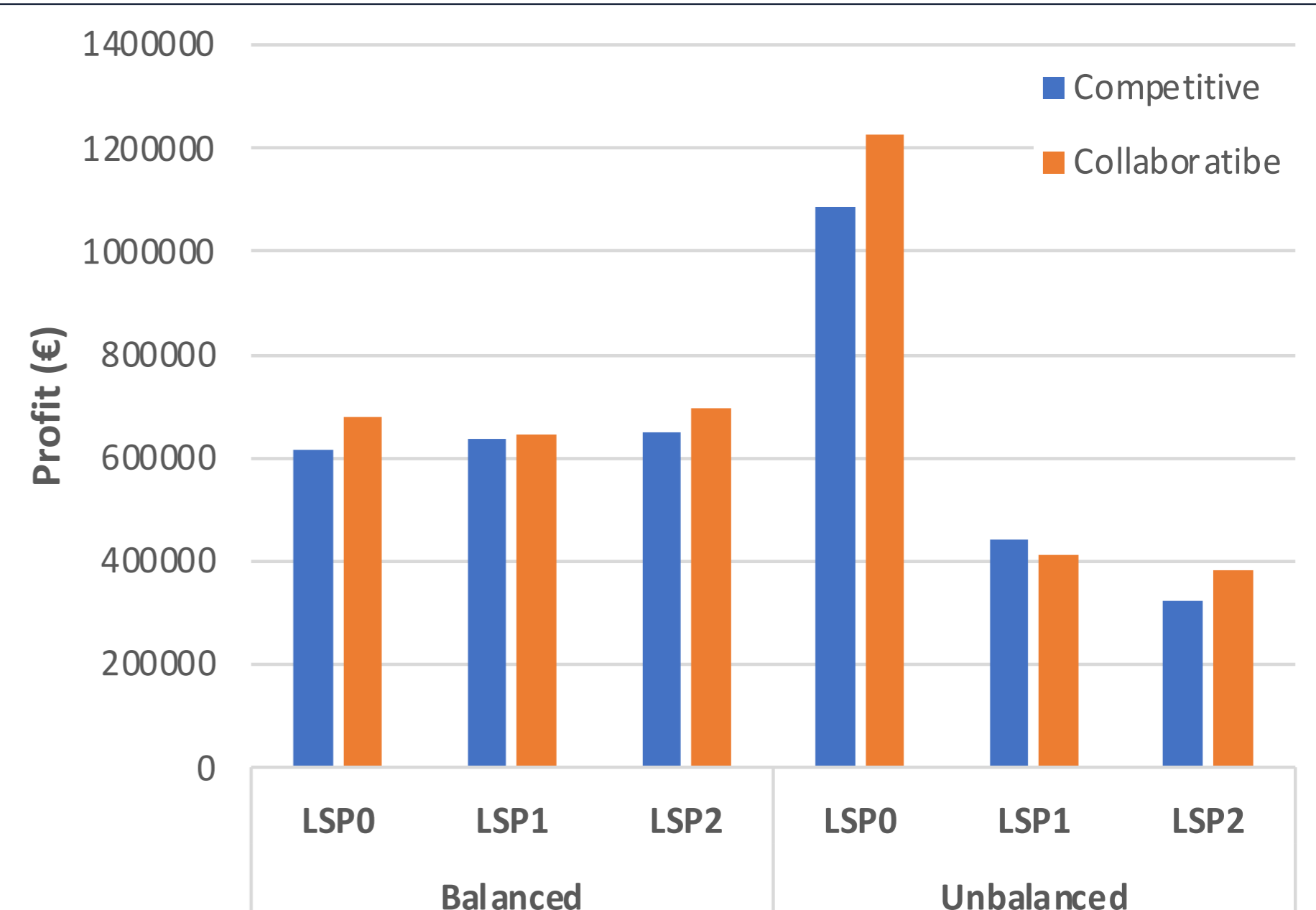
Conclusions

The proposed model allows to estimate the impact of collaboration on individual players, and could be used as a tool to support the design and validation of gain distribution schemes. This is necessary to make collaboration attractive to all actors and generate efficient and fair logistic systems.

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A DIGITAL TWIN FOR PI-STORE AUTOMATED WAREHOUSES

Massimo Rebuglio, Andrea Ferrari, Giovanni Zenezini, Antonio Carlin, Carlo Rafele

CONTEXT

Automated storage and retrieval systems (**AS/RSs**) are instrumental in achieving efficiency and quickness of logistics processes

RESEARCH GAP

AS/RS studies focus on optimization and analytical models. However, analytical evaluation often consider deterministic and stable input parameters which are not necessarily found in real-life AS/RS systems. Cyber-physical systems such as **Digital Twins** represent a way to generate better predictive performance measures for a given system configuration.

PROPOSAL

We propose a **Digital Twin (DT) architecture** of an AS/RS specifically designed for smaller containers such as plastic totes. This system can thus recreate the condition of a PI-store holding modular P-containers.
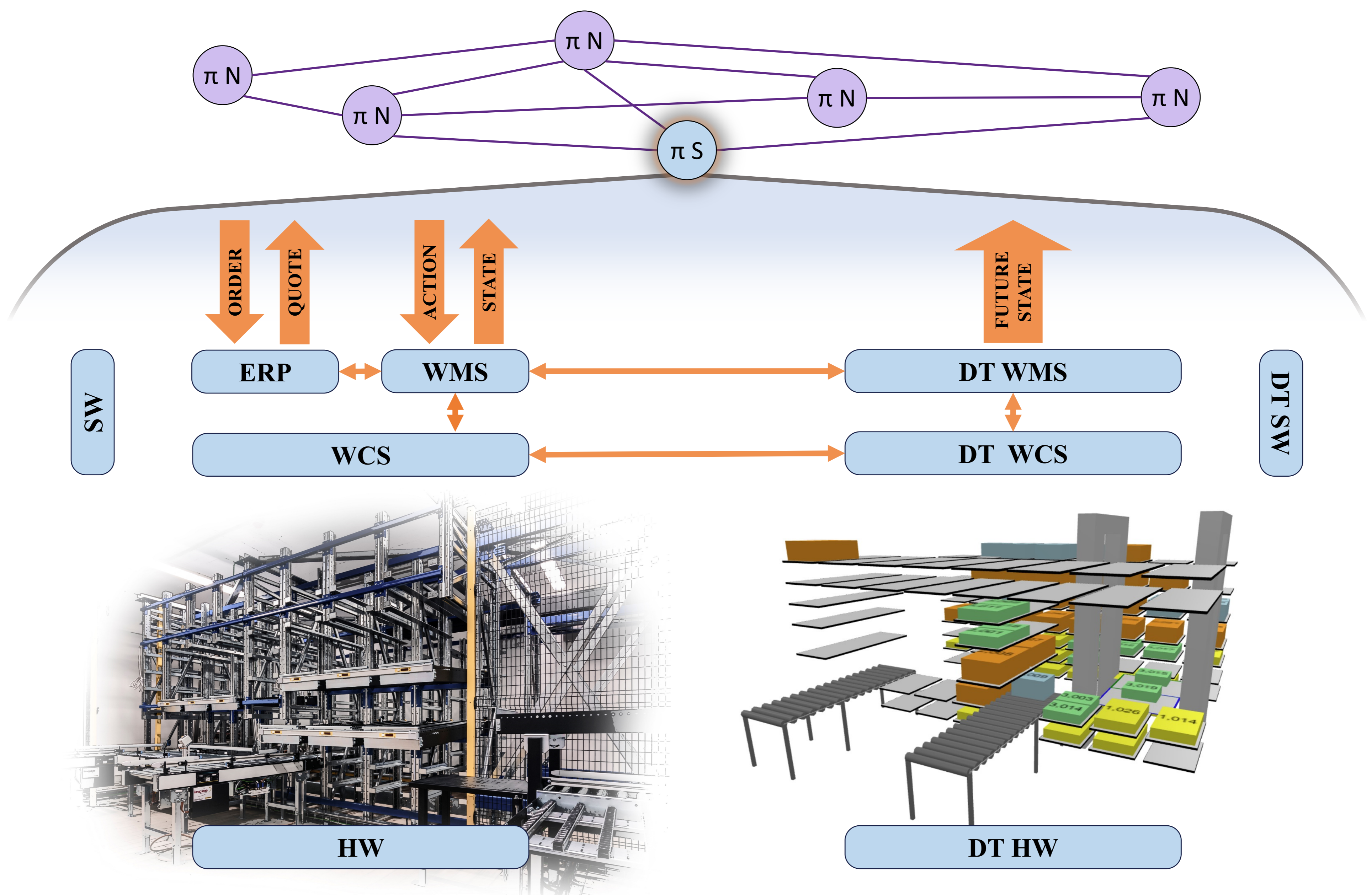
VALUE OF THE PROPOSED DT FOR PI APPLICATIONS

The proposed DT allows for:

- **Real time monitoring of the PI-store operations to improve synchronization with PI-movers**
- Adjusting the operational parameters of the AS/RS to **fit with real-time demand** from the PI network
- **Assessing the efficiency** of higher protocols established by the PI network stakeholders

Cyber-Physical-Internet-Driven Logistics Infrastructure Integration in the Greater Bay Area

Hang Wu, Ming Li and George Q. Huang

OBJECTIVE

• To establish a logistics infrastructure integration network based on the existing logistics infrastructure in the GBA;

• To migrate the general features of the computer network fusion to CPI and establish an infrastructure integration network with good real-time performance;

• To design an innovative path evaluation mechanism and specific routing mechanisms for CPI with motivation of data package routing in computer networks.

METHODOLOGY

This research proposes a framework with two-layer for the infrastructure integration network in GBA.

For the fusion of link layer, this research propose an approach to establish the connection between different areas to form an integrated CPI network to achieve the integrated and persistent management.

For the fusion of transport layer, this research has developed two routing mechanisms with different path evaluation mechanisms for the integrated CPI network.

Finally, a simulation experiment is conducted for integrating pharmaceutical logistics network in the GBA to verify the effectiveness and efficiency of the proposed framework from multiple dimensions. The result of the experiments demonstrates that the framework is effectively applied to the medical logistics network in the GBA with high-capacity utilization and more stable load balance.

CONTRIBUTION

1. The computer network concept is migrated in the proposed framework, which provide a new perspective for logistics infrastructure integration.

2. The proposed routing mechanisms of the framework can adapt to different network scales and has good scalability.

3. The experiment used a data-driven approach to verify the effectiveness of the proposed framework.

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Blockchain-based electronic exchange of freight transport information (eFTI)

Rachaniotis N., Dasaklis T. and Kopanaki E.

INTRODUCTION

Electronic Freight Transport Information (eFTI) refers to the electronic exchange of information between different parties involved in freight transport chains. It aims at the efficiency and transparency of freight transport by allowing the quick and accurate exchange of information between all parties involved.

EXISTING SITUATION

Most transactions related to the transport of goods are still paper-based, due to:

- The **fragmented legal framework** forming inconsistent requirements of electronic documents acceptance by different authorities.
- The **fragmented IT environment** comprising non-interoperable systems and varied standards of electronic messages and documents.
- The **low level of electronic documents' acceptance** by different stakeholders.

