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Unlocking the Potential of the Physical Internet: a Trust-enabling Decentralized Process Sharing Connector

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Abstract: *The Physical Internet (PI) hinges on extensive collaboration across logistics stakeholders. Although the benefits have been confirmed by numerous studies and despite its potential for business success, there is a noticeable reluctance to adopt and implement concepts such as PI. We put forward that this hesitancy is in no small part attributed to trust. Therefore, we establish a trust framework that provides a better understanding of trust and its concerns in the context of PI. This paper aims to reason about trust in relation to architecture with commercial stakeholders.*

In our research, we introduce a novel, decentralized, connector-based architecture leveraging dataspaces and event-based data sharing. This architecture prioritizes data ownership and transparency, enabling universal process sharing while eliminating the need for fully centralized platforms.

Surveys demonstrated that the proposed architecture, initially unfamiliar to some, ultimately fostered greater trust due to its federated nature. We conclude by advocating for a transparent design approach to expedite PI adoption and collaboration, highlighting the persistent challenges in this domain, and setting the stage for future research.

Keywords: *Physical Internet Connector, Trust, Process Sharing, Logistics Data Spaces*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☒ PI Networks, ☒ System of Logistics Networks, ☒ Vertical Supply Consolidation, ☒ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☒ Access and Adoption, ☒ Governance.*

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1 Introduction

The Physical Internet (PI) aims to create an open, global logistics system inspired by the interconnectedness of the digital internet (Montreuil et al., 2012). This fosters collaboration among participants, leading to more efficient and sustainable logistics (El Omri, 2009). Decentralized architectures like blockchain hold promise for secure and transparent data sharing within PI (Meyer et al., 2019). Additionally, PI leverages automation, distributed intelligence, and smart contracts to facilitate collaboration (Cortes-Murcia et al., 2022; Wang et al., 2016).Despite its potential to improve logistics performance, achieving the envisioned level of collaboration in PI remains a challenge. Trust is a critical but often overlooked factor, as evidenced by the limited success of centralized collaboration platforms like Tradelens (Louw-Reimer et al., 2021; Prandtstetter et al., 2016; Simmer et al., 2017).

Our paper addresses the trust challenge by establishing a trust framework for logistics collaboration in Section 2. This framework derives from established academic frameworks that although valuable, are not suitable for communication with a non-academic and non-technical audience. Therefore, we have derived eight key trust drivers: *Confidentiality*, *Control*, *Altruism*, *Interest*, *Adoption*, *Compliance*, *Transparency*, and *Reputation*, which we validate with key logistics stakeholders in Section 3. We then propose a trust-enabled architecture for PI in Section 4, building on dataspace principles and process-sharing concepts. In Section 5, we assess stakeholder perception of trust for this architecture, after which we present our findings and directions for further research in Section 6.

2 Establishing a Trust Framework for PI

2.1 Existing Trust Models

Trust is crucial for collaboration in PI, which involves multiple diverse stakeholders like shippers, logistics service providers (LSPs), and receivers (Pan et al., 2019). Existing trust models often have complex factors because it is often multidisciplinary (Moorman et al., 1993; Rotter, 1980; Rousseau et al., 1998). Here, we concentrate on key trust aspects relevant to PI. Beyond the typical focus on the inter-organisational aspect, this also requires us to look at trust factors related to innovative technologies and automation, two aspects that are often overlooked but considered very sensitive to logistics stakeholders (see **Figure 1**).

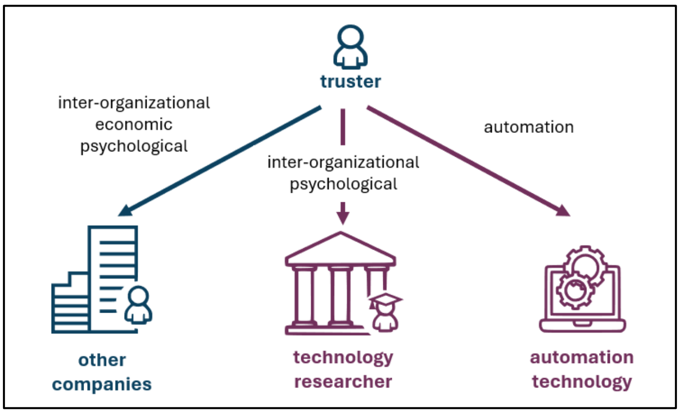

Figure 1 *Aspects of trust in the context of PI. Existing models typically focus on trust in relation to other companies. New technologies and automations need to be trusted before they are adopted.*

Inter-Organizational Trust: This emphasizes trust in business relationships. Three key factors are (Mayer et al., 1995):

- **Ability**: Belief in a partner's competence (e.g., efficient operations).
- **Benevolence**: Perceived willingness to prioritize shared interests (e.g., fair profit sharing).
- **Integrity**: Adherence to established principles (e.g., ethical conduct).

Psychological Trust: This refers to faith in others' promises (Cho et al., 2015; Rotter, 1980). It aligns with individual-level interpretations of integrity and benevolence from the inter-organizational perspective.

Automation Trust: This is the belief in a system's ability to perform correctly (Lee et al., 2004). It's crucial as PI uses automation heavily. Both *overtrust* and *undertrust* can be detrimental.

Economic Trust: Collaboration in PI can lead to economic benefits for all participants (Cho et al., 2015). This potential gain is a driver of trust.

2.2 Trust Drivers for the Physical Internet

The above trust framework under review is typically elaborate and well-founded but also complex and academically focused. When engaging with logistics stakeholders, we need a clear and concise trust framework. Taking the abovementioned aspects and factors into consideration, we have distilled the following eight trust drivers to outline trust in PI: *confidentiality*, *control*, *altruism*, *interest*, *adoption*, *compliance*, *transparency* and *reputation*. The trust drivers are formally defined in **Table 1**.

Our framework translates the complex trust aspects above into clear terms for better communication. These trust drivers allow us to engage with logistics stakeholders to discuss trust in the Physical Internet using plain and understandable terms. Consequently, any architectural decisions can be justified by referring to the trust drivers as well.

Table 1 *Definition of the Trust Drivers for PI*

Trust Driver	Explanation
Adoption	The belief that a critical mass in the ecosystem will adopt common policies, and technologies to affect joint outcomes.
Altruism	The willingness to put collective benefits first to fulfil individual interests within collaborative settings.
Compliance	Adherence to agreed norms, standards, and obligations, ensuring reliability and predictability in collaborations.
Confidentiality	The assurance that data and cargo information are accessible only to authorized parties, safeguarding against unauthorized exposure.
Control	The ability to exercise authority over one's data and cargo, ensuring decisions align with individual or organizational preferences.
Interest	The anticipated individual/organizational gains derived from participation in collaborative endeavours.
Reputation	The perceived reliability based on an entity's historical behaviour and adherence to ethical standards. Reputation can be objectified with governance.
Transparency	The clarity and availability of relevant information and the traceability of assets, fostering openness and accountability.

3 Validation of the Trust Framework

3.1 Methodology

To assess the relevance and completeness of the proposed trust drivers, we conducted a survey with a limited group of nine key logistics stakeholders (shippers, LSPs, etc.) in an interactive workshop. In this survey we focused on two questions.

- **Part 1: Trust Driver Importance**
  - Participants were asked to rate the importance of each of the eight trust drivers in **Table 1**.
  - There were also queries about potential missing trust concerns in order to assess the completeness of the trust framework.
- **Part 2: Architectural Preferences**

- Participants were presented with three different collaboration platform models: centralized, decentralized with a trusted third party, and fully decentralized (peer-to-peer).
- They were asked to assess each model's trustworthiness based on the proposed trust drivers.

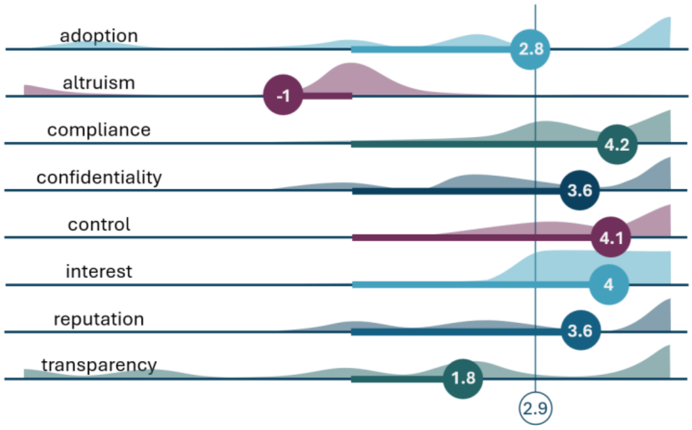

Figure 2 Perceived importance scores of the trust drivers along with voting distribution.

3.2 Findings

Most trust drivers were deemed important. Altruism is a clear outlier, while transparency scores relatively low as well (as shown in Figure 2). It is unclear at this point if this is because altruism is truly irrelevant. A possible explanation is that the role and importance of altruism in a collaborative setting is misunderstood. Transparency in turn, can be interpreted in several ways, which could attribute to its low score.

In addition to the proposed trust drivers, prior relationships, 3rd party endorsement, mandatory use of standards, timeliness and security were presented as additional concerns. However, these can all be traced back to one or more of the existing trust drivers, providing reasonable confidence in the trust mode's completeness.

Part 2 of the survey indicated a preference for a centralized platform for information sharing. Interestingly, when a decentralized model with a trusted third-party governing body was introduced, trust levels significantly increased. This suggests a preference for decentralized architectures with some centralized oversight. The fully decentralized model received mixed reviews, with trust levels averaging between the previous two architectures, but left some stakeholders expressing concerns about potential security issues.

Overall, this survey confirms the relevance and completeness of the proposed set of trust drivers and sheds light on stakeholder sensitivity to separate trust concerns. Although with a limited population, designing PI as a decentralized architecture with a trusted third party appears to be the most promising approach for encouraging collaboration in PI.

4 Design for a Trustworthy Physical Internet

This section introduces a novel reference architecture for PI that builds on existing initiatives and prioritizes trust. The industry often operates within a "platform logic" mindset, requiring participants to connect to numerous platforms. This leads to some issues: the risk of a single platform gaining excessive control and disrupting the balance of power, known as **Dominant Platform Risk**, an increased integration burden for small and medium-sized enterprises, i.e., **Complexity for SMEs** and partly resulting from this a **Vendor Lock-in**.

4.1 Technical Foundation and Innovations

As established in the survey above, logistics stakeholders, hesitant to share data and distrustful of centralized platforms, prefer a decentral architecture with governance. Since dataspaces enable secure and controlled data sharing and collaboration between different parties (Nagel & Lycklama, 2021), we posit that dataspace architecture can serve as a solid foundation for trustworthy collaboration in logistics and thus, for the Physical Internet as well.

Some logistics dataspace initiatives such as *iShare* in the Netherlands and *Catena-X* in Germany are gaining momentum. In parallel, the *FEDeRATED* project (van Bockel et al., 2023) introduced novel concepts for event-based data sharing and process orchestration for decentralized collaboration. Finally, our previous work in the *PILL* project (Michiels et al., 2024) focuses on PI discoverability using abstract PI concepts as initially described in (Montreuil et al., 2010). Bringing together these ingredients, we propose a decentral, federated architecture in line with dataspaces with trustful collaboration between logistics stakeholders in mind.

4.2 Layered Architecture

The architecture combines the results and insights from several existing technologies, projects and initiatives. The layered design in **Figure 3** separates five concerns, which we discuss in detail below. This layering of concerns is analogous to the layering of the internet and fosters interoperability and scalability.

Figure 3 *A layered design for PI connectivity with a clear separation of concerns. The design is inspired by dataspace architecture, which addresses several shared concerns.*

4.2.1 Connectivity: Physical Internet Connector (PIC)

A PIC is an extension of a dataspace connector. Data space connectors facilitate trusted data exchange between stakeholders. This can be operational data such as electronic invoices or B/Ls, logistics events, etc. But our architecture adds the following PI-specific extensions that allow to:

- Connect to specific PI communities, governed by a neutral instance,
- Manage and publish network state (Cassan et al., 2023),
- Synchronize network state locally,
- Manage agreements with process-sharing support,
- Orchestrate processes bilaterally.

An easily deployable PIC can lower entry barriers for accessing and integrating with the PI.

4.2.2 Identity & Trust: Governance with Dataspace Components

An open PI ecosystem requires identities usable across ecosystems. This necessitates a uniform trust framework where credentials can be verified by independent trusted parties. The W3C Decentralized Identity (DID) and Verifiable Credentials (VC) specifications provide the foundation for such a system.

Additionally, PI communities can govern their networks. Like dataspaces, this governance could include a *Participant Management Service* (ParIS), which is used to register members and manage key metadata and a *Federated Service Catalog*, which lists (technical) services offered by participants.

4.2.3 Discoverability: Publishing and Synchronizing Network State

LSPs publish their PI Network State, which is essential for others to discover them. The network state service can also provide detailed, up-to-date data like availability and pricing.
In addition to the common federated dataspace services above a *Federated Network State* service can be used to help participants synchronize their local copy of the network state for routing and other purposes.

4.2.4 Agreements: Extending Policies with Process Descriptions

Network state publication should include conditions under which logistics services are offered. This includes legal agreements and a machine-readable process description with the following components:

1. **Data Format and Semantics:** E.g., PEPPOL XML format with semantic definitions.
2. **Process Roles:** Identifies participants in the process (e.g., supplier, customer).
3. **Formal Process Description:** Uses states and transitions with allowed roles for each step.

This information can be accompanied by policy clauses like service level agreements and terms of use. The FEDeRATED ontology describes how logistics processes can be captured in terms of events and orchestrated according to a process description. An example is given below in **Figure 4**.

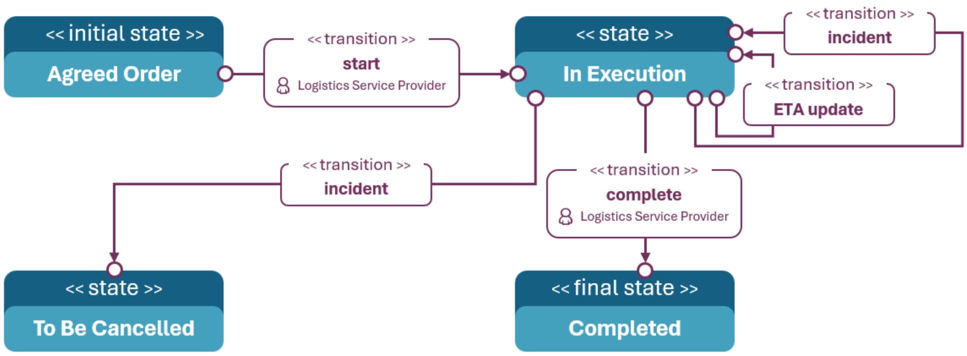

Figure 4 *A description of a process, or interaction pattern based on* (Van Gessel et al., 2023)

4.2.5 Process Sharing: Decentral Logistics Process Orchestration

The final addition is the engine that allows process execution based on the agreed-upon process description (see **Figure 5**). Prior work on event-based data sharing and process orchestration in the FEDeRATED project has led to an implementation demonstrating such a system.

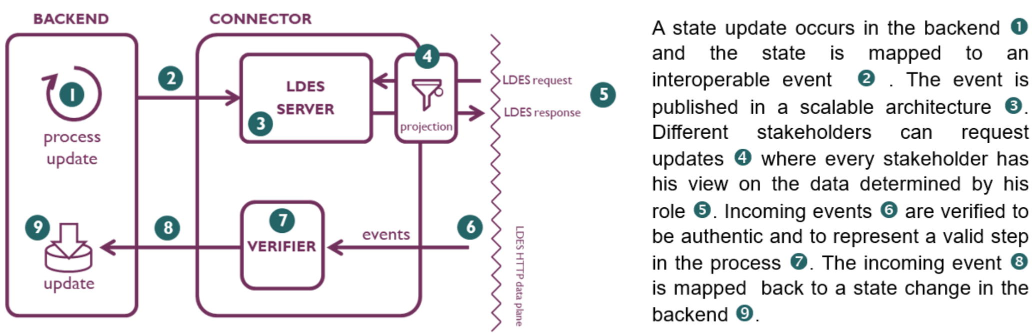

Figure 5 *A high-level design for an event-driven API for decentral logistics process orchestration. (Source: imec)*

4.3 Reflection of Trust Drivers in the PI Reference Architecture

The reference architecture is designed with trust in mind. To underpin this claim, we revisit the trust drivers and explain how the reference architecture addresses them in **Table 2**.

Table 2 *Overview of how the Trust Drivers are reflected in the Reference Architecture.*

Trust Driver	Description in Reference Architecture
Adoption	• **Standardized Approach**: Uses established technologies and open standards (e.g., W3C DID/VC). • **Modular Design**: Allows phased adoption of individual components (e.g., PIC). • **Reduced Vendor Lock-in**: Decentralization avoids reliance on a single platform provider.
Altruism	• **Focus on Collective Benefits**: Simplifies collaboration, potentially leading to increased efficiency and cost reductions for all. • **Transparent Network**: Promotes visibility through discoverability of services and real-time network state sharing. • **Bilateral Agreements**: Enables direct agreements for negotiation of mutually beneficial terms.
Compliance	• **Machine-Readable Agreements**: Formalizes agreements with process descriptions and policy clauses for clarity. • **Automated Enforcement (potential)**: Integrates process engine with automated compliance checks based on policies. • **Audit Trail**: Event-based data sharing creates a verifiable record of actions for accountability.
Confidentiality	• **Decentralized Data Storage**: Stores data within individual, controlled dataspaces, not a central platform. • **Access Control Mechanisms**: Leverages DIDs and VCs for granular access control based on roles and permissions. • **Data Minimization**: Encourages "need-to-know" principle, sharing only essential data. • **Data Encryption**: Uses standard encryption for data in transit between stakeholders.
Control	• **Participant-Owned Connectors**: Each participant has its own PIC, granting control over data flow and network integration. • **Process Description Flexibility**: Agreements can include formal, machine-readable process descriptions defining roles and responsibilities. • **Decentralized Orchestration**: Process execution relies on event-based data sharing, not a central authority. • **Revocable Credentials**: Enables revoking previously awarded credentials if needed.
Interest	• **Reduced Entry Barriers**: Open standards and existing technologies like dataspaces lower joining costs and complexity. • **Improved Resource Utilization**: Facilitates efficient resource allocation and service discovery, potentially leading to cost savings. • **Focus on Value Creation**: Streamlines collaboration, allowing participants to focus on core competencies and value creation.
Reputation	• **Decentralized Governance**: Enables building reputations based on past performance and adherence to agreements. • **Verifiable Credentials**: Allows showcasing credentials and qualifications to establish trust and expertise. • **Public Network State**: Network state information (e.g., service availability, performance) contributes to building trust.
Transparency	• **Discoverable Services**: LSPs can publish network state and service offerings for easy discovery. • **Real-Time Data Sharing**: Enables controlled data sharing for maintaining visibility into collaborative processes. • **Traceability**: Supports data and cargo traceability through event-based logs for tracking movement of goods and data.

5 Trust-based Evaluation of the Architecture

This section evaluates how well the proposed architecture addresses the eight trust drivers identified earlier. To achieve this, a follow-up survey was conducted with the same participants as the initial survey. The results are shown in **Figure 6** and **Figure 7**.

Our interpretation of this preliminary survey is summarized in **Table 3**. For the future refinement and validation of the architecture, we consider the following improvement points:

- Not all aspects of the architecture are fully understood by all participants, leading to some discrepancies between initial importance scores and responses to coverage.
- Clearer definitions of trust drivers using more examples could be helpful in future surveys.
- The perceived importance of trust drivers should be weighed when interpreting the results. For instance, one initially rated low in importance (like adoption) might still be a significant concern if participants perceive the architecture as not addressing it well.

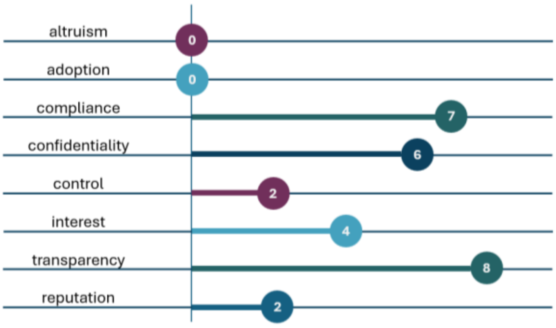

Figure 6 *Survey result: what trust drivers are well-covered by the architecture?*

Figure 7 *Survey result: what trust drivers are* ***not*** *well-covered by the architecture?*

Table 3 *A brief interpretation of the fit-gap survey results.*

Trust Driver	Survey Scores		Discussion
Adoption	**Importance:** **Covered:** **Less covered:**	Low: 2.8 No High: 6	Disconnect between initial rating and later concerns. Participants likely understand critical mass is necessary but are concerned about stakeholder integration challenges. The architecture itself can't guarantee neutral governance, but it can facilitate transparency and fair access.
Altruism	**Importance:** **Covered:** **Less covered:**	Very Low: -1 No High: 6	A negative initial score might be a misunderstanding. The architecture does not explicitly address altruism, which may be a concern for some. More clarity might be needed.
Compliance	**Importance:** **Covered:** **Less covered:**	High: 4.2 Well Covered: 7 Low: 1	Positive finding. Compliance was rated highly important, and most participants felt the architecture addressed it well.
Confidentiality	**Importance:** **Covered:** **Less covered:**	Moderate: 3.6 Good: 6 No	Moderately important concern initially. Most participants felt the architecture adequately addresses confidentiality.
Control	**Importance:** **Covered:** **Less covered:**	High: 4.1 Low: 2 Low: 1	Discrepancy. Rated highly important, but few felt control was well-covered. A clearer explanation of how the architecture addresses control is needed.
Interest	**Importance:** **Covered:** **Less covered:**	High: 4.0 Moderate: 4 Moderate: 3	Significant concern. While some felt the architecture addressed it, there is room for improvement.
Reputation	**Importance:** **Covered:** **Less covered:**	Moderate: 3.6 High: 8 Moderate: 3	Moderate importance. The architecture seems to need further explanation regarding how it addresses reputation.

Transparency	**Importance:** **Covered:** **Less covered:**	Low: 1.8 High: 8 Moderate: 3	Initially rated low, but became a concern for some. The high rating for architecture coverage is positive, but some participants still lack clarity on how transparency is implemented.

6 Conclusions and Further Work

This paper explored trust within PI and identified eight key trust drivers influencing logistics stakeholder collaboration. We proposed a trustworthy architecture by implementing dataspace principles and adding support for decentral process orchestration. Exploratory surveys with a limited group of logistics stakeholders validated the trust drivers and assessed the architecture's effectiveness.

The identified trust drivers appear comprehensive for PI. Survey participants favoured a decentralized, federated PI design, aligning well with the proposed dataspace-inspired architecture. The architecture addresses stakeholder trust concerns, but broadening the survey to more stakeholders is needed to assess its effectiveness with greater certainty.

Widespread stakeholder adoption is crucial for a true Physical Internet and is identified as a major challenge. While trust can encourage adoption, the survey highlighted a need for improved clarity regarding the architecture's principles. Participants struggled with concepts like data control, decentralized orchestration, and federated services. Addressing this communication gap is essential for broader adoption.

These results are a starting point for further research on a larger scale. Surveys with a broader audience, more participants and a focus on clear trust driver definitions will provide deeper insights into stakeholder concerns. Our insights will be used to further refine the architecture with trust in mind. Ultimately, through iterative surveys and practical testing within Living Labs, we aim to establish a robust foundation of trust within the Physical Internet, empowering increased collaboration and paving the way for a truly interconnected PI that unlocks its full potential.

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Study of the Potential for Using the Physical Internet in Urban Spaces

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Abstract: *This study investigates the perspectives of researchers and business professionals on the Physical Internet (PI) and its application in city logistics. Through a two-part survey involving 83 participants from Europe and the United States, the research explores the perceived key elements for PI's successful implementation, its potential to enhance the efficiency and sustainability of urban logistics operations, and the main challenges to its adoption. The findings reveal a general optimism about PI's potential, with technology, collaboration, and infrastructure identified as critical success factors. However, concerns regarding costs, resistance to change, and technological limitations are also highlighted. The study concludes with suggestions for increasing awareness and fostering cross-sector collaboration to realize PI's full potential in transforming urban logistics.*

Keywords: *Physical Internet; Urban Logistics; Sustainability; Stakeholder Collaboration. Technology Integration; Regulatory Frameworks.***.**

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☐ PI Networks, ☐ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☒ Access and Adoption, ☒ Governance.*

Targeted Delivery Mode-s*: ☒ Paper, ☐ Poster, ☒ Flash Video, ☐ In-Person presentation*

1 Introduction

Cities, being congested and polluted, make the last mile the most challenging, expensive, and least efficient part of the entire supply chain. Traditional approaches in logistics often lead to isolated operations and limited collaboration, resulting in resource underutilization and duplicated efforts. Physical Internet (PI) aims to standardize and interconnect logistics operations, similar to data packets in digital networks, transforming isolated operations into an integrated system. This integration, offers a transformative approach towards sustainable, efficient, and environmentally responsible urban logistics, promising a more sustainable future.

However, many are still unaware of what the Physical Internet is, and without knowledge, transformation cannot begin. This paper involves conducting a survey among transport and logistics experts. It examines the respondents' awareness of existence of PI and its potential of transforming urban goods distribution through collaboration, technology integration, and standardization. This study delves into the perceptions of two distinct groups: researchers primarily from Europe, who have a scholarly interest in PI or city logistics, and business professionals from the United States, representing sectors like transportation, delivery, and telecommunications technology. By analyzing their responses to a structured questionnaire, this research aims to uncover the collective optimism and reservations towards PI, identify the elements deemed crucial for its successful implementation, and discuss the perceived challenges and opportunities it presents for urban logistics.

2 Literature review

"Economic and political institutions and entry into formal and informal entrepreneurship" by Erkko Autio and Kun Fu highlights the importance of economic and political institutions in shaping the entrepreneurship landscape, suggesting that high-quality institutions promote formal entrepreneurship and reduce reliance on informal activities. The authors point to the need for coordinated actions to improve both economic and political institutions to support the growth of formal entrepreneurship and address issues related to informal entrepreneurship.

Eric C. Dahlin's article "The Sociology of Innovation" examines the impact of organizational and environmental context on innovation. Dahlin introduces a sociological perspective on innovation, highlighting the role of social networks and institutions in shaping innovations. The article emphasizes that innovativeness is relative and depends on the observer's perspective, and innovation success is achieved through the use of internal and external knowledge. Dahlin argues that the interdependence between companies and their environment is crucial for innovative success, and utilizing available resources reduces risk and increases the chances for innovation. The work offers insights into managing innovation challenges, emphasizing a strategic approach to innovation.

The article "The Impact of Entrepreneurship Education on Entrepreneurial Attitudes and Intention: Hysteresis and Persistence" by Alain Fayolle and Benoit Gailly shows that entrepreneurship education programs can positively influence entrepreneurial attitudes and intentions.

In the article "The influence of socio-cultural environments on the performance of nascent entrepreneurs: Community culture, motivation, self-efficacy and start-up success" by Christian Hopp & Ute Stephan, it is stated that entrepreneurs and their personal traits significantly vary depending on sub-national and community socio-cultural contexts. Therefore, the community context should be considered when tailoring assistance and advice for entrepreneurs.

"The relationship between transformational and transactional leadership styles and negative innovation perception" by Mutlu Tokmak shows that there is an inverse relationship between transformational leadership style and negative innovation perception, suggesting that managers employing transformational leadership have less negative beliefs about innovation. Transactional leadership style increases negative innovation perception, including fears of risk, additional costs, customer and staff resistance. The study emphasizes the importance of transformational leadership in promoting a positive attitude towards innovation among managers and overcoming potential concerns related to new initiatives. At the same time, it highlights the risk associated with the transactional leadership style, which can increase negative perception of innovation.

3 Methodology and respondents' profile

The first part of the study was conducted among researchers who dedicate their studies to either the Physical Internet or city logistics. The author sent out an email requests to fill out a questionnaire. The majority of respondents were researchers from Europe, though not exclusively. Out of 250 inquiries, 32 researchers completed the survey. Then, to reach the business sector, the author first used the Orbis database to send inquiries to entrepreneurs in the transport, logistics, and warehousing sector, without success. Subsequently, the author used the Survey Monkey tool, purchasing a pool of guaranteed completions in a specific group of recipients. The group was defined as representatives of the industry: Transportation & Delivery, Telecommunications, Technology, Internet & Electronics, without other restrictions (like household income or age). The tool required limiting the survey to its country. Therefore, since the first part focused on Europe, the United States was chosen for this part. This resulted in 51 completions. However, this group of respondents had a greater tendency to skip open-ended questions. The first part of the article presents the general results of the study, and then the second part distinguishes the stages of the survey - first stage addressed to (mostly) researchers from (mostly) Europe and the second addressed to (mostly) business from the USA.