REGULATORY FRAMEWORK

The European Commission formed a **Regulation** aiming to enhance the trust of businesses and authorities in Member States and ensure that eFTI platforms and service providers meet the required functional standards.

BLOCKCHAIN

Blockchain technology can be used to create a *decentralized*, *tamper-proof* and *immutable* ledger to store and share eFTI data.

- It may improve the **transparency**, **security** and **traceability** of transport information.
- The **data** stored on the blockchain is **immutable** and can be used as evidence in case of disputes.
- **Smart contract capabilities** can automate payment processes and transfer of ownership.

REQUIREMENTS

Blockchain-enabled pan-European eFTI infrastructure operational requirements:

- *Interoperability*: seamless communication and data sharing between all parties involved.
- *Common standards* widely accepted across Europe
- *Scalability*: To support increased volume of transactions.
- *Smart contract development* and *execution* to automate processes and enable real-time tracking of information
- *Technical support*: To ensure smooth operation
- *Legal* and *regulatory compliance* including EU data protection and customs' regulations.

CHALLENGES

- Lack of *awareness* and *business readiness*
- *Technical architecture* under consideration
- Varied technical solutions considered
- Lack of unified messaging/document *standards*
- Many *small companies* (e.g., truck owners) involved, unable to make changes or investments

CONCLUSIONS

Blockchain technology has the potential to revolutionize the way eFTI systems work, by offering reliability, transparency, traceability and data security. However, alternative technical solutions are still considered in the European Union, while legal and business are not yet resolved.

ACKNOWLEDGEMENTS

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Lead-time-based Routing of Freight in PI Networks

Alireza Shahedi, Nicola Sacco, and Mahnam Saeednia

Introduction

Freight transport sector is responsible for a substantial share of carbon emissions (Lemmens et al.,2019) and considering its growth and reliance on fossil fuels, reducing this share seems challenging (McKinnon, 2018). Transitioning to a low-carbon economy requires a joint effort in decarbonizing road transport and fostering a modal shift towards the more sustainable option of rail transport (McKinnon, 2016).

However, in practice, lack of flexibility in delivery quantity, frequency, and strict scheduling are major barriers to the attractiveness of intermodal transport (Meers et al., 2017). Horizontal integration of different transport modes, as in synchronized intermodality (Tavasszy et al., 2017), allows for parallel deployment of different transport modes, where intermodal transport is one of them.

To substantially increase the efficiency and sustainability of logistics, the concept of physical internet (PI) was introduced by (Montreuil, 2011) based on the digital, operational, and physical interconnectivity of global logistic systems (Meller et al.,2012). Inspired by the data packets in the digital internet, the idea of PI is that products are dispatched in special standard containers. In this regard, Montreuil et al. (2010) introduced three main elements of PI as PI-containers, PI-nodes (e.g., PI-hubs, PI-sorters, etc.), and PI-movers (PI-conveyors, PI-vehicles, etc.). In PI-hubs, arriving PI-containers are transferred to the (same or different) departure modes. As an essential component of the PI-network, PI-hubs have been studied in the context of intermodal transport. (Chargui et al., 2019) considered a MILP to optimize the operations in a rail-road PI-hub cross-dock terminal. They minimized the energy consumption for the PI-conveyors used in the PI-hub and the cost of using outbound trucks. (Essghaier et al., 2022) proposed a multi-objective truck-scheduling problem in rail-road PI-hubs considering uncertainty. They utilized the Fuzzy Multi-objective MIP approach to cope with uncertainties. They optimized the truck's delay as well as the travel distances of the PI-containers in PI-hubs.

This study explores PI-based synchronized transport of standard containers of various sizes where intermodal transport is considered horizontally alongside direct trucking. To ensure increased sustainability, the approach seeks minimizing the number of trucks required to transport goods. The proposed model is inspired by the work by (Di Febbraro et al, 2016) to plan intermodal transport chains in a cooperative manner. They considered three sets of sub-problems to optimize the entire intermodal chain.

Problem Definition

In this section, the modeling framework is presented where shipments are transferred using two alternative transportation modes:

1. Rail and truck via PI-hub: It is assumed that the rail schedule is created to accommodate the demand and to create economies of scale. The rail-road PI-hub represents a class of PI-nodes that facilitates the transfer of PI-containers delivered by trains to trucks departing from the site. It incorporates a PI-sorter and two maneuvering zones situated at the train and loading dock sections. The cross-docking procedure commences with the unloading of PI-containers from the wagons, followed by their categorization by destination and delivery to the designated outbound docks. Finally, the PI-containers are loaded onto the outgoing trucks and the trucks deliver them to their related nodes.

2. Only direct trucks: This mode is much faster than the previous one, but it is not much sustainable and also imposes more cost on the transportation chain. Hence, the model seeks minimizing the number of trucks with the same destination by utilizing truck capacities while respecting the delivery time of shipments. As modular containers are assumed, the delivery time of a shipment is equal to the delivery time of its last module.

Other assumptions include:
- The considered shipping flow is only the one from node A to node B.
- The trains of the first transportation mode are scheduled and depart from node A.
- Trucks are not scheduled but the objective is to use their maximum capacity.
- Each of the modules has a specific operation time in the PI-hub.
- Delivery time of a shipment is equal to delivery time of its last module.
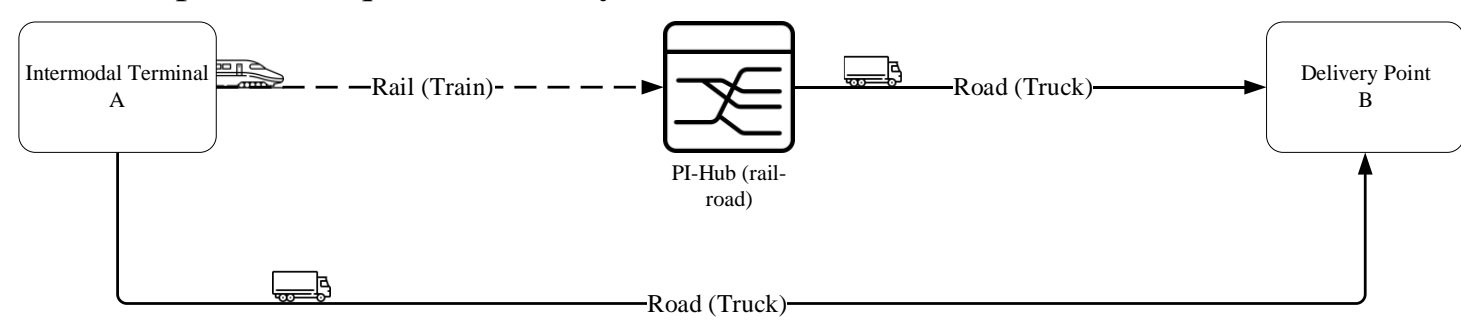

Fig. 1: A schematic view of the proposed intermodal freight transportation chain

Methodology

Optimization Model:

The first and the second objective function minimizes the total number of direct trucks and total delivery time of the modular shipments, respectively.

$$J_1 = \sum_{s \in \mathcal{S}} \sum_{i \in \mathcal{I}_s} \sum_{\ell \in \mathcal{T}} z_\ell^{is} \quad \text{and} \quad J_2 = \sum_{s \in \mathcal{S}} \beta_s \cdot DT_s$$

The combination of the above objective function using weighting coefficients in order to prioritizing them.

$$[z^\star, w^\star, r^\star] = \arg\min[\alpha J_1 + J_2]$$
$$s.t.$$
$$DT_s \geq \varphi^{is} \qquad \forall i \in \mathcal{I}_s, s \in \mathcal{S}$$
$$DT_s \geq \sigma^{is} \qquad \forall i \in \mathcal{I}_s, s \in \mathcal{S}$$
$$\rho^{is} \geq (d_\ell + tt_\ell)w_\ell^{is} - M(1 - w_\ell^{is}), \qquad \forall \ell \in \mathcal{R}, i \in \mathcal{I}_s, s \in \mathcal{S}$$
$$\sigma^{is} \geq \rho^{is} + t_p^{is} + tt_\ell - M(1 - r_\ell^{is}), \qquad \forall \ell \in \mathcal{C}$$
$$\varphi^{is} \geq Ar_A^s \cdot z_\ell^{is} + tt_\ell - M(1 - z_\ell^{is}), \qquad \forall \ell \in \mathcal{T}$$
$$\sum_{s \in \mathcal{S}} \sum_{i \in \mathcal{I}_s} V^{is} z_\ell^{is} \leq Cap_\ell \qquad \forall \ell \in \mathcal{T}$$
$$\sum_{s \in \mathcal{S}} \sum_{i \in \mathcal{I}_s} V^{is} w_\ell^{is} \leq Cap_\ell \qquad \forall \ell \in \mathcal{R}$$
$$\sum_{s \in \mathcal{S}} \sum_{i \in \mathcal{I}_s} V^{is} r_\ell^{is} \leq Cap_\ell \qquad \forall \ell \in \mathcal{C}$$
$$\sum_{\ell \in \mathcal{R}} w_\ell^{is} + \sum_{\ell \in \mathcal{T}} z_\ell^{is} = 1 \qquad \forall i \in \mathcal{I}_s, \forall s \in \mathcal{S}$$
$$\sum_{\ell \in \mathcal{C}} r_\ell^{is} = \sum_{\ell \in \mathcal{R}} w_\ell^{is} \qquad \forall i \in \mathcal{I}_s, \forall s \in \mathcal{S}$$
$$z_\ell^{is}, w_\ell^{is}, r_\ell^{is} \in \{0,1\} \qquad \forall i \in \mathcal{I}_s, \forall s \in \mathcal{S}, \ell \in \mathcal{C}, \ell \in \mathcal{R}, \ell \in \mathcal{T}$$
$$Ar_A^s \geq 0, \qquad DT_s \geq 0 \qquad \forall s \in \mathcal{S}$$

Parameters	
V^{is}	Volume of module i of shipment s
V_s	Volume of the whole shipment s
Cap_ℓ	Capacity of transport mode $\ell \in \mathcal{T} \cup \mathcal{R} \cup \mathcal{C}$
tt_ℓ	Travel time of module i of shipment s with transport mode $\ell \in \mathcal{T} \cup \mathcal{R} \cup \mathcal{C}$
t_p^{is}	Operation time of the module i of shipment s in PI-hub
d_ℓ	Departure time of train $\ell \in \mathcal{T}$
α, β_s	Weight coefficients (s referring to shipments)
Decision variables	
z_ℓ^{is}	1 if module i of the shipment s is assigned to direct truck $\ell \in \mathcal{T}$, and otherwise, 0
w_ℓ^{is}	1 if module i of the shipment s is assigned to train $\ell \in \mathcal{R}$, and otherwise, 0
r_ℓ^{is}	1 if module i of the shipment s is assigned to truck $\ell \in \mathcal{C}$, and otherwise, 0
Other variables	
Ar_A^s	Arrival time of module i of shipment s at node A
DT_s	Delivery time of shipment s to its destination
φ^{is}	Delivery time of module i of shipment s sent by only truck
ρ^{is}	Delivery time of module i of shipment s to the PI-hub
σ^{is}	Delivery time of module i of shipment s sent via train + truck

Computational Results

The optimal value of the cost function ($G^\star = \alpha J_1^\star + J_2^\star$) and the optimal values of $J_1^\star$ (minimum number of trucks), and $J_2^\star$ (minimum weighed delivery time of shipments) for α and β equal to 1 and 0.5, respectively, are presented. In addition, also the train and truck pairs are assigned to the delivery via the PI-hub, and the optimal truck number directly connecting nodes A and B are provided.