As for the profile of all respondents, the majority represented the Information Technology (IT) in Logistics group (34.94%), followed by City Logistics (15.66%), Transportation Management (13.25%), Supply Chain Management (12.05%), and Sustainability in Logistics (7.23%). Regarding the professional roles represented by the respondents, 32.53% represented business, 55.41% represented academia, and 24.10% - others. Most respondents are experienced experts, dealing with their area for over 10 years. The areas of specialization of the respondents are presented in the figure 2 (left).

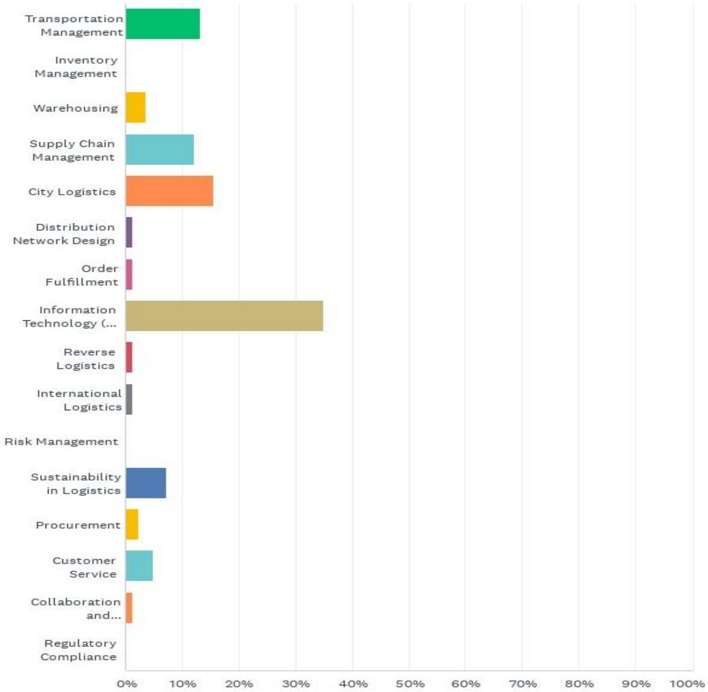

Figure 1: Expertise areas represented by respondents.

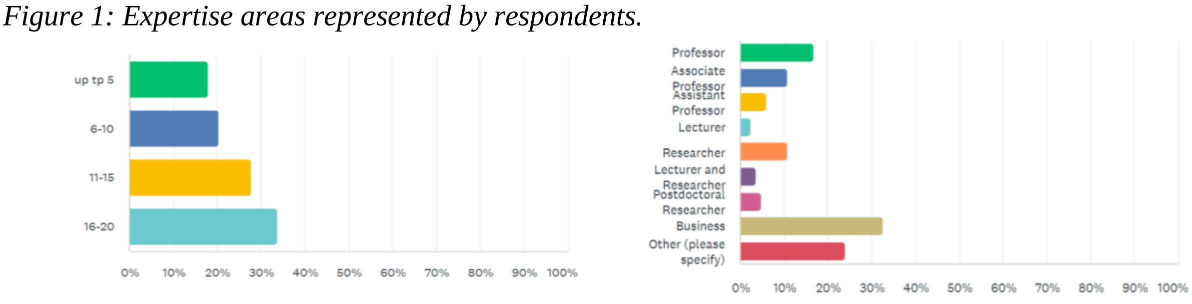

Figure 2: Years of experience of respondents (left); their current professional role (right)

4 Survey results

4.1 Cumulative results

Moving to the core of the survey, the majority was familiar with Physical Internet. Regarding experience with PI-related projects, more than half had dealt with them.

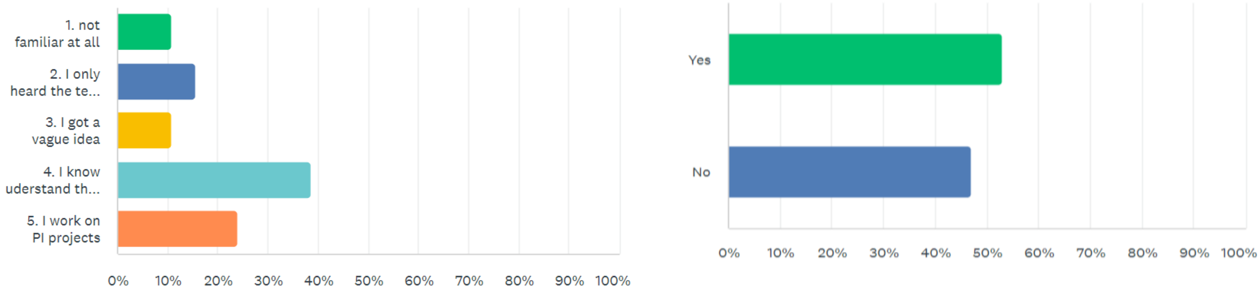

Figure 3: Familiarity with Physical Internet (left); participation in implementation of a PI project (right); 83 respondents.

The respondents, when asked to indicate the key element of PI development, pointed to technology first, followed by collaboration and infrastructure.

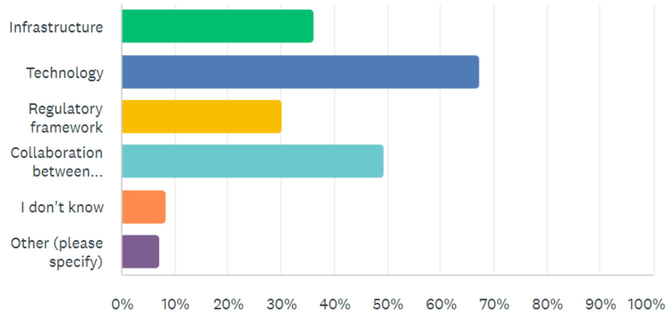

Figure 4: Crucial factors for the efficient integration of the Physical Internet concept into existing urban logistics systems?; 83 respondents.

As for the Physical Internet in urban logistics, the majority (58%) evaluate the potential of PI to increase the efficiency of logistic operations in cities positively and very positively. A neutral attitude towards this potential is held by 21%. One person considered the potential impact to be very negative. Similarly, respondents referred to the impact of PI on increasing the sustainability of urban logistic operations – 61% agree with such potential.

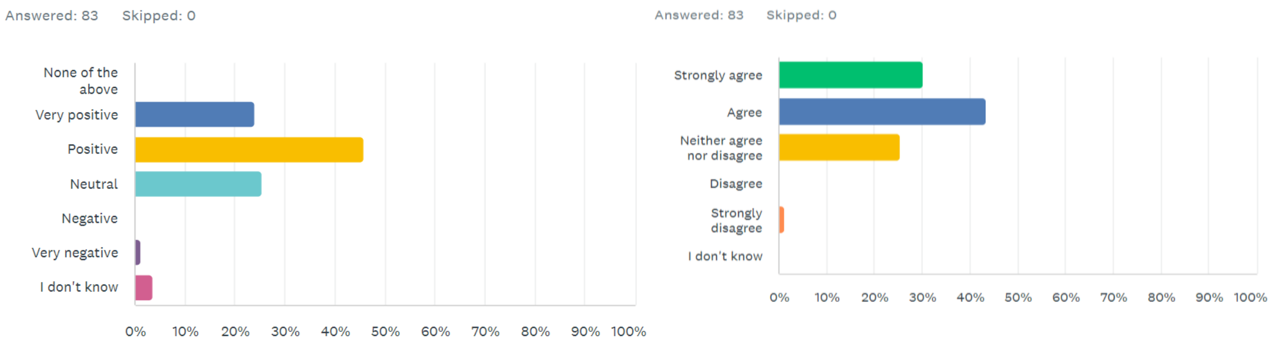

Figure 5: Impact of PI on the efficiency of urban logistics (left); Agreeing with statement that PI can make urban logistics more sustainable (83 respondents)

The further part of the study examined how important individual elements of PI are for its implementation. Collaboration emerged as the leading factor, followed by awareness, and technology in third place. The average response for the importance of standardization in PI, on a scale from 1 to 100, was 66. The majority of respondents see the future of urban logistics in PI.

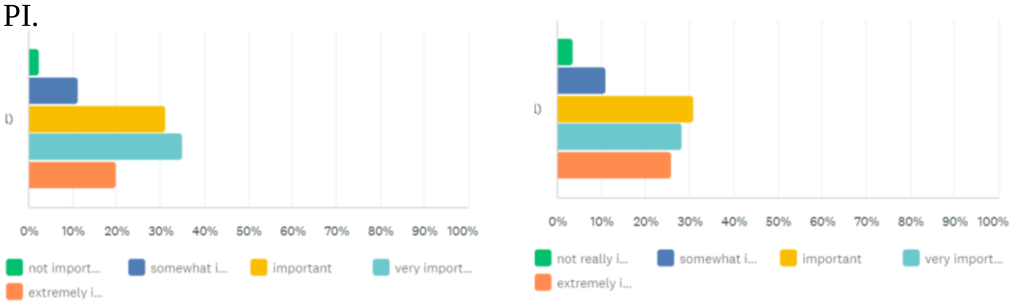

Figure 6: Importance of integration of technology (left) and importance of collaboration (right) in implementation of PI in cities.

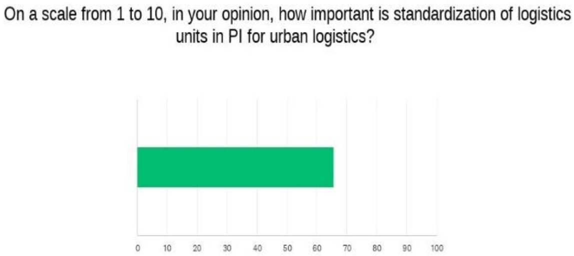

Figure 7: Importance of awareness of existence and benefits of PI (left) and average importance of standardization (right) in implementation of PI in urban areas.

Once again, the vast majority of respondents assert that the implementation of PI in cities is inevitable due to climate change, and even that mandatory implementation of the Physical Internet principles in cities would be a good idea.

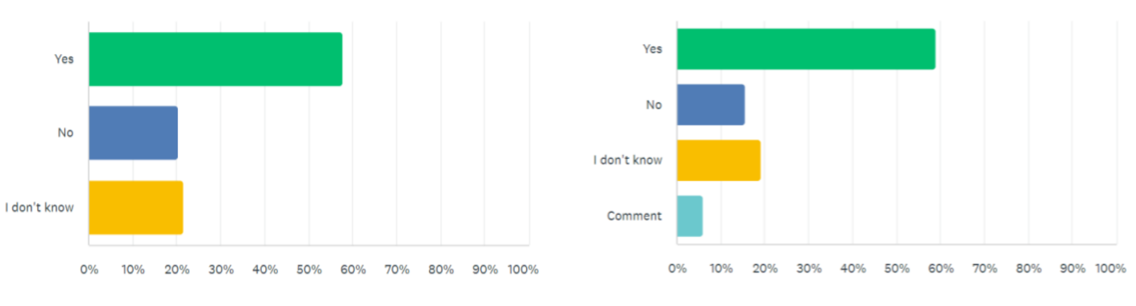

Figure 8: Is adoption of PI in cities is inevitable, due to climate changes (left);
is it a good idea to mandate the operation of logistics based on the concept of PI, similar to how low emission zones are imposed, from a top-down perspective?

The main challenges identified were costs, resistance to change, lack of knowledge, and technological limitations.

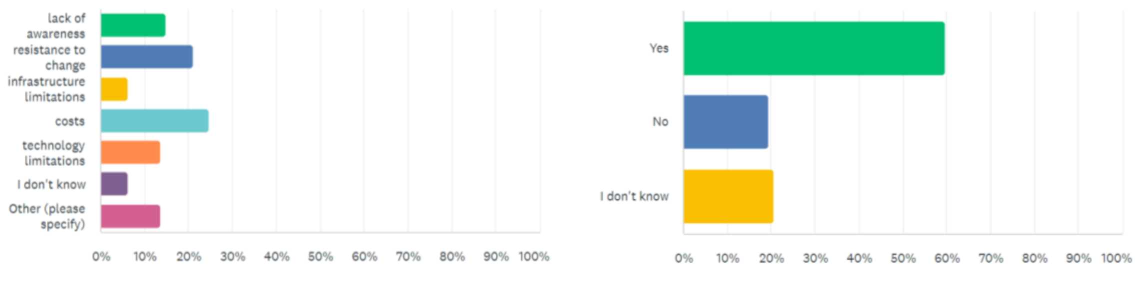

Figure 9: Main challenges in implementing PI for urban logistics (left); does future of logistics lays in Physical Internet? (right)

4.2 Separated results

In the next part of the article, responses from both surveyed groups are presented: surveys sent by the author to contacts acquired at conferences (referred to as group I) and completions obtained through the Survey Monkey tool, according to industry profiling (referred to as group II). Regarding the area of expertise – in the first group, respondents mainly represented city logistics, supply chain management, and sustainability in logistics; whereas in the second group, 49.02% of respondents represented the field of information technology in logistics, and 15.69% transportation management. In group I, the vast majority of respondents had over 16 years of experience, while in group II, the dominant group had 11-15 years of experience. Concerning the occupation in group I, most respondents marked "other" – perhaps indicating that they represent both academia and business. The most positions in this group were academic. In the second group – there were mostly entrepreneurs.

Figure 11: Separated respondents profile (area of expertise, years of experience, current professional role) and familiarity with the PI concept.

In both groups, the majority of respondents are familiar with and understand the concept of the Physical Internet. However, in group I, significantly more respondents are working on projects related to PI. Regarding the main factors determining the implementation of PI in cities, group I identified primarily collaboration and technology, whereas group II pointed to technology and infrastructure. In both groups, about half of the respondents had experience with implementing a PI project. The average estimation of the importance of standardization on a scale from 1 to 100 was 76 for group I and 59 for group II.

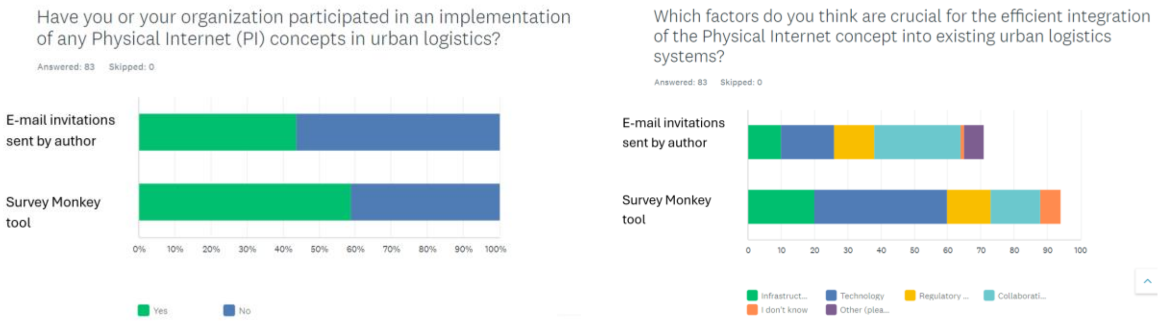

Figure 12: Participating in PI projects for urban logistics (left); crucial factors of efficient integration of PI in city logistics (right).

Regarding the impact of PI on increasing the efficiency of urban logistics, over 84% in group I considered this impact to be positive or very positive, while in group II, it was nearly 61%. Also, more than 84% of the first group believes that PI would contribute to increased sustainability in urban logistics operations, while in group II, this was over 66%.

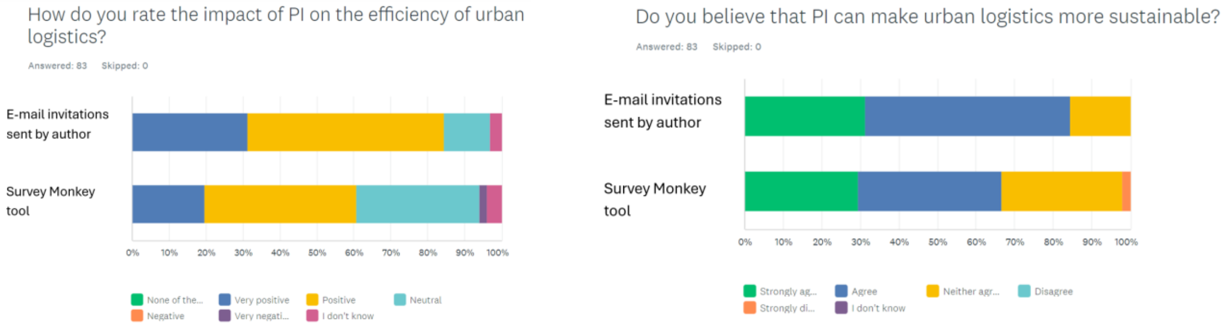

Figure 13: Physical Internet impact on urban logistics operations, left - efficiency, right - sustainability

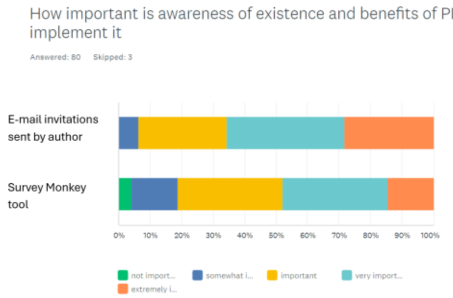

Figure 14: Importance of awareness

In relation to the challenges associated with implementing PI, group I identified resistance to change, costs, and lack of awareness as the main challenges, while group II listed costs first, followed by resistance to change, and then technology. Both groups agreed that the future of city logistics lies in the Physical Internet, and that the implementation of PI will be inevitable due to climate changes. Surprisingly, when asked if mandatory implementation of PI is a good idea, nearly 61% of group II responded 'yes', compared to 56.25% in group I.

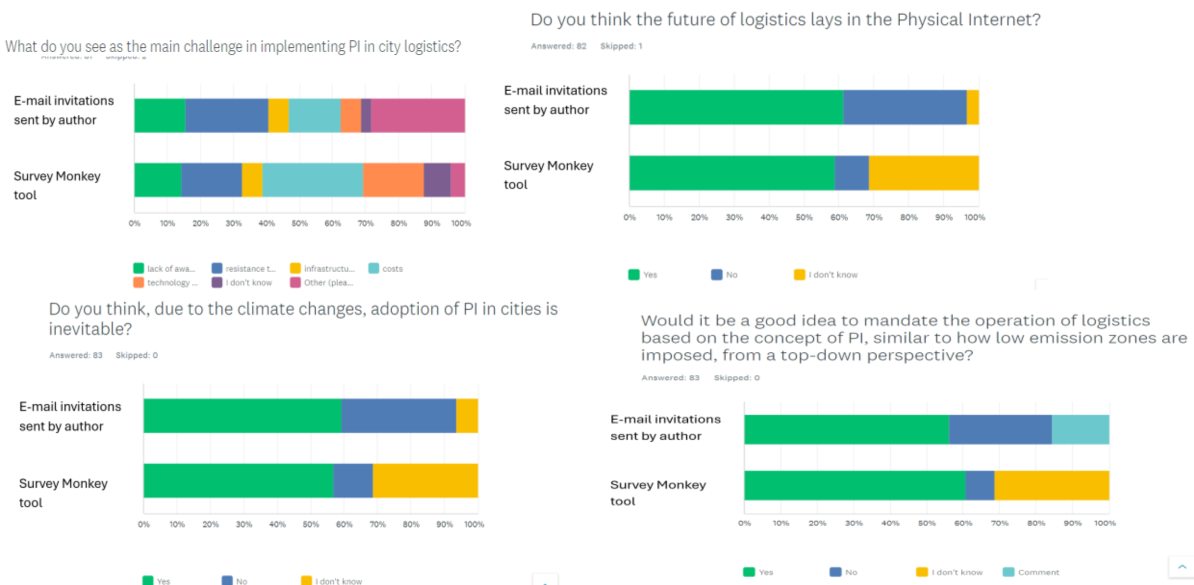

Figure 15: Challenges and future

The last questions were open-ended and concerned the key elements for successful implementation of PI-based solutions in urban areas (fig.16), ideas for encouraging stakeholders to engage in a PI project (fig.17), and examples of successful implementation of PI projects (fig.18).


Figure 16: Word cloud made of answers to the open question: "What do you consider as the key elements for the successful implementation of the Physical Internet in urban goods distribution"

The keyword clouds from researchers and business professionals highlight a shared focus on collaboration, efficiency, and adaptability within the context of the Physical Internet (PI) in urban logistics. Researchers emphasize data sharing, stakeholder engagement, and the integration of technology and urban infrastructure, indicating an interest in information exchange systems and smart city development. Business representatives stress certainty, efficiency, affordability and responsiveness to climate change, showing a pragmatic approach to adopting new technologies with climate awareness. Both sectors recognize the importance of collaboration and technological innovation for the advancement of urban logistics. The discussions reflect a complex approach to PI, integrating technological, social, ecological, and economic aspects, and acknowledge PI as more than just technology but a new paradigm for cooperative change management facing global challenges like climate change.

Figure 17: Word cloud made of answers to the open question: "What is the best idea, in your opinion, to encourage stakeholders to join a PI network"

The keyword clouds from both researchers and business sectors underscore the emphasis on the tangible benefits and quality that the Physical Internet (PI) can bring, with case studies highlighted as evidence to foster development and stakeholder engagement. Researchers focus on show cases and the clarity and transparency of PI benefits to ensure all network participants understand the value, while the business sector concentrates on costs, quality, and the necessity of collaboration, indicating financial aspects and value as key decision factors. Both groups agree on the importance of clear benefits and quality outcomes to encourage PI network participation, highlighting development and cooperation as essential for future success. Researchers are keen on showcasing successful case studies to demonstrate PI's value and effectiveness, emphasizing the need for academic and practical engagement. Businesses pay attention to practical aspects like costs and quality, directly linked to their operational decisions, viewing communication and education as tools to overcome potential barriers. For both, the clear, measurable benefits of PI are seen as crucial for attracting new members, with collaboration and communication being vital, alongside an awareness of costs and potential challenges that need thoughtful addressing.

Figure 18: Word cloud made of answers to the open question: "Have you encountered any successful PI implementations in urban logistics? If yes, please provide details".

Analysing word clouds for question 19 reveals a focus on specific projects and their urban implementation among researchers, emphasizing safety and service aspects. This indicates an interest in both theoretical concepts and practical implementation of the Physical Internet (PI), including its impact on urban services and infrastructure. Business responses strongly affirm the PI concept, highlighting the importance of quality, standardization, internet capabilities, shipping, and storage, showcasing these as key to improving logistics operations and supply chains.

Both sectors agree on the importance of effective implementation and quality outcomes for PI project success, showing a practical focus on PI's application and its potential positive impact on urban environments. Researchers are interested in deployment details and potential innovations, with a focus on safety and service quality. In contrast, businesses prioritize the practical use of the internet and standards to enhance logistics and supply chains, emphasizing quality and standardization as success factors.

5 Conclusions

This study investigates the adoption and impact of the Physical Internet (PI) in urban logistics, drawing insights from both the research community and business professionals across Europe and the United States. It highlights a general optimism about the potential of PI to revolutionize urban logistics by enhancing efficiency, sustainability, and stakeholder collaboration. The key elements identified for successful PI implementation include technology, collaboration, and infrastructure, with technology leading as the primary driver. Despite the positive outlook, concerns regarding costs, resistance to change, and technological challenges persist, suggesting a need for increased awareness and cross-sector collaboration to overcome these barriers.

The study reveals a strong consensus on the inevitability of PI adoption driven by climate change pressures and a broad agreement on the benefits of mandating PI principles to ensure sustainable urban logistics practices. The challenges of cost, resistance to change, and lack of knowledge are recognized as significant obstacles to PI implementation. However, there is a shared belief in the transformative potential of PI to address these issues through collaborative efforts and technology integration.

In conclusion, this study emphasizes the transformative role of the Physical Internet in urban logistics, advocating for a strategic approach to harness its benefits fully. It calls for a concerted effort among stakeholders to foster an environment conducive to PI adoption, focusing on collaboration, technological advancement, and overcoming resistance to change. By addressing the challenges and leveraging the identified key elements for success, the adoption of PI can significantly contribute to the sustainability and efficiency of urban logistics operations, paving the way for a more resilient and environmentally friendly future.

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Reinforcement Learning-Based Optimization of Logistical Hubs and Routing in the Context of the Physical Internet - A Case Study from Japan

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Abstract: *The global logistics industry is currently facing a number of challenges, including labor shortages and inefficiencies due to a lack of logistics facilities and resources, as well as increasing disruptions. Under these circumstances, Physical Internet (PI) is attracting attention as an innovative logistics system that can realize a sustainable society by sharing warehouses, trucks, and other means of transportation, improving utilization rates, and reducing fuel consumption. One of the important research themes in PI implementation is how to determine the location of logistics hubs and associated transport routes. In this research, we propose a reinforcement learning-based hybrid algorithm that combines NeuroEvolution of Augmenting Topologies (NEAT) and Lin-Kernighan Heuristic (LKH-3) to solve the location and route optimization problem. To evaluate the proposed hybrid algorithm, we applied real data from Japan to simulations and evaluated the performance of NEAT. The simulation results suggest that the proposed model could quantify the reduction of CO2 emissions in different scenarios, thus identifying the optimal scenario.*

Keywords: *Physical Internet, Transport Route Optimization, Logistics Hub, Lin-Kernighan Heuristic, NeuroEvolution of Augmenting Topologies, Reinforcement Learning*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

Targeted Delivery Mode-s*: ☒ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation*

1 Introduction

With the rapid increase in Internet usage, online shopping has consistently grown as a percentage of total retail sales and absolute sales volume. In recent years, especially with the pandemic of the new coronavirus, online retailing has grown explosively, especially in grocery, apparel, food, and many more industries (Mohammad et al., 2023). For example, the BtoC e-commerce (EC) market size and EC conversion rate in Japan's goods sales sector increased from 599.3 billion yen and 3.85% in 2013 to 1399.7 billion yen and 9.13% (METI). As the volume of online shopping increases, demand for freight forwarding services is growing, and freight forwarding services face two challenges: reducing profit margins due to the high frequency of smaller shipments and reducing greenhouse gas emissions. For logistics providers, keeping cost efficiency and service levels high in the distribution system is key to staying competitive in the online shopping business (Anderson et al., 2007). Meanwhile, freight transport is seen as one of the most difficult sectors of the economy to decarbonize, as it is the only industry with ever-increasing emissions (McKinnon, 2016). Under these circumstances, the Physical Internet (PI) is currently attracting attention as the ultimate logistics efficiency measure (Montreuil et al., 2010). The central concept of the PI logistics system is to use advanced modular containers through transit centers (known as PI hubs) to create a highly efficient transport network that optimizes the opportunities for consolidation (Venkatadri et al., 2016). This study aims to solve these problems by optimizing the placement of PI nodes and truck routes between nodes. The goal is to reduce the number of trucks, reduce fuel consumption, and minimize greenhouse gas emissions. To solve this problem, we propose a new hybrid algorithm that combines NeuroEvolution of Augmenting Topologies (NEAT) and Lin-Kernighan Heuristic (LKH) -3. The proposed model is applied to Geographic Information System (GIS) data for empirical validation. The contributions of this work can be summarized in three areas: 1) introduction of the PI concept to logistics networks, 2) improvement of existing optimization methods, and 3) incorporation of realistic route calculations using real data for validation. The remainder of this paper is organized to provide a comprehensive overview, including a review of previous studies on the PI concept, a detailed methodology for addressing the logistics problem, a description of the data used, experimental results, and conclusions. The literature review reveals a growing body of research on PI, with various models demonstrating the potential benefits of PI in terms of efficiency, sustainability, and cost savings. However, this study fills a gap in the existing literature by presenting a novel model that integrates the concept of PI with optimal logistics hub placement and route optimization.