	$G^\star$	$J_1^\star$	$J_2^\star$	Number of modules transferred via (train number, truck number)	Number of modules transferred via (truck number)
Optimal value	26.099	3	24.6	22	3

The table below indicates assigning modules of shipments to each transportation mode.

(Module number, Shipment Number)	Intermodal Transport via PI-hub (Train number, Truck number)	Direct Trucking (Truck Number)
(5, 1)	-	3
(3, 2)	-	3
(2, 1)	-	1
(1, 1)	(1, 7)	-
(1, 2)	(1, 4)	-
(1, 3)	(2, 1)	-
(1, 4)	(1, 4)	-
(1, 5)	(2, 5)	-
(2, 2)	(1, 1)	-
(2, 3)	(2, 7)	-
(2, 4)	(1, 5)	-
(2, 5)	(2, 7)	-
(3, 1)	(1, 1)	-
(3, 3)	(2, 2)	-
(3, 4)	(1, 1)	-
(3, 5)	(2, 3)	-
(4, 1)	(1, 3)	-
(4, 2)	(1, 6)	-
(4, 3)	(2, 7)	-
(4, 4)	(1, 6)	-
(4, 5)	(2, 2)	-
(5, 2)	(1, 4)	-
(5, 3)	(2, 4)	-
(5, 4)	(1, 2)	-
(5, 5)	(2, 3)	-

Sensitivity Analysis

The sensitivity analysis was performed by varying the coefficient amounts (α and β) for each objective. As it is shown in Fig. 1 and Fig. 2, the variation of α and β can affect the optimal values of both objectives. In this analysis, the sum of α and β is equal to 1 for all the scenarios.

The first analysis shown in Fig. 2 and Fig. 3 measures the impact of changing α and β on the first objective optimal solutions. As it is illustrated, dropping the amount of α, followed by the rise of β, emerges in the growth of the first objective and a decline in the second objective optimal solutions. That is to say, the number of modules sent by only trucks witnessed a moderate increase, according to the mentioned trend. Also in the same way, the delivery time of the modules would become lower. As depicted in Fig. 2, $J_1^\star$ witnessed significant growth from 3 to 12 in scenario 9 which shows a sensitivity of the graph at this point by varying α and β.
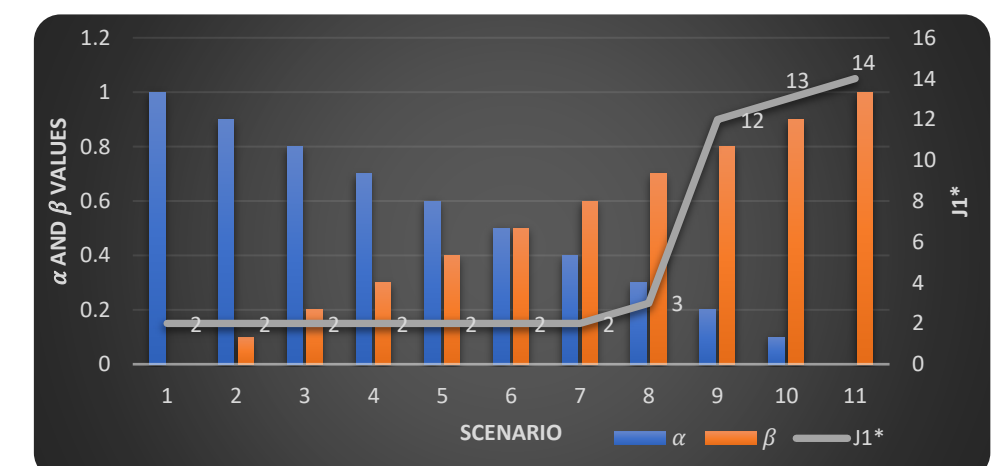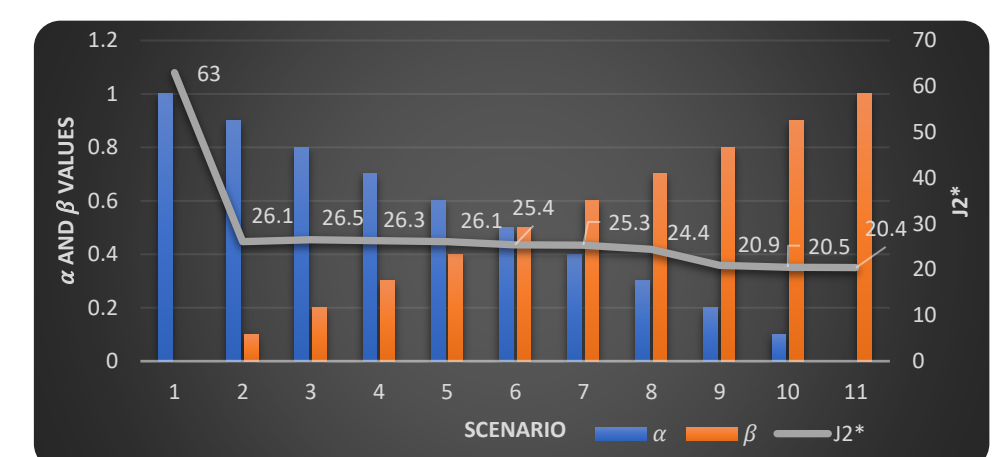
In the second analysis, the impact of the operation time of each module in the PI-hub on the mode choice is considered. This analysis shows that by increasing the operation time of the PI-hub for each module, the preference for selecting the second transportation mode (only trucks) increases and the chain experiences shifting the transportation mode from the first mode to the second one. In this case, 4 scenarios are considered for variation of operating time. As shown, the number of modules sent by the first transportation mode (train + truck) decreased substantially after adding 3 hours to the default operation time for each module. By contrast, in the same scenario, the figure for the modules transferred by the second transportation mode (only trucks) rises significantly, from 3 to 15.
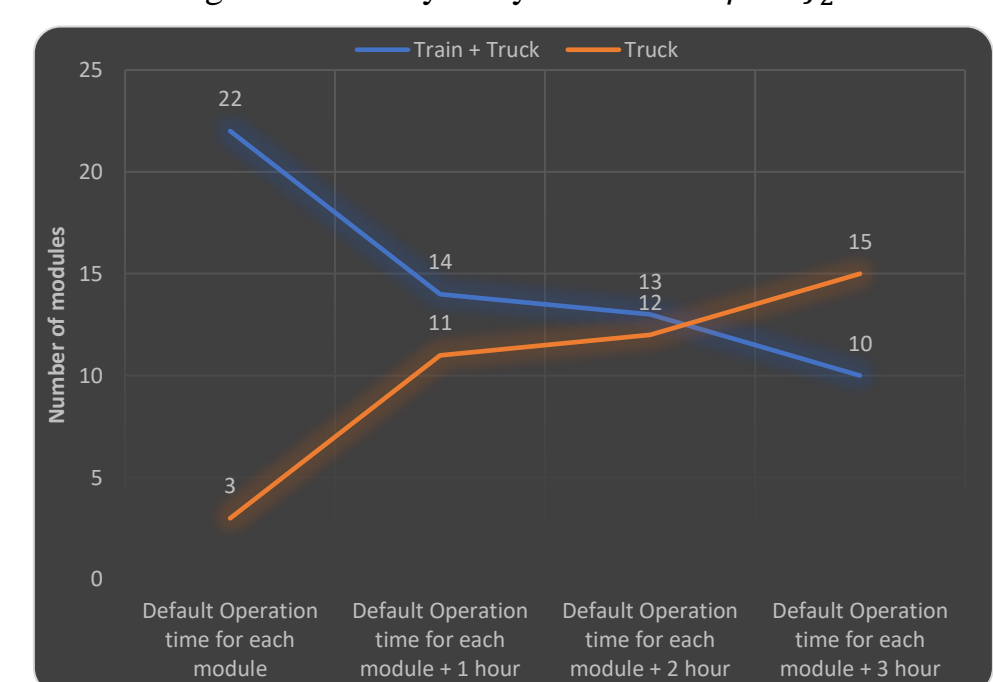

Fig. 2: Sensitivity analysis for α and β on $J_1^\star$

Fig. 3: Sensitivity analysis for α and β on $J_2^\star$

Fig. 4: Sensitivity analysis for the operation time of each module in PI-Hub

Conclusion

This study proposes a PI-based planning model for synchromodal operation of a transport network considering the parallel operation of intermodal and truck-only routes. The proposed multi-objective model seeks to satisfy the delivery time of goods while minimizing the number of trucks. The results obtained from the implementation and analysis of the model show the interplay between the importance of delivery time versus the environmental impact of transporting goods. However, it is possible to find a spot where these two objectives meet. A major impacting factor is the efficiency of the PI-hub in handling goods. Future work includes enhancing the model for consideration of constraints related to a more detailed load planning to consider the dimensions of modular containers and modeling the internal PI-hub operations and mirroring its impact on network operations.

Application of Web3 and Blockchain Technology in Physical Internet-Based Synchromodal Freight Transportation
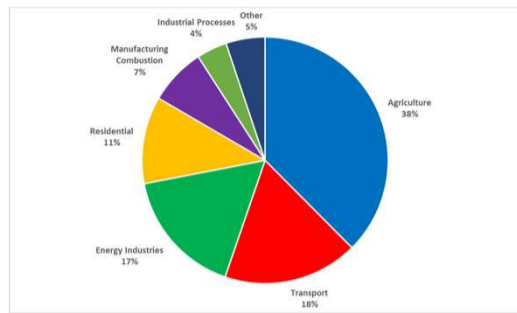
Siyavash Filom[a], Saiedeh Razavi[b]

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[b] Professor, Civil Engineering Department & McMaster Institute for Transportation and Logistics, McMaster University, Hamilton, ON, Canada
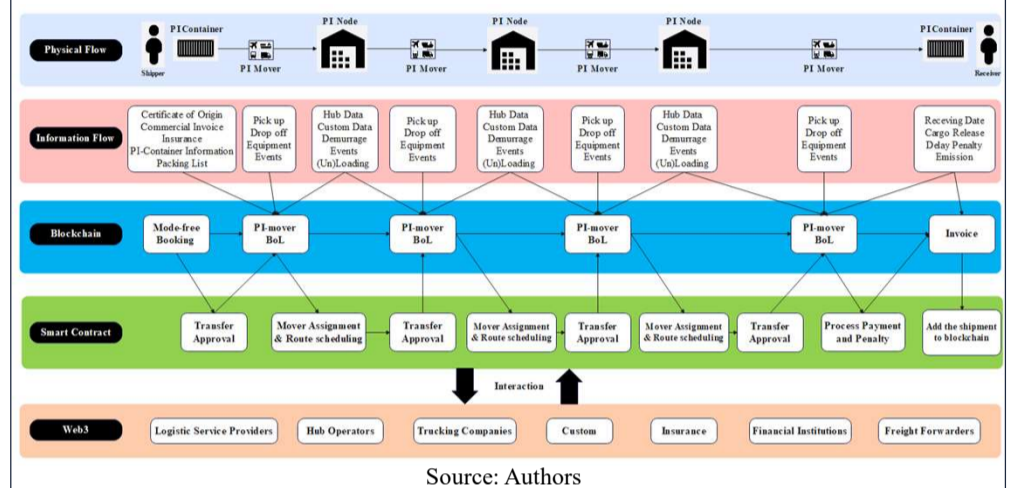
Introduction

As the backbone of the global economy, the freight transportation industry has seen an increasing rise in the prevalence of sustainability, efficiency, and integration problems. Accordingly, today's industry practices of shipping, warehousing, production, distribution, consumption, and waste collection of goods are not sustainable from many aspects: operational, financial, environmental, and social.