2 Literature review

The PI concept was introduced by Montreuil in 2010, who defined PI as an open, global logistics network built on the efficient and sustainable interconnection of all aspects of the logistics process (Montreuil et al., 2010). The PI concept has attracted numerous stakeholders who support the development of PI logistics networks in the last few years. ALICE[1] and JPIC[2] were formed to promote the practical application of the PI concept by aligning the interests of experts with those of companies and other stakeholders. Demonstration studies for practical application of PI concepts such as MODULUSHCA and ICONET are underway, mainly in Western countries. The literature on PI has increased dramatically over the past decade. The literature on PI has increased dramatically over the past decade. Previous studies and future issues related to PI have been summarized by Neila et al. (2022) and Münch et al.(2022). The challenges of PI distribution and transportation network optimization, optimized routing, loading patterns, and truck scheduling are being addressed by many researchers. Table 1 is a consolidated and redacted version of the table prepared by Neila et al. (2022) for PI distribution and transportation network optimization and optimized routing. In the table, the decision-making levels are classified as L1: strategic, L2: tactical, and L3: operational. The table also classifies sustainability dimensions as D1: economic, D2: social, and D3: environmental.

After 2020, more and more studies are using hybrid heuristic algorithms. Pan et al. proposed a hybrid algorithm integrating genetic algorithms (GA) and LKH for a collaborative delivery network using parcel lockers (Pan et al., 2019). Feng et al. proposed crowdsourced integrated production and transportation for smart city logistics for the scheduling problem using a genetic algorithm and showed that GA outperformed the commercial mixed integer programming problem (MIP) solver CPLEX (Feng et al., 2021). However, multi-agent system (MAS) is often used to optimize PI transport networks, and none of the studies have incorporated artificial neural networks or other techniques into their research methodology. It is clear from this

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1 ALICE: Alliance for Logistics Innovation through Collaboration in Europe

2 JPIC: Japan Physical Internet Center

literature review that research leading to the realization of PI has developed significantly over the past decade. Recent studies have proposed various models that confirm the usefulness of logistics networks in the framework of PI. This study proposes a method to incorporate a new artificial neural network into a model that addresses the optimal placement of logistics hubs and optimization of delivery routes in the framework of PI. Furthermore, it makes a significant contribution to the literature by presenting it together with empirical validation using real data.

Table.1 Classification of literature on PI distribution and transportation network optimization and optimized routing

Authors	Year	Methods	Levels	Dimensions
Chargui et al.	2019	MAS (multi-agent system)	L2+L3	D1+D3
Gontara et al.	2018	BGP (border gateway protocol)	L3	D1
Fazili et al.	2017	MC (Monte-Carlo simulation)	L2+L3	D1+D3
Venkatadri et al.	2016	MIP (mixed integer programming)	L2+L3	D1
Walha et al.	2016	SA (simulated annealing)	L2+L3	D1
Montreuil et al.	2012	KPIs (key performance indicators)	L1	D1+D2+D3
Zheng et al.	2019	MAS	L3	D1+D2+D3
Ben Mohamed et al.	2017	MIP	L3	D1+D2+D3
Chen et al.	2016	DES (destination-orientated spreading)	L3	D1+D2+D3
Pan et al.	2021	GA	L3	D1+D2+D3
Feng et al.	2020	GA	L1+L3	D1+D2
Zhang et al.	2023	MIP	L1+L2	D1+D3
Li et al.	2023	HA (heuristic algorithms)	L1+L3	D1+D2
Essghaier et al.	2023	MIP	L3	D1
Ji et al.	2023	MIP	L2+L3	D1+D2
Kantasa-ard et al.	2023	MIP	L3	D1+D2+D3
H. Liu et al.	2024	MIP	L1+L3	D1+D3
Liu X. et al.	2024	SOP (stochastic optimization programming)	L2+L3	D1+D2

3 Formulation of the mathematical model

This section describes the challenge of identifying optimal locations for logistics hubs and devising efficient vehicle routing strategies for delivery companies operating within the PI. We also present a model designed to address this particular problem. The model incorporates a clustering approach, and a detailed description of this approach is provided, as well as a hybrid algorithm that combines NEAT and LKH-3.

3.1 Assumptions

To construct the model of the joint delivery network, let S be the set of suppliers and $\boldsymbol{C}$ be the set of customers. $p\alpha = (s, c)$ denote the delivery task, where $p\alpha = [10,30,60]$, where goods are transferred from supplier s to collection point Sc between logistics node l in set L and collection point C_c, and from there to customer c delivery. In the context of our modeling, we assume that each customer (called a distributor) generates a single delivery request addressed to a single customer (distributor). Given this basic assumption, the set of requests $A_s(A_c)$ originating from supplier s (for customer c) contains exactly one delivery task. Furthermore, to keep the model simple, we do not specify pickup or delivery times.

3.2 Logistics nodes

The logistics nodes set, denoted as L, includes all logistics nodes identified by their geographical positions. Within L, there exists a delivery task represented as $p\alpha = (s, c)$. Each logistics hub is equipped with a capacity of $q_l = 2000$. We assume the existence of a transport service for the exchange of goods between logistics nodes, if necessary. The costs of setting up logistics hubs are not considered and their capacities are known a priori. Accordingly, the collection points S_c ,C_c are connected to the nearest logistics hub. It is assumed that S_c ,C_c can replace the logistics hub l that is supposed to be newly generated.

3.3 Transport by trucks

For the transport of goods, a set of trucks V can be operated and these vehicles are associated with a collection point or a distribution centre. The set of vehicles includes three types of trucks with different carrying capacities $q_v = [10,30,60]$. Operational costs, consisting of financial and environmental costs due to truck ownership, are not considered.

3.4 Constraints

The proposed model has a structure consisting of three levels. First, any given number of suppliers and customers are clustered using the fuzzy c-means method to obtain supplier agglomeration S_c and customer agglomeration C_c. Next, we consider the least-cost trucking network flow problem associated with generating an appropriate number of distribution points between agglomerations by NEAT, and finally, we address the multi-depot capacity vehicle routing problem between agglomerations and distribution points by LKH-3. Given a set of vehicles V tasked with picking up goods at pickup point S_c, let $x_{ijv} = 1$if vehicle $v \in V$ moves from node i to node j (either supplier or pickup point) $(i, j \in S \cup \{d\})$ and $x_{ijv} = 0$ if it does not move. The variable x_{ijv} is used to indicate the transportation route of trucks from the supplier's depot S_c to the logistics depot l, and the variable z_{ijv} is used to indicate the transportation route of trucks from the logistics depot l to the customer depot C_c. The multi-depot capacity vehicle routing problem does not explicitly consider demand, vehicle, and DC capacity constraints. Instead, they are considered in the least-cost trucking network flow problem. In the formulation of the least-cost trucking network flow problem, we classify collection points, logistics nodes, and trucks as intermediate nodes, while suppliers and customers are designated as "origin" and "destination" nodes, respectively. The objective is to efficiently distribute goods throughout the network while adjusting for capacity constraints at each node. The optimization aims to meet the demand requirements at the origin and destination nodes while minimizing the total truck mileage. The binary variable y_{ij}^{α} represents a flow variable, specifying whether the goods in delivery task α pass through node i and node j, and adapts all capacity constraints through y_{ij}^{α}. Next, we consider the least-cost track network flow problem together with the multi-depot capacity vehicle routing problem. When node i is a supplier, the binary variable y_{ij}^{α} is defined by the vehicle flow variable x_{ijv}. The right side of (1) represents the number of loads sent by the supplier. The maximum value of the right side is 1.

$$\sum_{j \in S \cup \{l\}} x_{sjv} = \sum_{\alpha \in A_s} y_{sv}^{\alpha} \quad \forall l \in L, \forall v \in V, \forall s \in S \tag{1}$$

Once the connection between the parcel flow and vehicle flow variables is set, the vehicle and depot capacity constraints are imposed using the variable y_{ij}^{α}.

$$\sum_{s \in S} \sum_{\alpha \in A_s} p\alpha y_{sv}^{\alpha} \leq q_v \quad \forall v \in V, \forall l \in L \tag{2}$$

$$\sum_{v \in V} \sum_{s \in S} p\alpha y_{sl}^{\alpha} \leq q_l \quad \forall l \in L \tag{3}$$

The left sides of (2) and (3) determine the total quantity of goods carried to track v and distribution point l, respectively. The same capacity constraints as in (2) can be applied to the trucks used.

$$\varepsilon = \sum_{i=1}^{n} y_{il}^{\alpha} \quad (4)$$

$$T_d = min \sum_{l_i, l_{i+1} \in L} \|l_i - l_{i+1}\| + min \sum_{l_i \in L} \sum_{s_{c_i} \in S_c} \|l_i - s_{c_i}\| + min \sum_{l_i \in L} \sum_{c_{c_i} \in C_c} \|l_i - c_{c_i}\| \quad (5)$$

$$p = \sum_{i=1}^{n} \sum_{v \in V} \sum_{s \in S} p \times \alpha \times y_{sl}^{\alpha} - \varepsilon q_l + \sum_{s \in S} \sum_{\alpha \in A_s} p \times \alpha \times y_{sv}^{\alpha} - q_l \quad (6)$$

$$f = T_d - p \times C_{penalty} \quad (7)$$

(4) determines the number of logistics hubs to be used (ε) and limits the number of logistics hubs to be used by a maximum value n. (5) represents the distance between the logistics hub and the supplier's collection point and the minimum distance between the logistics hub and the customer's collection point. (6) is the sum of the difference between the total cargo at the distribution depot and the capacity of the distribution depot and the total truckload capacity and the capacity of the distribution depot. Adapt the difference between (5) and (6) as the evaluation function. $C_{penalty}$ is the penalty coefficient. Figure 1 is a flow diagram of the algorithm.

3.5 Neuro Evolution of Augmenting Topologies (NEAT)

NEAT is a method proposed by Stanley et al. (2002) that uses GAs to optimize the structure and weights of neural nets for a problem. NEAT addresses the challenges associated with evolving neural networks, including the delicate balance between exploring new architectural possibilities and reusing existing solutions. In contrast to traditional neural network optimization methods which require human design and hyperparameter adjustment, NEAT uses a process modeled on genetic algorithms. Its starting point is a population of small, simple neural networks, or "genomes. Through processes such as mutation, crossover, and selection, these genomes evolve over many generations into more complex and sophisticated network structures.

3.6 LKH-3

The LKH-3 heuristic solver developed by Helsgaun (2017) demonstrates its adaptability in solving a wide range of problems involving capacity, time, pickup, and distance constraints (known as vehicle routing problems or VRP) (Helsgaun, 2017). It also excels at handling facility processing constraints and multi-traveling salesman problems (mTSP), and sensitivity analysis can be used to guide and constrain the solution search. In our study, we used a Python library known as elkai (Dimitrovski 2023) based on LKH-3. This library has been shown to provide optimal solutions for problem sizes up to N=315, outperforming the accuracy of Google's OR tool. It also simplifies the retrieval of results with a single line of code.

4 Introduction to data

Data on logistics facilities and factory sites were obtained from e-Stat, a government statistics portal site, where GIS data for each prefecture was combined into a single dataset and converted into a format suitable for the purpose of the survey (e-Stat, 2023). Average total floor area data from 2019 to 2022 was used as an indicator for the total floor area of distribution centers. Warehouse area data was the product of the allowable storage volume ($1900\ \mathrm{m}^3$), which is the floor area of each building divided by the number of buildings, the assumed height of the storage building ($5.5\ m$), and the occupancy rate (40%). Truck bed dimension data was obtained from Isuzu Motors, a Japanese automobile manufacturer that mainly produces trucks, buses, and other commercial vehicles. Table 2 shows the capacity of the warehouse and the three types of trucks used in the simulation.

Table 2. Warehouse and truck capacities

Type	Capacity (m^3)
Warehouse	1900
Light-duty trucks (2t)	12
Medium trucks (4t)	34
Heavy trucks (10t)	59

5 Depiction of the results and evaluation of the proposed algorithm

Depiction on map

The map displays the actual simulation results for determining the optimal placement of logistics centers and the corresponding delivery routes. Optimal routes are indicated by black lines, suppliers by red dots, supplier cluster centers by red pins, customers by blue dots, customer cluster centers by blue pins, and logistics nodes by green pins. Figure 2 depicts only centers, lockers and their routes.

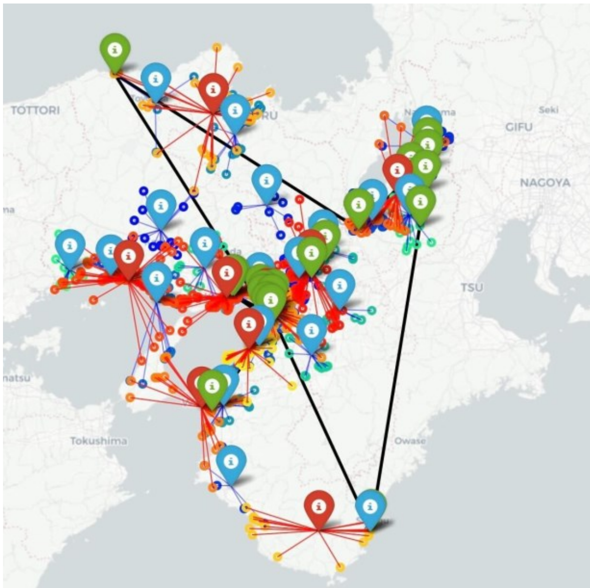

Figure 1. Drawing on the map (1)

Figure 2. Drawing on the map (2)

5.1 Evaluation of NEAT

The graphs in Figure 1 show the maximum fitness of NEAT for different population numbers (20, 30, 40, 50, and 60), the maximum fitness per generation, and the average fitness. In the early generations, the population had a low level of adaptation; once NEAT was initiated, the level of adaptation increased rapidly during the early stages of evolution. Later, after a certain number of generations, the level of adaptability reached a stable state and became less variable. The graph in Figure 2 compares the results of NEAT with different population numbers (30, 40, 50, and 60). In the case of our algorithm, the best results are shown when the population is 40.

5.2 Sensitive test

Sensitivity test was performed with $C_{penalty}$ as [0,250,500,750,1000] The population number of NEAT was fixed at 40.