Data Source: Environmental Protection Agency (Link)

Synchromodal Transportation

The Physical Internet (PI) concept has been introduced as a potential solution to overcome the above-noted problems. According to the PI roadmap by ALICE, we are currently experiencing the second generation of logistic networks that is about synchromodality.
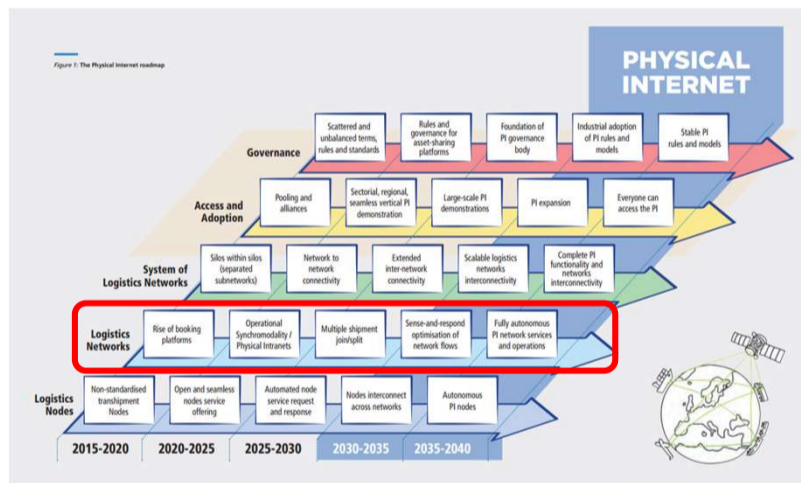
Source: Roadmap to the Physical Internet, ALICE, 2020

Why Blockchain?

By considering the breadth of the coverage and depth of the interaction in the PI notion and the data as the currency in the synchromodal transportation, a centralized data warehouse and mutual-benefit-oriented solution provider are prone to malfunction, and it can easily become a single point of failure. Standard protocols for the stakeholders to trust the massive data inventory across the supply chain should be an inevitable feature of any synchromodal freight transportation system. Blockchain, as a distributed ledger idea, fundamentally seeks to handle the complex multi-stakeholder network.

Source: Authors

Blockchain-Enabled PI Framework

In addition to the problems of centralized planning systems, the PI idea entails too many physical movements. Accordingly, an even higher number of document and financial transactions should occur in parallel, which might become the bottleneck. The blockchain-based smart contracts could bring decentralized, secure, and on-demand executable and pre-defined agreements for financial and information flows. The overall architecture of the blockchain and smart contracts have been illustrated for Bill of Lading (BoL) as an example. The architecture is reproducible for other documents.

Source: Authors

Web 3.0 for Blockchain-Enabled PI

Instead of the Web 2.0 platform, where the entire functionality has been organized by a few matchmakers, the Web 3.0 argument has a decentralized network that allows all the participants to perform the transactions securely and trustfully based on the blockchain idea established above, embedded in the Ethereum Virtual Machine (EVM). Web 3.0 allows network users to interact directly with smart contracts without needing a central authority or intermediary.

Source: Authors

Future Works

In order to foster and promote the adoption of blockchain in the physical internet context, eclectic perspectives could be addressed. From the managerial point of view, blockchain technology adaptation is the most important hurdle that should be tackled. On the theoretical side, different avenues of research shall be addressed, such as finding the most robust and sustainable consensus mechanism, network tokenization, scalability, and embedding AI-based smart contracts into the network. From the technological perspective, further research and developments are needed to increase the interconnectivity of the three main flows and to develop Web 3.0 infrastructure and machine-to-machine communication.

Conference Sponsor-Logo Area

eNegotiation for Logistics Resource Reservation

Shinji NAKADAI (NEC Corporation, Intent Exchange, Inc.)
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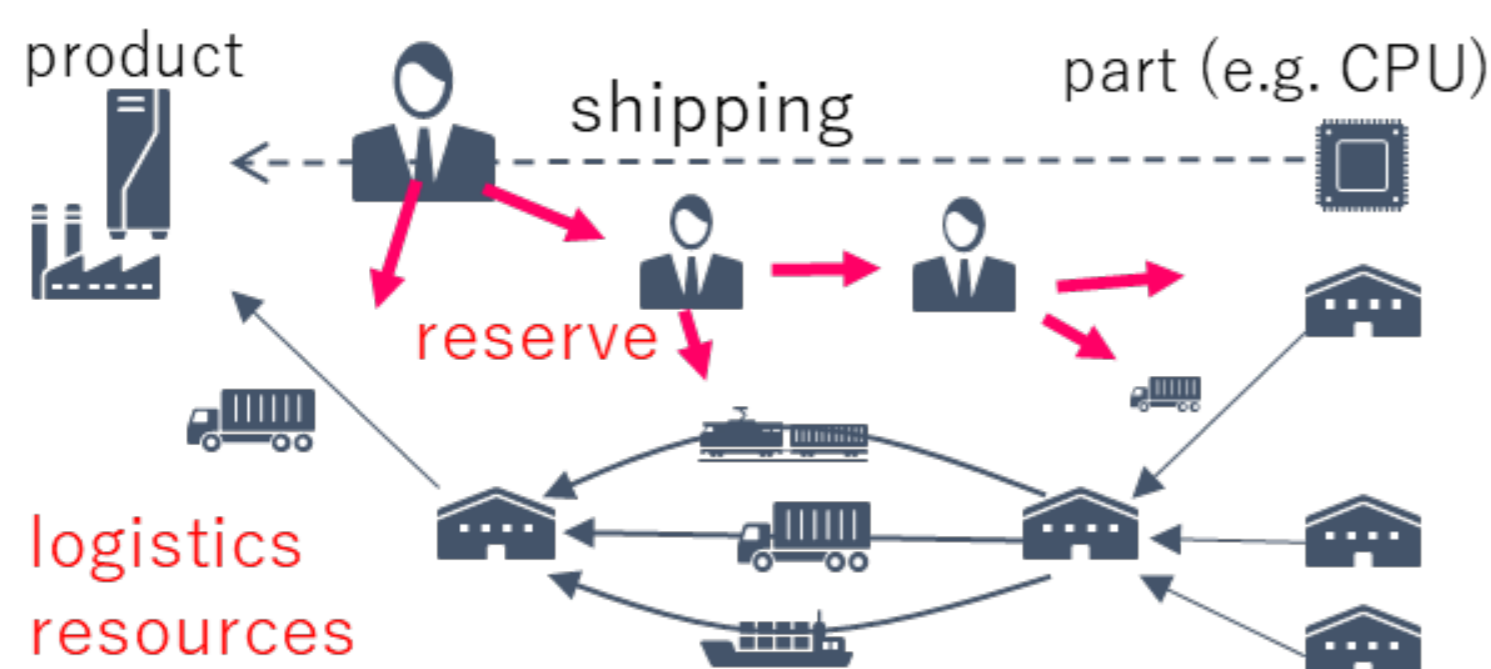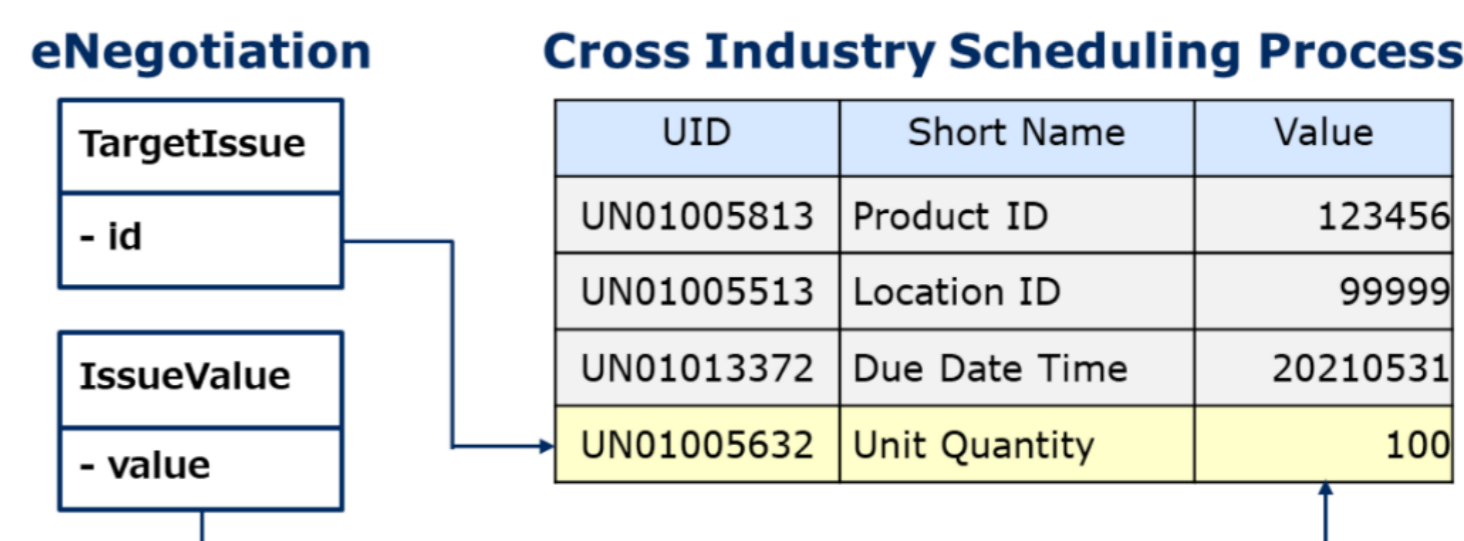
Introduction