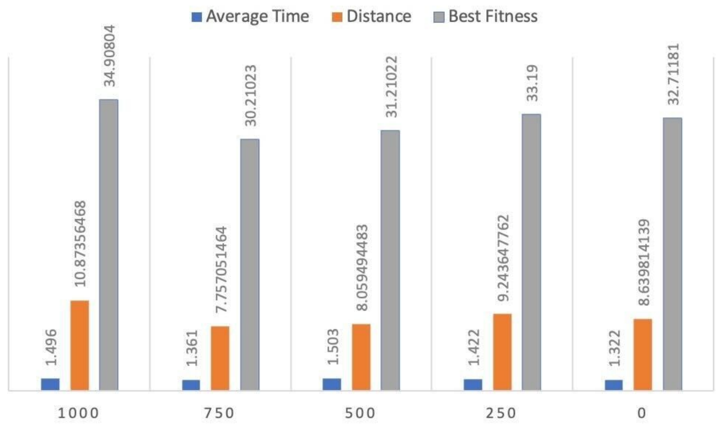

Figure 5. Sensitive test

6 Conclusion

Optimal location of distribution centers and optimization of delivery routes in the physical Internet are indispensable for the establishment of an efficient logistics system. The sharing of logistics resources can improve the efficiency of logistics processes, reduce costs, and mitigate environmental burdens. In this study, a method is proposed to identify the optimal location of logistics centers using NEAT, and to calculate the shortest and optimal delivery routes using LKH-3.

This paper contributes to research related to urban logistics, physical Internet, and logistics hubs. In addition, the proposed hybrid method using LKH-3, clustering, and genetic algorithm to derive the optimal number of clusters is applicable to other real data sets such as factory sites, logistics hubs, and important logistics roads, and can be applied to solve real problems in society.

This study is currently limited to truck transportation. There remain challenges, such as the combination of appropriate transportation modes among different modes based on the concept of physical Internet and the optimization of transportation planning. Future studies may focus on addressing these issues and developing more practical optimization models. In general, this study provides a novel method to obtain important insights for the optimal location of logistics hubs and the optimization of delivery routes.

7 Acknowledgements

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8 Appendix

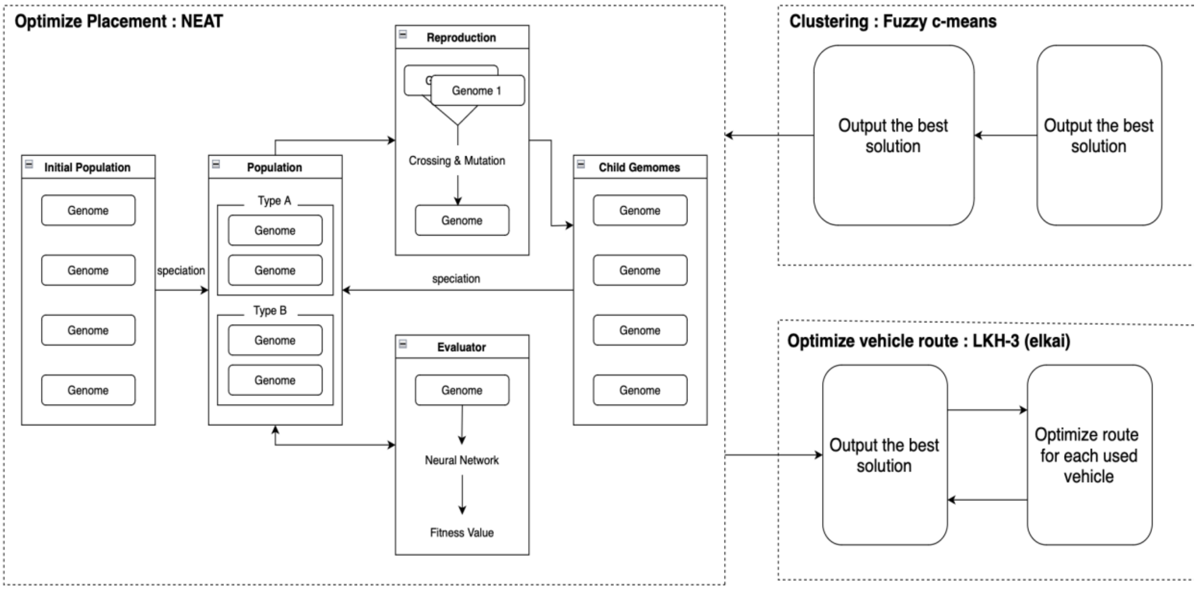

Figure A1. Algorithm flow diagram

Optimizing Service Networks of Eurasian Rail Freight Transport

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Keywords: *Global supply chain, Eurasian rail freight transport, Intercontinental rail freight freight, I-SSND, Scheduled Service Network Design, Physical Internet, Information Integration.*

Conference Domain Fitness: *Our contribution to IPIC 2024 closely aligns with the themes outlined in the call for contributions, with a particular emphasis on the optimization of intercontinental rail freight transport in the Eurasian region. By addressing the challenges posed by diverse stakeholders and fragmented rail networks. The Intercontinental-Scheduled Service Network Design (SSND), which is specifically tailored for Eurasian rail operations, aims to improve the efficiency and reliability of the intercontinental rail system.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☐ PI Networks, ☒ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

Contribution abstract

Eurasian rail freight transport has made significant progress in recent years, demonstrating its potential as a critical player in the global supply chain. However, this intercontinental rail transport involves a wide range of stakeholders, including shippers, logistics service providers, rail undertakings, infrastructure and terminal operators, railway operators, and other equipment operators. Multiple interfaces across totally different rail systems complicate information exchange. Due to a lack of information integration, intercontinental rail freight planning has a long history of manual rail planning, relying heavily on planner experience and knowledge. This work extracts relevant information from the supply chain and rail freight system to create a time-space formulated Intercontinental-Scheduled Service Network Design (SSND) that is specifically designed for Eurasian rail system. This model aims to incorporate heterogeneous service requirements from the global supply chain into intercontinental rail planning. It calculates potential delays, determines the length of stay for each order at each terminal, and synchronises order schedules at border crossing terminals. The initial application of this model in Eurasian rail freight transport has produced promising results, demonstrating its potential for wider implementation in intercontinental rail freight transport.

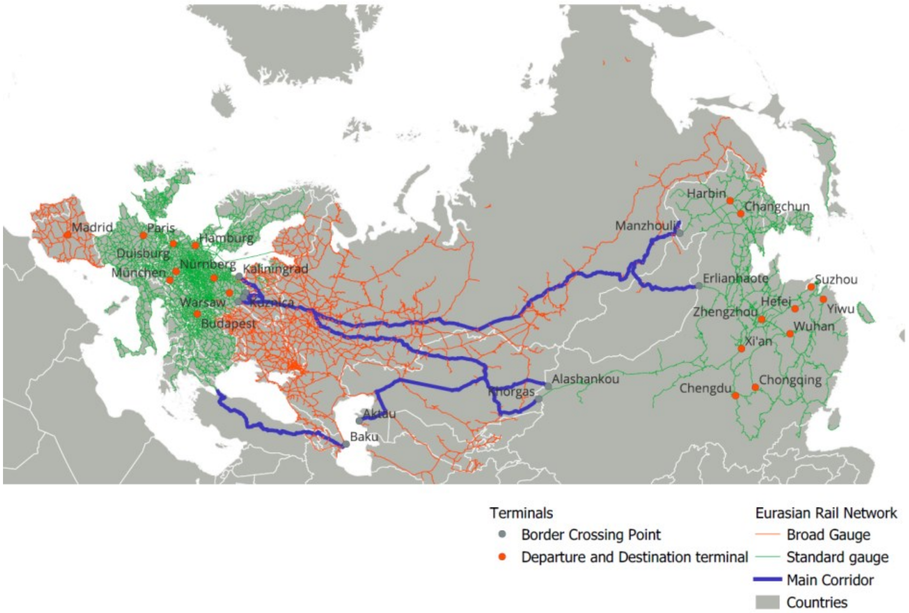

Figure 1: Parts of Eurasian rail network based on naturalearthdata

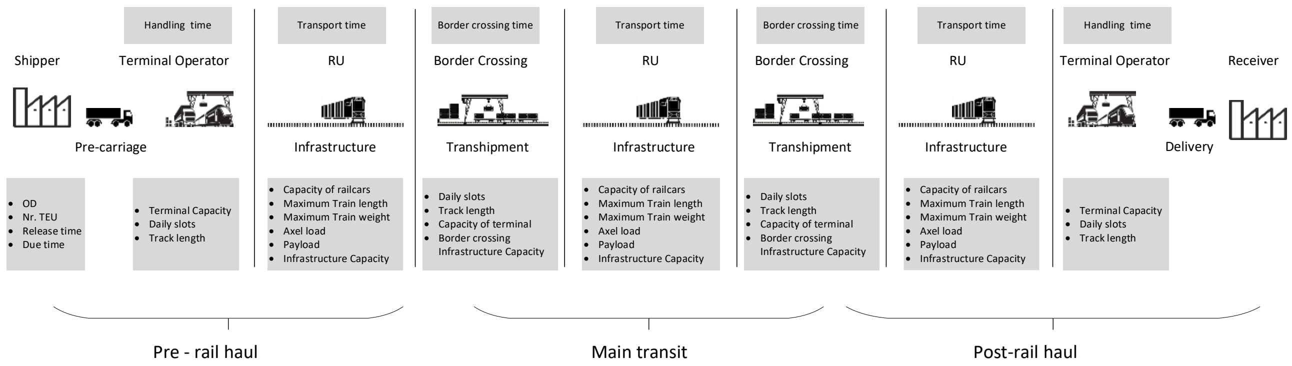

Figure 2 Actor-related information on Eurasian rail freight transport

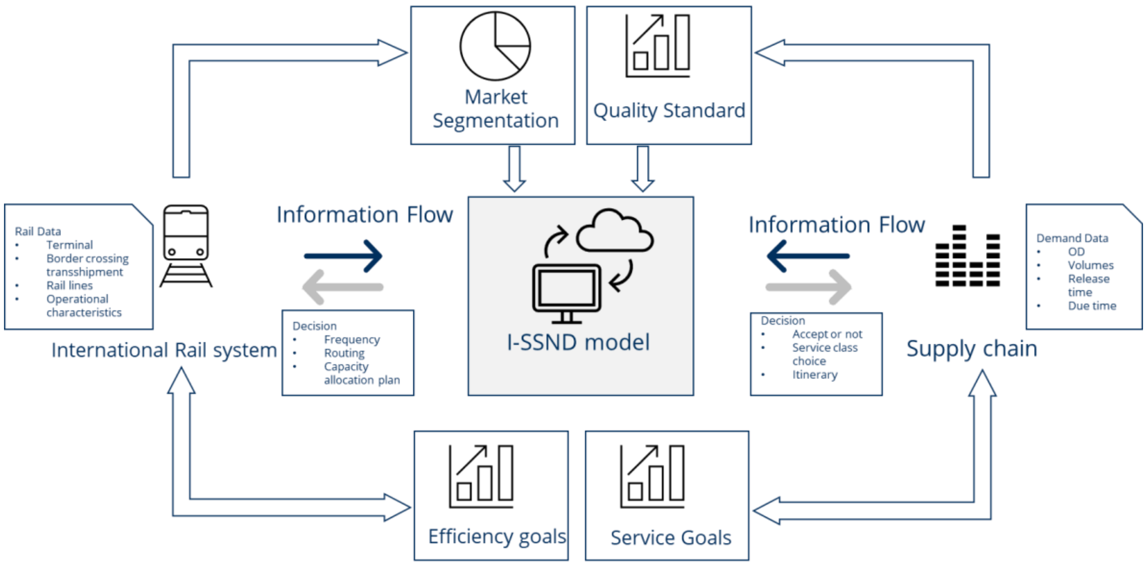

Figure 3 Information integration in the I-SSND model

Exploring the Effect of Network Configuration Topologies on the Dynamics of Freight Delivery: A Comparative Analysis of Physical Internet and Traditional Supply Chain Methods

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2. PI Networks, System of Logistic Networks, PI Nodes, Logistic hubs

Abstract

This paper compares the effect of network configuration on the dynamics of freight delivery. A comparison is made between Physical Internet (PI) and traditional distribution for the line, tree, square, circle, and cluster topologies. A mixed-integer linear program (MILP) model is presented to optimize the trade-off between dispatching and inventory costs. Quicker dispatch reduces inventory costs but increases the cost of transportation. This model is then applied for both the PI and traditional distribution contexts for each topology to understand the conditions favorable to PI. The key factors affecting the performance of the two methods are the distance ratio and the capacity of vehicles relative to dispatch flows. In terms of topology, the line configuration is always beneficial to PI but in the case of the other topologies, PI is good when the distance ratios and the flow quantity in relation to vehicle capacity increase.

1. Introduction

The literature on PI has grown considerably since 2010 when it was first introduced. In this paper, we are interested in the effect of the configuration and shape parameters of a logistics network to see how that impacts its operations within both the PI and traditional distribution constructs. The strength of PI lies in its ability to exploit the use of modular containers and create opportunities for consolidation.

Some standard PI configuration patterns are emerging in the literature. In Montreuil (2011), the point-to-point transportation physical internet case study had all the cities lined up (Figure 1.1). Fazili et al. (2017) consider a tree structure in Eastern Canada, which can be seen as a spine with offshoots (Figure 1.2). The case study in Li et al. (2022) can be clearly thought of as square grid (Figure 1.3). This can be thought of as a cluster like configuration with the hubs forming a network and a cluster of nodes in the vicinity of the hubs. Venkatadri et al. (2016) present a 26 city European PI network. A closer look at it reveals a hub and spoke structure which we call the circle configuration (Figure 1.4). Chadha et al. (2021) consider a case study in the automotive sector of Mexico (Figure 1.5).

The objective of this paper is to look at how well these PI network configurations compare when contrasted against their counterparts in point-to-point traditional networks. Specifically, we are interested in viewing the performance of a network based on the trade-off between dispatching and inventory costs. As evident, unless the arrival rate between two nodes in a point-to-point traditional network is very high, efficient dispatch implies waiting for loads, and therefore, shipments take longer. The PI network, on the other hand, offers opportunities for consolidation. Therefore, if there are opportunities for consolidation at a subsequent hub, a load might be opportunistically dispatched from a node to the closest hub to allow this to happen. Therefore, the hypothesis in this paper is that the dispatch rate and inventory cost trade-off take place differently. In this paper, we assume that all PI containers adhere to the tree-tier characterization of transport, handling, and packaging method proposed by Montreuil et al. (2010). This allows PI to generalize and standardize unit loads. The rest of this paper is organized as follows. Section 2 presents a brief literature on PI directly relevant to this paper. Section 3 presents two MILP models for dispatch planning: one for the traditional system and the other for PI. Section 4 shows how the experiments to evaluate PI and traditional networks for the various configurations are designed. Section5 presents some numerical results. Section 6 presents conclusions and Section 7 identifies some areas for future research.

Figure 1.1 (Adapted from Montreuil et al., 2011) Line shape case study conceptual transformation

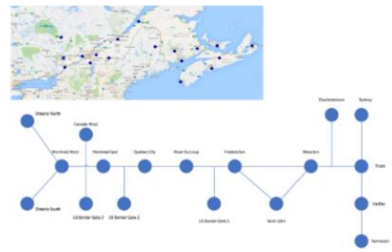

Figure 1.2 (Adapted from Fazili et al., 2017) Tree shape case study conceptual transformation

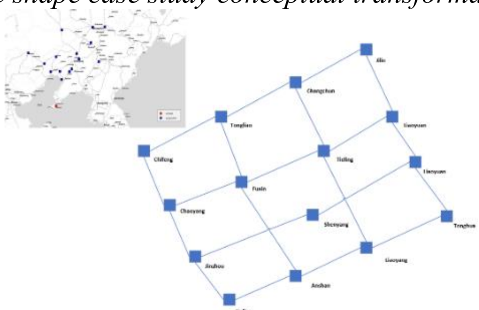

Figure 1.3 (Adapted from (Li et al., 2022) Square shape case study conceptual transformation

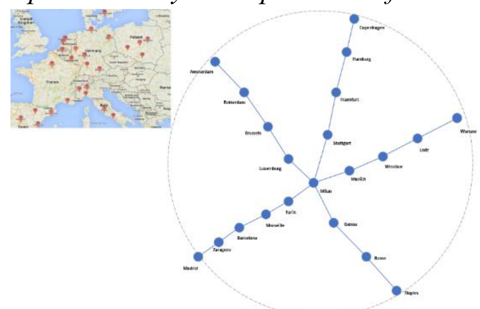

Figure 1.4 (Adapted from Venkatadri et al., (2016) Circle shape case study conceptual transformation

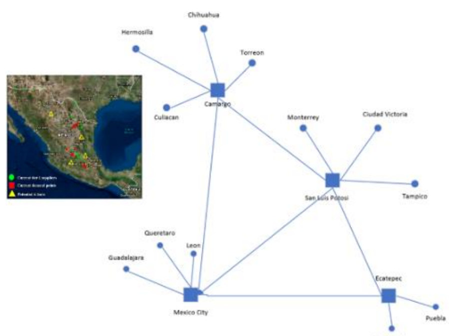

Figure 1.5 (Adapted from (Chadha et al., 2021) Cluster shape case study conceptual transformation

2. Literature Review

We present a brief history of the research relevant to dispatch planning in the PI starting with a foundational overview of essential physical elements underpinning the Physical Internet infrastructure, namely, containers, movers, and nodes (Montreuil, 2010; Montreuil et al. 2010). When simulating logistic network services using a model, employing unified units can streamline the complexity of the model. Transportation companies often use standardized units such as containers and vehicles. Montreuil et al. (2010) highlighted the importance of π-containers, which are unit loads manipulated, stored, and routed through the systems and the shared logistics infrastructure of the Physical Internet. These containers must adhere to standardized logistics modules worldwide and be designed to facilitate handling, storage, and transportation while ensuring the protection of goods. Ballot et al. (2010) developed a three-step topology evaluation of PI based on flow travel, transportation, and supply chain inventory. It is mentioned in the paper that the deployment of PI needs to show a significant reduction in the resources necessary to realize logistics operations through better operational efficacy, elimination of unnecessary journeys and use of more appropriate transportation means. A consequence of this transition toward the Physical

Internet can be the change of topology of the logistic service networks. Therefore, it is very important to study PI based on logistics configuration.

Ballot et al. (2012) describes the logistics paradigm for decentralized and distributed routing in PI compared to traditional centralized supply chain networks. Montreuil et al. (2012) explore the basis of the Physical Internet, designed to markedly improve the efficiency and sustainability of global physical object operations. Montreuil et al. (2012) proposed three types of PI business models: extension-driven business model, journey business models, and ephemeral business model.

Coming to transportation planning in PI, Hakimi et al. (2012) present a multi-agent mobility web simulator designed to facilitate the examination and analysis of the shift from the current freight transportation system to an open logistics network in France. Sarraj et al. (2013) presented a transportation protocol in PI and a container consolidation protocol, describing the basic logic of consolidation process in consolidation hubs. Lin et al. (2014) introduced a mathematical program and a decomposition algorithm to address the problem of optimizing space utilization when packing a collection of products. Ahmadi-Javid & Hoseinpour (2015) studied a profit-maximization location-inventory problem in a supply chain distribution network in uncapacitated and capacitated cases, determined location, allocation, price, and order size decisions to maximize the profit. Crainic & Montreuil (2016) present a synergy between City Logistic and Physical Internet, introduced the idea of Hyperconnected City Logistics system and its fundamental concepts, made a rich framework of designing efficient and sustainable urban logistics and transportation systems.

The current paper is based on the model in Venkatadri et al. (2016) who compare PI and the traditional logistics model based on dispatch optimization. The trade-off between delayed or expedited dispatch and inventory cost is considered for each pair of nodes in the two networks. Fazili et al. (2017) compare the performance of three logistics systems in a road network: conventional (CO), Physical Internet (PI), and a hybrid (HY) system. The study finds that the PI system reduces total driving distance but increases handling costs compared to CO and HY systems. Montreuil et al. (2017) presented a three-tier characterization of transport, handling and packaging containers for the Physical Internet to enable generalizing and standardizing unit load design worldwide. Chadha et al. (2021) explore how peddling, a traditional logistics consolidation strategy, can enhance a PI based automotive supply chain for three configurations: Model P (PI-based), Model S (standard peddling), and Model H (hybrid). They characterize the performance of the models for different types of cost, average distance traveled, and truck utilization. Ezaki et al. (2022) included three types of routing algorithms which are static shortest path (SSP) algorithms, temporary fastest path (TFP) algorithms, and adaptive fastest path (AFP) algorithm for PI. Li et al. (2022) suggested implementing the concept of PI by assigning a single request to multiple trucks, enabling transfers between trucks at logistics hubs, representing it as a PI-based selective vehicle routing problem (PI-SVRP).

Andersen et al. (2009) look at service network design with management and coordination of multiple fleets. Crainic & Hewitt (2020) present a comprehensive overview of the general service network design methodology, covering models, solution methods, and applications. Wang & Qi (2020) employ probability-free uncertainty sets to identify potential scenarios and develop a column-and-constraint generation approach as the solution method to solve the introduced robust models. All three papers have relevance to the issues studied in the paper, although space and scope limitations prevent us from exploring these issues. However, we focus instead on a gap in the PI literature which has to do with how the PI logistics system fares for the different configurations mentioned, namely the line, tree, square, circle, and cluster.

3. MILP Models for Dispatch

This section introduces two models employed in the designed logistic experiments: the

Traditional model and the PI model. The primary aim of these models is to plan dispatches in a network to optimize the total cost dispatch and waiting (inventory). Both the PI and Traditional models allow for two-way dispatches between nodes.

These models are extensions of the two-way model presented in Venkatadri et al. (2016), their logistic model minimize the total cost of inventory, transportation, fix costs, and variable costs, with constraints balancing the inventory level, dispatch and vehicle capacity, and the static initial and final states. For the PI model, there are some extra assumptions. Transshipment costs related to loading and unloading at source and destination points are not considered in the model because they do not change the decisions. However, these costs are added to the total cost of PI once a solution is found. In PI, the consolidation process is obligatory, requiring that all dispatch flows be routed through the consolidation hubs.

Following are the sets, parameters, and decision variables involved in both models:

Sets	
N	The set of nodes
H	The set of hubs
NH	The set of nodes and hubs
V	The capacity of the vehicle (in same unit as arrivals)
C	Inventory cost per period per unit
F	Fixed cost for a truck cost
W	Variable vehicle (truck) cost
Parameters	
A_{abt}	Number of orders that arrive at node *a* in period *t* destined for node *b*
d_{ab}	Distance from node *a* to *b*
w_{abc}	Binary, 1 if *b* is the next node when shipping from node *a* to *c* and *b* is not equal to *c*, 0 otherwise
z_{abc}	Binary, 1 if *b* is the next node when shipping from node *a* to *c*, 0 otherwise
Decision Variables	
D_{abt}	Order quantity dispatched (in truck load) from node *a* to node *b* at the beginning of period *t* using truck type *k*.
N_{at}	Number of trucks at node a at the end of period *t*
I_{abt}	Order inventory (in truck load) at node a destined for node *b* at the end of period *t*
Y_{abt}	Number of trucks dispatched from node *a* to node *b* at the beginning of period *t*

3.1 Traditional Logistic Model (P2P)

In the traditional P2P model, all pairs of nodes are considered, and the flows occur both ways in each pair. However, the fleet of vehicles used to manage these flows are centralized.

$$\min imize$$

$$\sum_a^N \sum_b^N \sum_t CI_{abt} + \sum_a^N \sum_b^N \sum_t (F + Wd_{ab}) Y_{abt} \qquad (1)$$

subject to:

$$I_{abt} = I_{a,b,t-1} + A_{abt} - D_{abt} \qquad \forall a,b \in N,\ t = 1 \ldots T \qquad (2)$$

$$N_{at} = N_{a,t-1} + \sum_b^N Y_{bat} - \sum_b^N Y_{abt} \qquad \forall a \in N,\ t = 1 \ldots T \qquad (3)$$

$$\sum_b^N D_{abt} \leqslant N_{at} V \qquad \forall a,b \in N,\ t = 1 \ldots T \qquad (4)$$

$$D_{abt} \leqslant VY_{abt} \qquad \forall a,b \in N,\ t = 1 \ldots T \qquad (5)$$

$$N_{a0} = N_{aT} \qquad \forall a \in N \qquad (6)$$

$$Y_{ab0} = 0 \qquad \forall a,b \in N \qquad (7)$$

$$I_{abT} = 0 \qquad \forall a,b \in N \qquad (8)$$

Objective function (1) seeks to minimize the total cost associated with handling and delivery. In Constraint (1), the first term accounts for the extra cost incurred due to consolidation, which results from delays in deliveries from source node 'a' to destination node 'b.' The second term encompasses the overall cost of vehicles, including fixed costs and transportation expenses, which are influenced by whether the vehicles are used or not. Constraint (2) addresses the balance of inventory, reflecting changes between consecutive periods. Constraint (3) concerns the equilibrium of the number of vehicles used in two consecutive periods. Constraints (4) and (5) place limits on dispatch loads based on vehicle capacity and the total number of available vehicles, respectively. Constraint (6) ensures that the initial and final states remain consistent in terms of the number of vehicles. Finally, Constraints (7) and (8) represent the boundary conditions at the beginning, where no vehicles are in use, and there is no inventory at the source points, respectively.

3.2 PI Logistics Model

In this model, we introduce an additional set referred to as 'H,' representing consolidation hubs which are pertinent to PI. Corresponding adjustments have been applied to parameters with subscripts denoting points. Specifically, the inclusion of consolidation hubs has resulted in modifications to the following parameters and decision variables: A, d, D, N, I, and Y.

Two new parameters, namely w_{abc} and z_{abc}, have been integrated into this model. They serve as conditions mandating dispatch loads to pass through the consolidation hubs, thereby recreating the consolidation processes. Of these two variables, '*w*' primarily functions to direct the flow along routes that initiate at source nodes, proceed to hubs for consolidation, and ultimately reach destination nodes (these are considered ideal routes). In constraint (10), '*w*' is utilized to calculate inventory levels at transit points. Conversely, '*z*' operates in a similar fashion to '*w*,' but it allows flows to depart from consolidation hubs. This functionality enables the calculation of dispatch flows between every point, encompassing source nodes, consolidation hubs, and destination nodes, as specified in constraint (12).

Objective function (9) minimizes the total cost, the first term is the total inventory cost caused by consolidation. The second term of (9) is total fixed cost of vehicles, and the last term of (9) is total transportation cost of vehicles. In the second and third term of (9), the fixed cost and transportation cost are associated with the dispatch load of trucks from source node a to destination b and vice versa.

Constraint (10) is the inventory balance at each node or hub. Constraint (11) ensures that the total number of vehicles in the two consecutive periods are the same. Constraint (12) and (13) impose the limit on dispatch loads based on the number of vehicles and vehicle capacity. Constraint (14) ensures the initial state and final state are the same with total number of vehicles. Constraint (15) and (16) are the boundary conditions of the initial state (No vehicles being used and no inventory at any points, respectively). To conclude this section, the PI logistics model builds in the consolidation process into the optimization. However, it assumes a fixed routing which needs to be expanded in the future.

$$\min imize$$

$$\sum_{a}^{NH}\sum_{b}^{N}\sum_{t} CI_{abt} + \sum_{a}^{N}\sum_{b}^{NH}\sum_{t} FY_{abt} + \sum_{a}^{NH}\sum_{b}^{NH}\sum_{t} Wd_{ab}Y_{abt} \qquad (9)$$

$$subject\ to:$$

$$I_{bct} = I_{b,c,t-1} + A_{bct} + \sum_{a}^{NH} D_{act}w_{abc} - D_{bct} \qquad \forall b \in NH,\ c \in N,\ t=1...T \quad (10)$$

$$N_{at} = N_{a,t-1} + \sum_{b}^{NH} Y_{bat} - \sum_{b}^{NH} Y_{abt} \qquad \forall a \in NH,\ t=1...T \quad (11)$$

$$\sum_{c}^{NH} D_{act} \leqslant N_{at}V \qquad \forall a,c \in N,\ t=1...T \quad (12)$$

$$\sum_{c}^{N} D_{act}z_{abc} \leqslant VY_{abt} \qquad \forall a,b \in NH,\ t=1...T \quad (13)$$

$$N_{a0} = N_{aT} \qquad \forall a \in NH \quad (14)$$

$$Y_{ab0} = 0 \qquad \forall a,b \in NH \quad (15)$$

$$I_{abT} = 0 \qquad \forall a,b \in NH \quad (16)$$

4. Design of Experiments to Evaluate PI and Traditional Networks

The design experiments are categorized into two main sections: PI model logistic experiments and traditional model logistic experiments. The primary objective of these design experiments is to assess and compare the performances of PI and traditional logistics transportation methods under various configurations and conditions. Six configurations are considered as shown below. The base distance unit between nodes (or hubs) is 300 km. The square configuration is of two types: the hubs only along the central line (Figure 4.3) and all nodes serving as hubs (Figure 4.4). All configurations have nine nodes.