Logistics resources shared on the Physical Internet should be seamlessly reserved (c.f. RSVP : Resource reSerVation Protocol). Negotiation among stakeholders is one of the key activities.
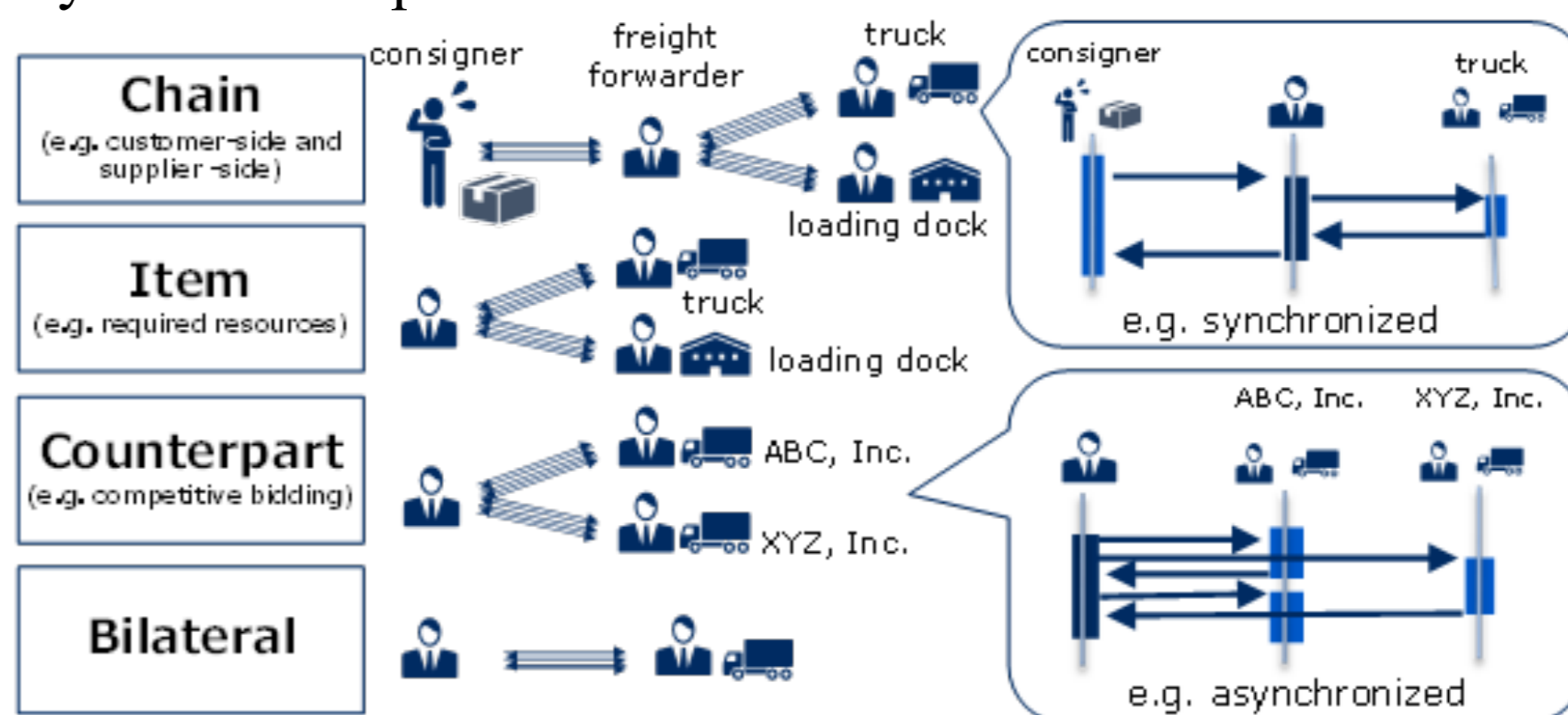

Objectives

Analogue negotiation communication (e.g. mail, telephone) should be replaced with a standardized digital protocol.

https://unece.org/sites/default/files/2021-11/BRS-eNego_v0.7.pdf

The protocol should not depend on the semantics of what to negotiate, but define the semantics of how to negotiate so that chained negotiation can be supported.


Chained negotiation among several business domains is useful to manage Scope3 emissions of GHG.

Methods

To represent negotiation issues in various business domains, eNegotiation defines how to specify target issue in a neutral way.

eNegotiation — **Cross Industry Scheduling Process**

	UID	Short Name	Value
TargetIssue — id	UN01005813	Product ID	123456
	UN01005513	Location ID	99999
IssueValue — value	UN01013372	Due Date Time	20210531
	UN01005632	Unit Quantity	100

To support real logistics arrangement, eNegotiation has four layers and each layer has synchronized protocol and asynchronized protocol.

Chain	A negotiation request from a customer triggers nested negotiations to suppliers.
Item	Several items are required to be negotiated to provide a certain service or product.
Counterpart	Several counterparts are involved in the negotiation for a certain item.
Bilateral	Several message are exchanged in a single session with a certain counterpart.

Extentions

Negotiation AI, which has been studied in the filed of AI and Game Theory, enables to automate negotiation. One-sided AI, or chatbot, is also useful to increase the efficiency of logistics arrangement.
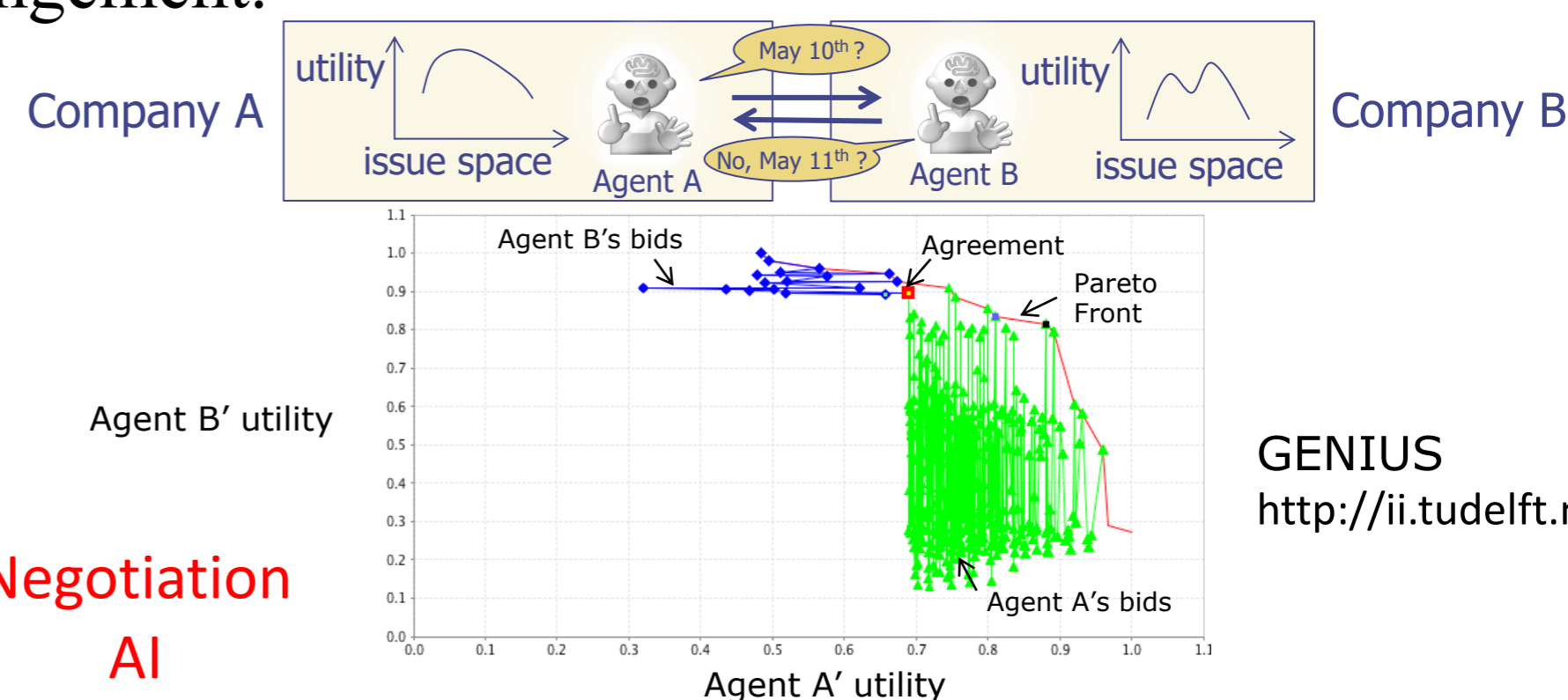
GENIUS
http://ii.tudelft.nl/genius/

Spatial-temporal Traceability for Cyber-Physical Industry 4.0 Systems

Zhiheng Zhao, Mengdi Zhang, George Q. Huang, Gangyan Xu, Qiqi Chen

Introduction

In this research, we first delineate and propose universal and interoperable spatial-temporal elements for cyber-physical industrial 4.0 systems (CPIS). A multi-modal bionic learning method for indoor positioning is developed to estimate the accurate and reliable location in a durable manner. Proximity, mobility, and contextual reasoning mechanisms are introduced to capture interplay, evolution, and synchronization among objects at operational level. To verify and evaluate the efficacy of our proposed solution, we implement it in a real-life case company and conduct a comparison study. Our results indicate that the proposed method outperforms the current indoor positioning methods and represents a significant step forward in achieving spatial-temporal traceability in CPIS.

Research Questions

(1) What is the most suitable representation standard to fulfil shared and interoperable spatial-temporal traceability considering objects shuttling between indoor and outdoor?

(2) How to realize accurate and reliable indoor positioning in a durable manner through multi-modal data from CIPS?

(3) How to manipulate spatial-temporal data through reasoning mechanism for supporting operation-related decision-making?

Spatial-temporal Elements in CIPS
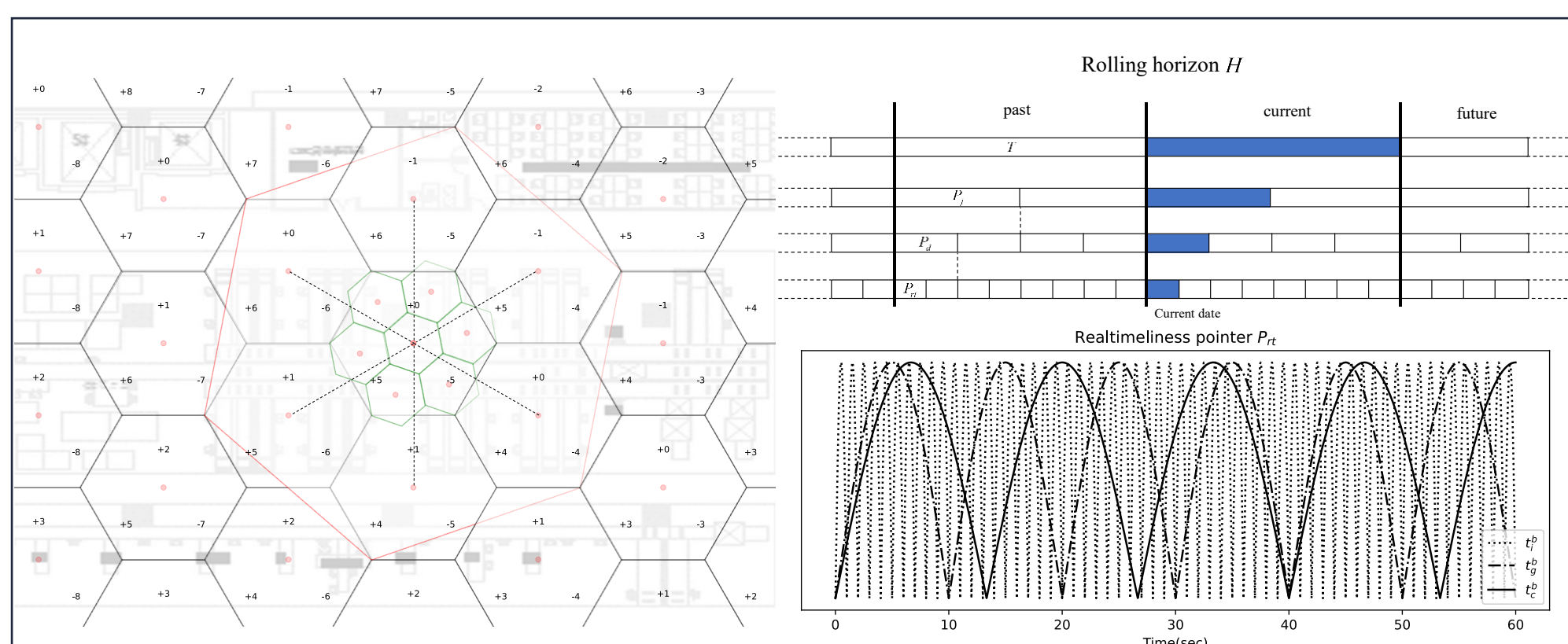
We blend self-contained coordinate system into the H3 model with extra height indicators. The coordinate system is direct representation of positioning results in limited indoor environments. We first map the coordinates derived from indoor positioning results to the H3 hexagon cells at we blend self-contained coordinate system into the H3 model with extra height indicators. The coordinate system is direct representation of positioning results in limited indoor environments. We first map the coordinates derived from indoor positioning results to the H3 hexagon cells at predefined resolution levels according to positioning accuracy requirements. The hexagon cells are like exact IP address in the computer networks where subnet mask implies higher level area. Then, we label the hexagon cells that tessellate in the same level of the building with height labelling. predefined resolution levels according to positioning accuracy requirements. The hexagon cells are like exact IP address in the computer networks where subnet mask implies higher level area. Then, we label the hexagon cells that tessellate in the same level of the building with height labelling.

Multi-modal Bionic Learning for IPS
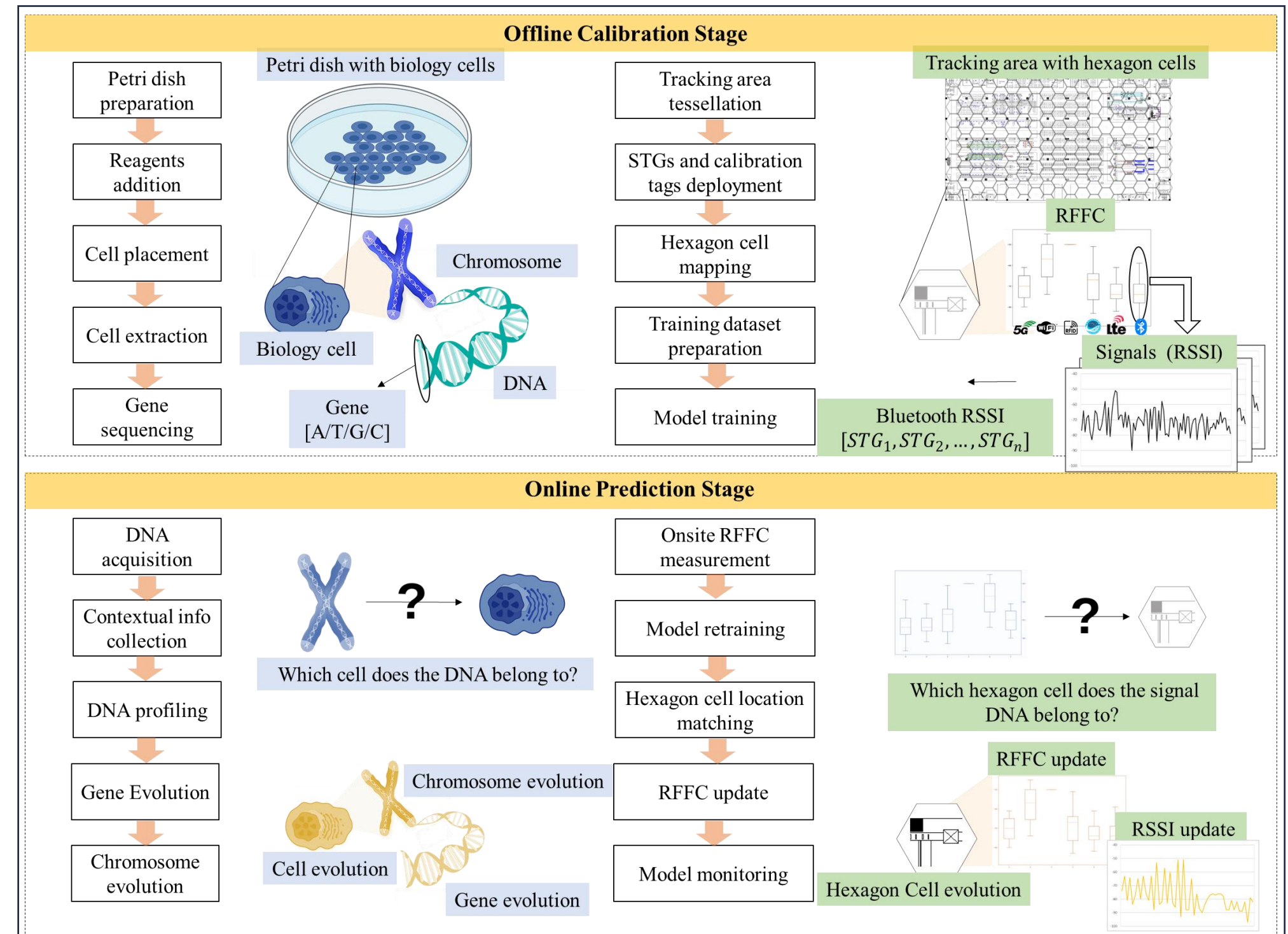
The Figure showcases the overall process of MMBL in the light of biological cell evolution. The left side of this figure tells the story of how the biology cell is cultivated, extracted, judged, and evolved, while the right side depicts the corresponding process implemented in the hexagon cell localization. MMBL consists of two stages, which are offline calibration stage and online prediction stage.
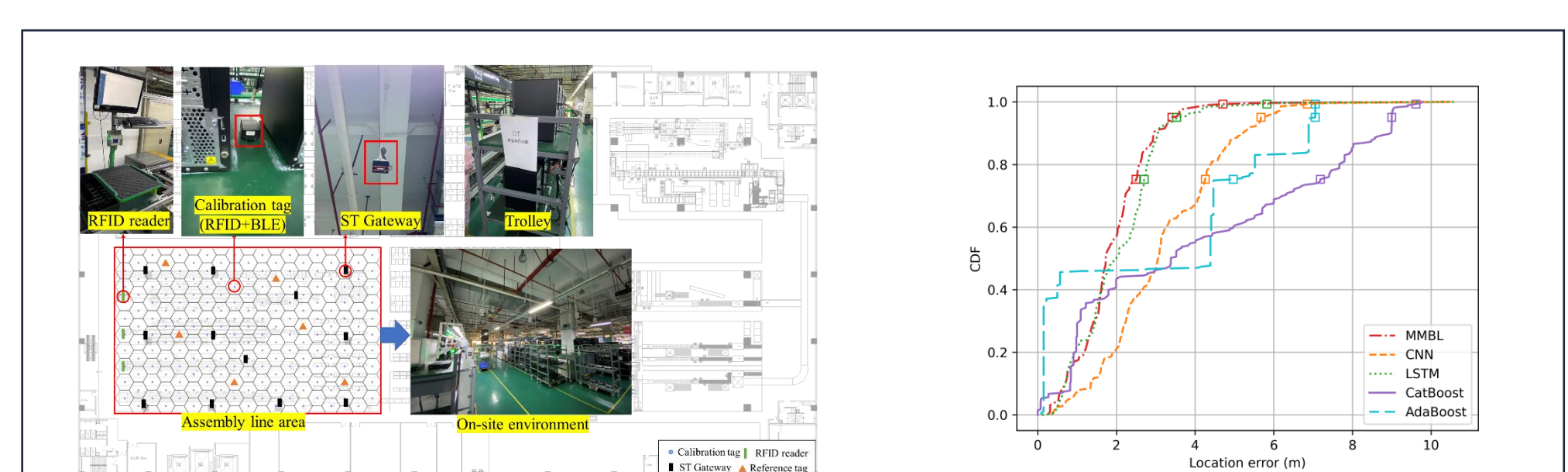
Case Study and Conclusions

Figure compares the location error with different methods using cumulative distribution function. In the figure, MMBL clearly outperforms the other methods with 95% of the errors are within 3.41m, which is lower than CNN (5.67m), LSTM (3.53m), and other gradient boosting methods. The 99% errors of MMBL are within 4.70m in the industrial settings. From the above result, the MMBL has a good anti-interference ability to instable RRFC.

This research delineate and compare basic spatial-temporal elements for geospatial traceability both in indoor and outdoor settings. A multi-modal bionic learning method is the proposed to realize accurate and reliable indoor positioning as analogous to the biology cell evolution and mutation. Three types of spatial-temporal reasoning mechanisms are put forward to generate insights and predictions entailing intelligent decision-making.

Acknowledgements

Conference Sponsor-Logo Area

Is Digital Twin a Better Solution to Improve ESG Evaluation for Vaccine Logistics Supply Chain: A Game Theoretic Analysis

Mengdi Zhang, Zhiheng Zhao, George Q Huang

IPIC 2023

9th International Physical Internet Conference
June 13-15, 2023
Athens, Greece

THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

Introduction

This research systematically analyzes the influence of digital twin service (DTS) on ESG evaluation and analytically investigates the long-term behavior of sustainability concerned stakeholders in the VLSC. Firstly, an architecture of DTS enabled ESG evaluation for VLSC is proposed to describe the DTS effectiveness. After that, a tripartite evolutionary game model in a two-tiered VLSC including CCLSPs, the public, and government regulators is proposed. And the conditions for the existence of equilibrium stable points are derived to capture the feature of the government incentives and the role of the public in the DTS investment decisions of CCLSPs. The association of the factors is validated by using analytical sensitivity analysis. Lastly, managerial insights are derived which indicate that DTS can offer better solutions to improve ESG evaluation for CCLSPs in VLSC with different strategic stakeholders.

Research Questions

1. What are the functions and benefits of DTS for ESG evaluation of the VLSC from technical perspective?
2. In the tripartite evolutionary game model, is there any game equilibrium point where the CCLSPs choose to invest in DTS for improving ESG evaluation and what kind of decisions should the public and government regulators make?
3. How can this model be used to explain the changes in the strategic choice preference of the three stakeholders, and what are the main influencing factors?
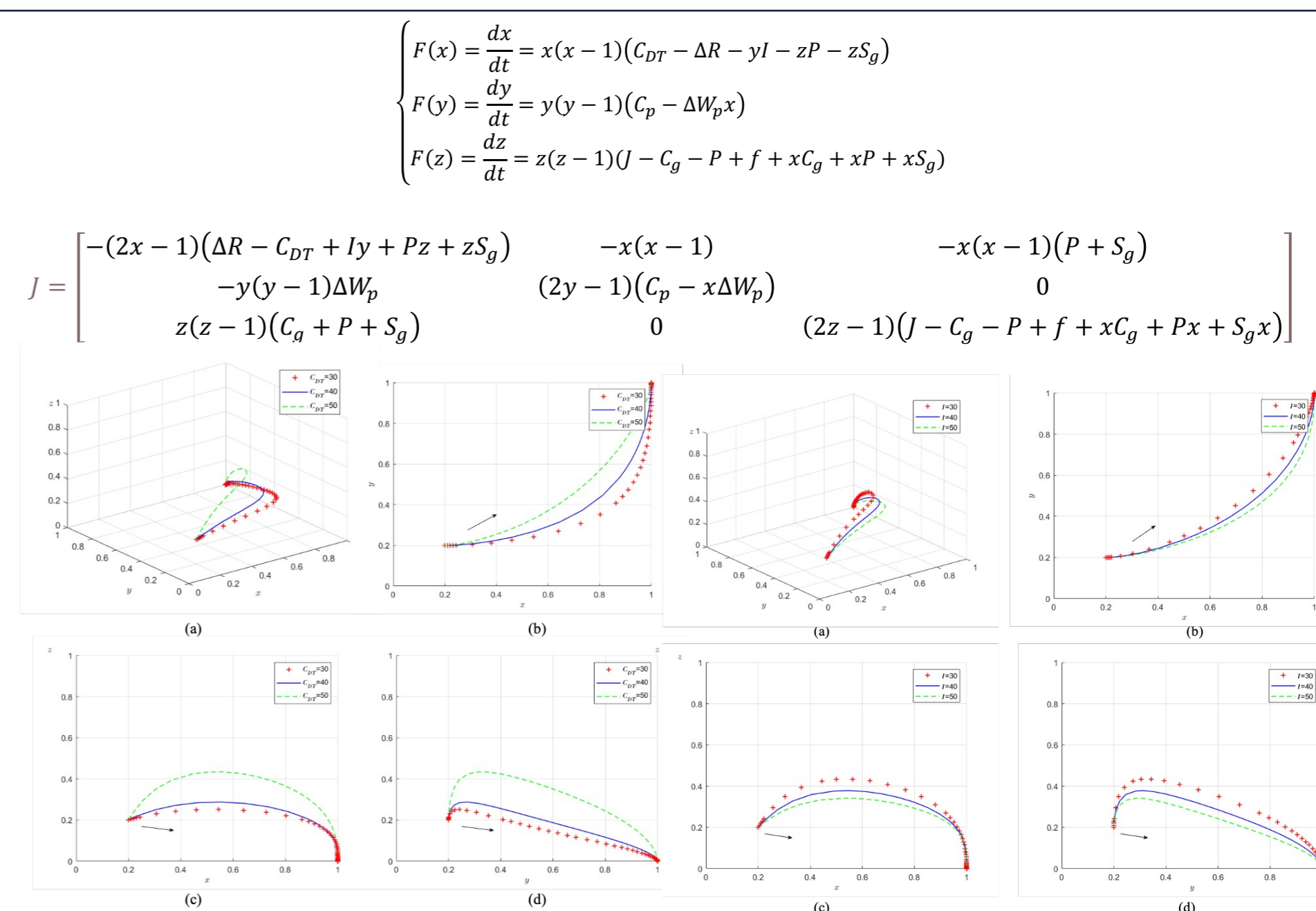
DTS Enabled ESG Evaluation
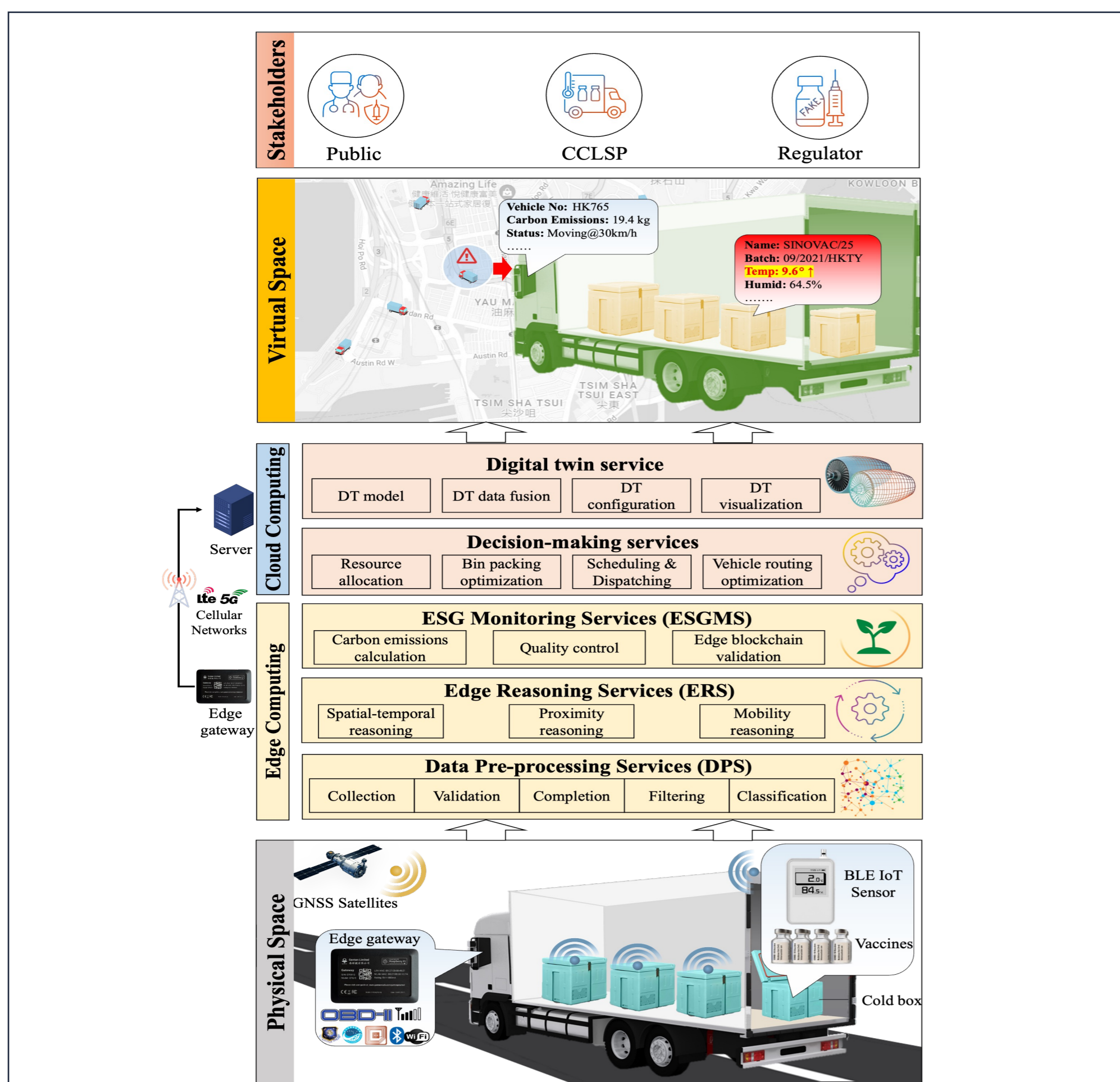
The Model

A two-tiered VLSC is considered, which composed CCLSPs who offer the logistics service, the public who are involved in the ESG evaluation process and the government regulators who supervise the vaccine logistics market. This research focuses on the design of the governance mechanism for facilitating the investment of DTS in the VLSC to improve the ESG evaluation of CCLSPs. Specifically, three main scenarios need to be discussed, the role of DTS in the ESG evaluation, the impact of government incentives on CCLSPs' investment in digital twins, and the role of public participation in the entire process.

	CCLSP payoff	Public payoff	Government regulator payoff
(I，P，S)	$R + \Delta R + S_g + J - C_{DT}$	$W_p + \Delta W_p - C_p$	$-S_g - f - J + M_g$
(I，P，NS)	$R + \Delta R - C_{DT}$	$W_p + \Delta W_p - C_p$	M_g
(I，NP，S)	$R + \Delta R + S_g + J - C_{DT}$	W_p	$-S_g - f - J + M_g$
(I，NP，NS)	$R + \Delta R - C_{DT}$	W_p	M_g
(NI，P，S)	$R - P + J - I$	$-C_p - L_p$	$-J - f + P - L_g - B$
(NI，P，NS)	$R - I$	$-C_p - L_p$	$-L_g - C_g - B$
(NI，NP，S)	$R - P + J$	$-L_p$	$-J - f + P - L_g$
(NI，NP，NS)	R	$-L_p$	$-L_g - C_g$

Model Analysis

$$\begin{cases} F(x) = \dfrac{dx}{dt} = x(x-1)(C_{DT} - \Delta R - yI - zP - zS_g) \\ F(y) = \dfrac{dy}{dt} = y(y-1)(C_p - \Delta W_p x) \\ F(z) = \dfrac{dz}{dt} = z(z-1)(J - C_g - P + f + xC_g + xP + xS_g) \end{cases}$$

$$J = \begin{bmatrix} -(2x-1)(\Delta R - C_{DT} + Iy + Pz + zS_g) & -x(x-1) & -x(x-1)(P+S_g) \\ -y(y-1)\Delta W_p & (2y-1)(C_p - x\Delta W_p) & 0 \\ z(z-1)(C_g + P + S_g) & 0 & (2z-1)(J - C_g - P + f + xC_g + Px + S_g x) \end{bmatrix}$$

Conclusions

Sensitivity results reveal that when the public have benefits, a higher probability of the public participation and a lower investment cost are conducive to CCLSPs choosing the DTS investment strategy. Government regulators can also promote the sustainable development by encouraging the social responsibility of the public by several means, such as expanding media influence and attracting the public supervision awareness. The supervision behavior of the government regulator will help CCLSPs to improve the ESG evaluation, but as CCLSPs continue to develop stably with a better image, the government regulators ten to relax the supervision conditions. Although CCLSPs are increasingly reluctant to choose the investment strategy because of the increasing DTS investment cost, the probability of the public participation increases. Interestingly, government regulators can set a high-level penalty in advance whether the public participate or not, the increasing penalty is an effective way to urge CCLSPs improving their ESG levels.

Acknowledgements

Conference Sponsor-Logo Area

Innovative Approach to Minimise Container Port Footprint

Bruce Allen, Philip Norman, Russell Thompson, and Dimitris Tsolakis

The Challenge

Expansion of the world's Container Ports is both uncontrollable and unsustainable.

Surging containerised-freight traffic flow creates major headaches for many:

- Governments,
- Port authorities,
- Transport industry, and
- The community.

Pressure on existing infrastructure causes:

- Congestion,
- Environmental degradation,
- Operating inefficiencies, and
- Increased operating cost challenges.

Over the last couple of decades there have been many proposed technological innovations, but very few have made it through to produce real-world efficiency gains. CFT innovation aims to break that mould and deliver tangible benefits.

The Paradigm Shift

The solution requires a paradigm shift in the way container ports are managed.

Innovative, sustainable and dedicated container-freight transportation infrastructure is necessary to:

- Provide seamless integration between ports and intermodal hubs, with ship unloading and loading techniques designed to maximise throughput

- Automate the transportation of urban freight, essential to reduce both operating and social-environmental costs

The CF Technologies (CFT) system offers such a paradigm shift, and facilitates seamless integration with existing infrastructure. CFT introduces a solution that matches ongoing long-term requirements. It is flexible, able to scale efficiently and cost-effectively as the context changes.

Key CFT Invention Features

All innovative features of the CFT system trace back to a simple core concept -- Attach wheels to a shipping container and turn it into a vehicle. The concept is not new, but no practical design has ever been successfully commercialised. Central to the CFT solution is the Detachable Drive Unit or DDU. These are electrically powered, semi-autonomous rail units that attach in pairs to containers when required, and can also function independently as vehicles without any container.

The attachment mechanism is novel in that it is automatic when the weight of a container is applied. But the most important unique feature of the wheels is their location relative to the vertical centre-of-gravity of the assembled vehicle. Being close to the centre is vital for minimising tipping forces when cornering at speed.

Combining the low centre-of-gravity with what is effectively a 4WD, split-axle vehicle, creates a huge advantage – cornering radius at a given speed is much less than can be achieved with traditional rail systems. Not only does this allow for more flexibility in the layout of rail pathways, but it also leads to another unique CFT innovation – the Double Helix. This intertwined bidirectional pathway can be implemented to shift containers vertically within a relatively small area.

Flexibility in rail pathways means that pipes conveying container-vehicles can be installed close enough to container ships to allow direct access by ship-to-shore gantries. Another CFT innovation relates to a gantry modification that claims to reduce ship loading and unloading times by about 20 percent.
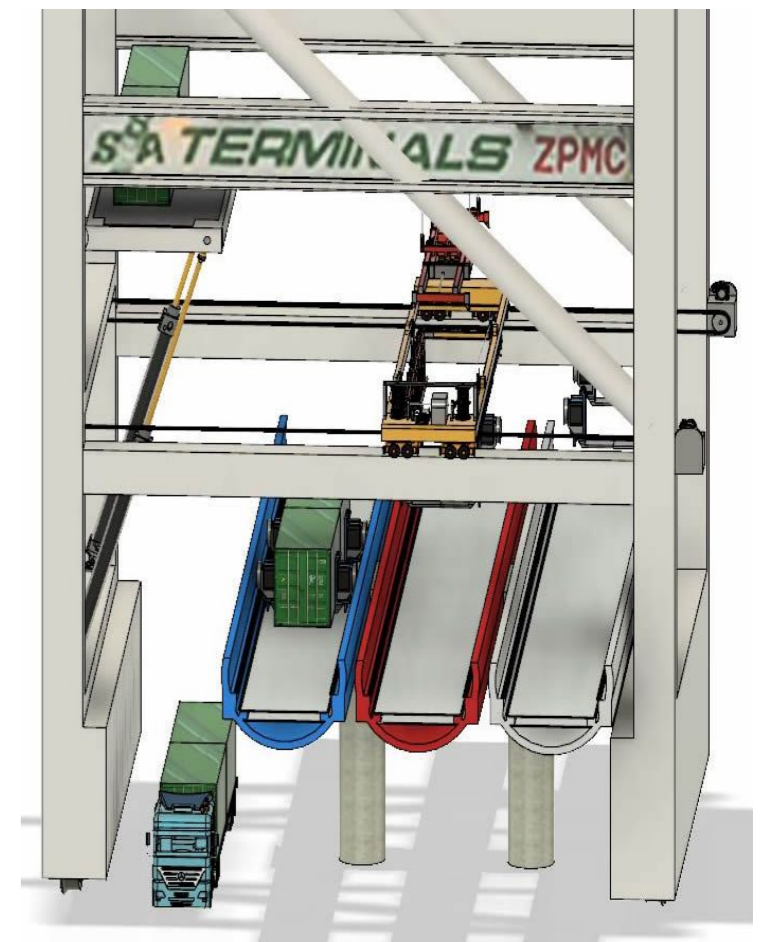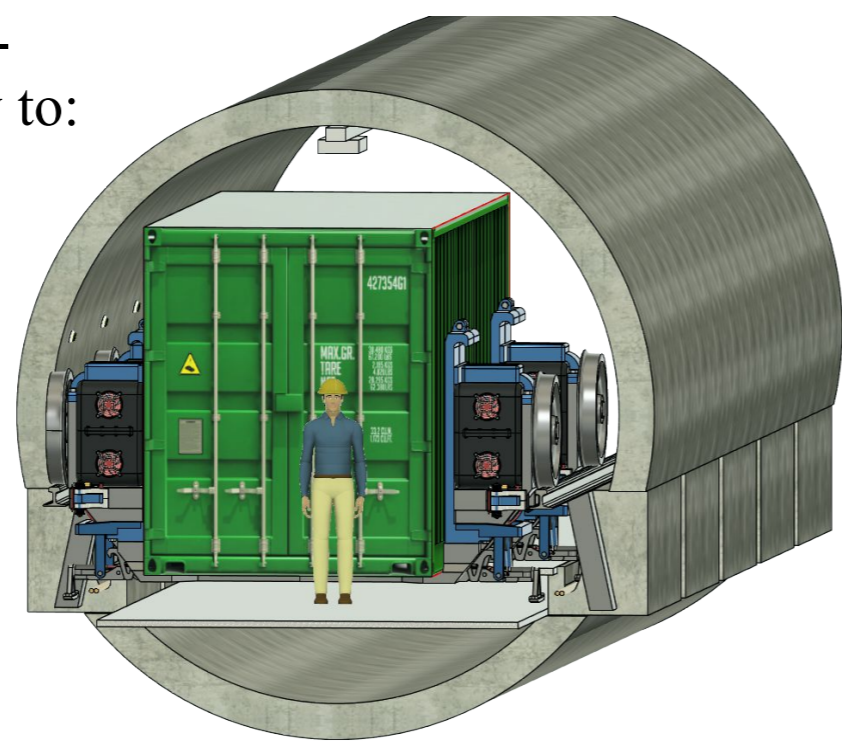
Implementation Blockages

There are critical obstacles to overcome when considering the application success for these innovations. Three key phases of development and completion are required:

- Planning and design,
- Development and testing, and
- Participation of governments and other stakeholders during all implementation stages.

So where is CF Technologies currently positioned?

- Advanced stage of design and planning at the theoretical and research level,
- Advanced Patent development and registration in multiple jurisdictions,
- Early stage of testing and simulation modelling at a research level,
- Continuing search for funding to build a prototype, and
- Various levels of engagement with governments and stakeholders in Australia and elsewhere.

Summary of Benefits

Environmental Benefits
- Low Noise
- Reduced Port Footprint
- No Pollution at the Point of Delivery
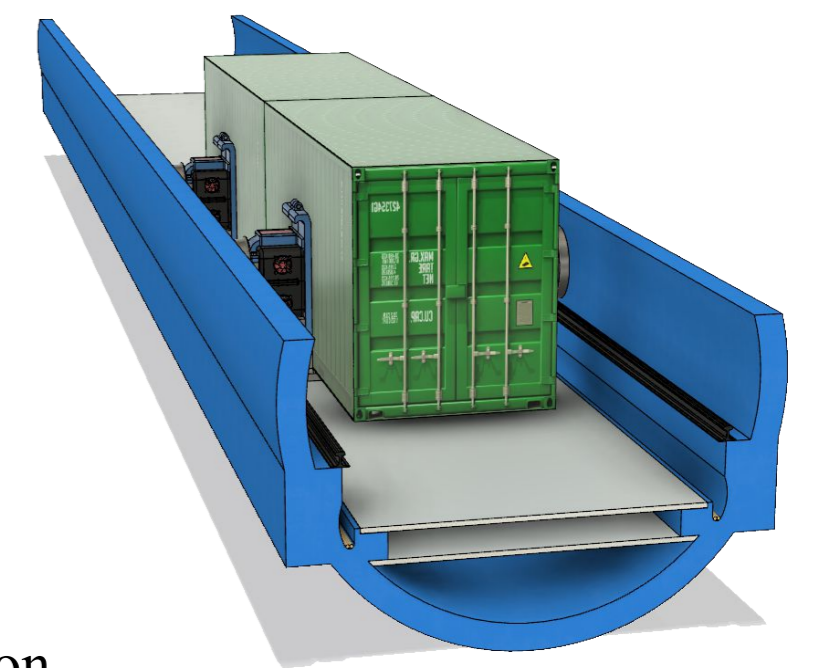- Minimal Impact on Surrounding Community

Operational Benefits
- Continuity of Container Flow
- Improved Crane Efficiency
- Reduced Need for Dock-side Storage
- Additional Flexibility for Track Routing
- Reduced Risk of Accidents due to Robotisation

Manufacturing Opportunities
- Local Design and Manufacture of Detachable Drive Units
- Develop Software for Central Control System
- Develop Communication System
- Pilot for Refinement and Testing of the Technology
- Establish New Construction Techniques for Pipe-Rail and Double Helix
- Research Crane Modifications to Improve Efficiency

Export Opportunities
- No System Like CFT Anywhere in the World
- Large Number of Docks Where Congestion is a Problem
- Increasing Competition for Valuable Dock-Side Real-Estate
- As International-Trade Grows, So Does the Demand for Continual Refinements to Ensure Maximum Freight-Handling Efficiency

The Long Road Ahead

The huge investment associated with port infrastructure and freight logistics has resulted in a reluctance to adopt new technology in a timely manner. CFT faces many challenges in delivering a radical solution for an industry adverse to change.

Container Ports are increasingly constrained both in size and in number. For many existing ports, the need for a new approach is critical. The solution proposed with the CFT system provides continuous and immediate transfer of containers between ports and remote hubs, thereby reducing the required dock storage-area.

Collaboration is key to our future success, and our immediate aim is to validate the patented technology to the point where a major industry player might seek a controlling stake in CF Technologies P/L.

CFTechnologies