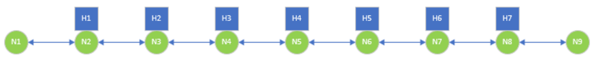

Figure 4.1 Line configuration

Figure 4.4 All-hubs square configuration

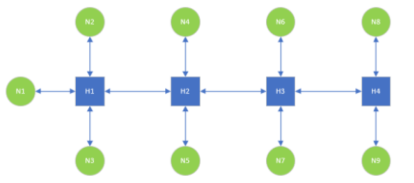

Figure 4.2 Tree configuration

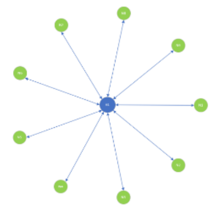

Figure 4.5 Circle configuration

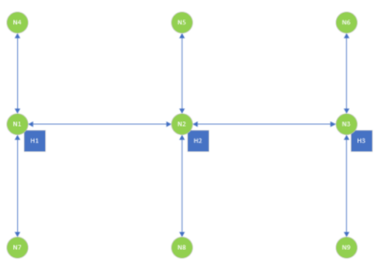

Figure 4.3 Central-line square configuration

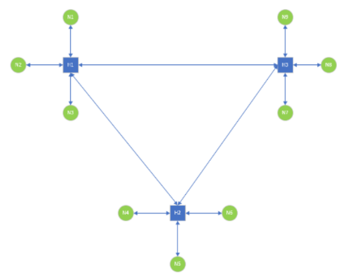

Figure 4.6 Cluster configuration (not to scale)

4.1. PI Distribution and Traditional Model Route Selection

In all PI model design experiments, the travel routes begin at nodes, proceed through one or more hubs, and ultimately reach the designated destination nodes. The distances between two points are composed of two components: node-to-hub (N-H) distances and hub-to-hub (H-H) distances. The cluster-type configuration in Figure 4.6 is not to scale because in the experiments we used all base distances to be 300 km, the hubs are strategically located at positions that have equal distances from all the nodes within each cluster, ensuring an even and balanced distribution.

4.2.Basic Experiment Parameters

For both the PI and Traditional logistic models, all design experiments consist of three periods, with loads from every node to all other nodes for each period. Consequently, each period comprises 72 dispatch flows, resulting in a total of 216 flows throughout the duration of each design experiment, maintaining consistency across both PI and traditional models. In the PI method, consolidation costs including loading, unloading and labor costs are added post *priori* after the model is solved. When designing distance experiments, we commence with a standardized distance value of 300 kilometers for all distances. Subsequently, we systematically adjust the standard values of different types of distances, ranging from a quarter (0.25 times, equivalent to 75 kilometers) of the original value to eightfold (8 times, equivalent to 2400 kilometers) expansion in multiples. This meticulous approach generates a total of six distinct sets of results, each corresponding to a different scale of distance variations within the experiments. The size of dispatch loads is initially set to 4 between all node pairs. Subsequently, adjustments are made to the capacity of vehicles, starting from a minimum of 1 and increasing in multiples of two reaching a maximum of 64. Consequently, this experiment produces a total of 7 sets of results, each corresponding to a different vehicle capacity setting. The base capacity of vehicles is initially 16. In experiments, we change it from 1 to 64 in multiples of two, yielding 7 distinct sets of results.

5. Numerical Results

5.1. Distance Experiment

Figure 5.1 illustrates the performance of adjusting H-H distances for all the shapes with H-H distances. From the plots of H-H distance experiments, all design experiments with shapes containing H-H distance have the same trend: when H-H distance increases, the growth rate of the cost curve of the PI method is slower than that of the traditional method. The performance of PI methods in most shapes will underperform the traditional method with small H-H distances at the beginning, outperforming it as H-H distance increases. One exception is the design experiment of the line shape, where PI is always superior. The reason for this is that in the line configuration, the distances are the same but there are opportunities for consolidation in PI. Figure 5.2 illustrates the performance of adjusting N-H distances for all shapes with N-H distances. From the grid of plots, the increase or decrease of N-H distance does not seem to produce a clear trend in performance change—there is no situation or trend where one method consistently outperforms the other with the increase or decrease. The all-hubs configuration has an advantage over the tree or central-line configurations for PI because for many node pairs, the flow does need to descend to the central-line. For this reason, the all-hubs configuration was not included in Figures 5.1 and 5.2. Figure 5.3 shows the effect of changing N-H or both N-H and H-H distances together. When the N-H increases, PI outperforms the traditional method. However, when both distances are increased together, there is no advantage for PI. Table 5.1 presents the total number of dispatched vehicles for each shape along with the average load per vehicle calculated under the condition of standard data in PI method. Through all three experimental periods, it is evident that all dispatch loads successfully reached their designated destination nodes by the end of the experiment, resulting in identical total transported loads for all configurations. The average load per vehicle reflects the degree of consolidation, with a higher number indicating a greater extent of consolidation. The line configuration exhibits the highest extent of consolidation, whereas the all-hubs square configuration demonstrates the lowest extent. The circle configuration uses relatively few vehicles and has a good degree of consolidation.

Table 5.1 Number of vehicles used during the experiment and average load per vehicle

PI	*Number of non-hub nodes*	*Number of hubs*	*Number of Vehicles*	*Total transported loads*	*Average loads per vehicle*
Line	*2*	*7*	*90*	*864*	*9.6*
Tree	*9*	*4*	*170*	*864*	*5.1*
Square Central-Line	*6*	*3*	*140*	*864*	*6.2*
Square All-hubs	*0*	*9*	*177*	*864*	*4.9*
Circle	*9*	*1*	*108*	*864*	*8*
Cluster	*9*	*3*	*150*	*864*	*5.8*

5.2.Experiment of Vehicle Capacity and Flow Quantity

The plots of vehicle capacity and flow quantity for all shapes are similar (Figure 5.4): as the vehicle capacity increases while keeping the flow quantities identical, the PI performance improves. For most shapes, except the line shape, the PI method will outperform the traditional method after reaching certain scales. In contrast, as the flow quantities increase while keeping the vehicle capacity identical, the traditional method starts to exhibit an advantageous performance compared to the PI method because it can utilize capacity better. In fact, the ratio of flow quantity to vehicle capacity is the key factor (as shown in the bottom of Figure 5.4.

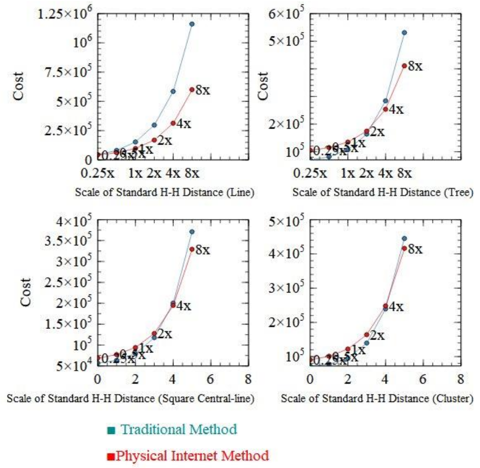

Figure 5.1 Plot of H-H distance experiments

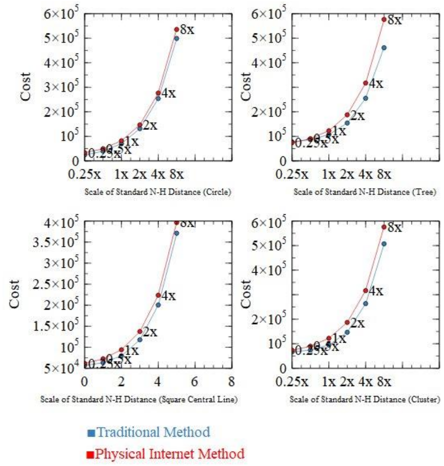

Figure 5.2 Plot of N-H distance experiments

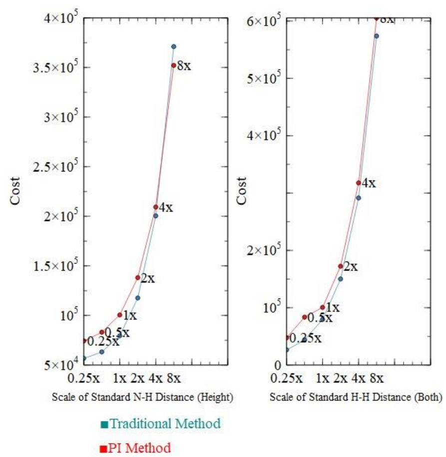

Figure 5.3 Plots of all-hubs square experiment

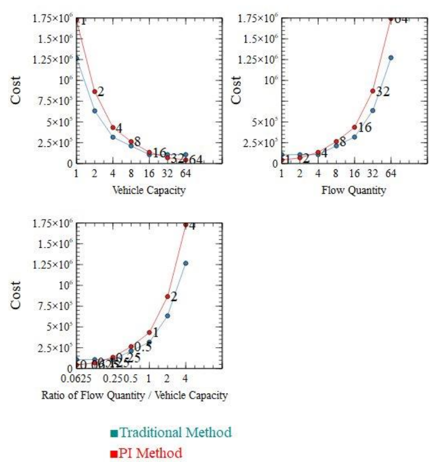

Figure 5.4 Plots of vehicle capacity and flow quantity experiments of tree experiment

6. Conclusion

The distance experiments show a trend for the various shapes. The smaller the ratio between the N-H and H-H distance, the more favorable it is for consolidation due to the clustering effect. On the other hand, increasing the N-H distance relative to the H-H distance makes the consolidated route distance much larger than the direct route distance in the traditional configuration, creating a condition that is not favourable to consolidation. In the experiments involving vehicle capacity and dispatch quantity, a smaller ratio of dispatch quantity to vehicle capacity results in each vehicle being able to transport more dispatch orders, leading to increased consolidation. As consolidation intensifies, the advantages of the Physical Internet (PI) model become more pronounced. Therefore, vehicle load capacity emerges as an important element in the success of the Physical Internet paradigm. From the design experiments conducted for each shape, it is evident that the Physical Internet (PI) method has its pros and cons in different scenarios. In the case of a line shape, except for extreme and unrealistic situations where transshipment costs at hubs are unusually high compared to transportation costs, PI transportation consistently outperforms traditional methods. However, in tree, square, and circle shapes, there are specific dispatch orders where PI performs worse than traditional methods. In such cases, a hybrid approach combining traditional transportation and PI may be more suitable. In cluster-shaped scenarios, both N-H and H-H distance adjustments can lead to performance outcomes favoring either traditional or PI transportation.

Based on the travel distance of all utilized vehicles, the Physical Internet (PI) method demonstrates clear advantages over the traditional method. Consolidation results in the PI method covering about one-third of the transportation distance compared to the traditional method. This reduction is significant and greatly aids in reducing fuel consumption associated with transportation and will also save greenhouse gas emissions.

7. Future Research

This research can be extended in many ways. The experiments can be repeated for time windows, transshipment delay costs, and vehicle speeds such as in Li et al., 2022. This paper only looked at PI and traditional logistics systems. Hybrid systems where consolidation is not obligatory can be explored, as in Fazili et al. (2017). The effect of transshipment cost on network topology could be considered when comparing PI with the traditional system. The PI consolidation model in Section 3.2 assumes a fixed routing. While this is reasonable for the scope of this paper which was at an overall design evaluation level, it could be expanded to allow for dynamic routings at the operational level. The types of vehicles and containers can be varied to allow for mixed fleets.

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Artificial Intelligence in the Physical Internet

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Abstract: *The primary objective of this study is to investigate the influence of Artificial Intelligence (AI) on the evolution of the Physical Internet (PI), a transformative vision for logistics systems, through a thorough analysis of pertinent literature. This research aims to bridge the gap in scientific knowledge regarding AI's integration into the PI by identifying AI methods to enhance both theory and implementation. Specifically, the study focuses on three aspects: (1) the most prevalent AI methods in PI, (2) the potential theme-specific AI enhancements of PI, and (3) the potential AI methods for employment in PI. The study proposes a novel AI-in-PI framework which will help academicians and practitioners in identifying current research patterns of AI in PI. Furthermore, the study identifies literature gaps requiring further investigation and offers valuable insights into the intersection of AI and PI.*

Keywords: *Physical Internet, Artificial Intelligence, Hyperconnected Logistics, Optimization, Autonomous Vehicles, City/Urban Logistics, PI-Adoption.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan:* ☒ *PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories),* ☒ *Transportation Equipment,* ☒ *PI Networks,* ☐ *System of Logistics Networks,* ☐ *Vertical Supply Consolidation,* ☐ *Horizontal Supply Chain Alignment,* ☐ *Logistics/Commercial Data Platform,* ☒ *Access and Adoption,* ☐ *Governance.*

Targeted Delivery Mode-s*:* ☒ *Paper,* ☐ *Poster,* ☐ *Flash Video,* ☒ *In-Person presentation*

1 Introduction

The Physical Internet (PI) is one of the burgeoning transformative paradigms poised to revolutionize global logistics networks by facilitating seamless interconnection. Serving as a tangible counterpart to the digital realm, PI advocates for the interconnectedness and openness of diverse logistics and supply networks, promising to deliver substantial benefits and opportunities. Since Herbert Simon's famous assertion in 1965 that "Machines will be capable of doing any work a man can do," the trajectory of Artificial Intelligence (AI) has been nothing short of remarkable. Originating with the inception of expert systems and fuzzy logic, the journey of AI gained momentum after 2010 with the advent of big data, analytics, and the proliferation of Graphical/Tensor Processing Units (GPUs/TPUs) and deep learning techniques. These advancements have collectively propelled AI into what we now recognize as modern AI.

Previous reviews (see Chen et al., 2021; Pan et al., 2021; Cortes-Murcia et al.,2022; Samadhiya et al., 2023) show a lack of AI focus in PI literature. This study aims to provide comprehensive coverage and incorporate the latest breakthroughs in AI. The research questions (RQs) stated in this paper are as follows:

RQ1: What are the most prevalent AI methods?

RQ2: What are the potential PI-Theme-specific AI enhancements?

RQ3: What are the potential AI methods for PI?

The subsequent sections of this article are organized as follows: the second section outlines the methodology for the review. Followed by bibliometric analysis (Section 3) and content analysis (Section 4). Section 5 provides the AI in PI conceptual framework with answers to the RQs and providing recommendations for future guidelines. Finally, Section 6 concludes with theoretical and managerial implications. To conserve space, the full list of references is available on the GitHub link:

https://github.com/SS-Chadha/AI-in-PI/blob/new-branch/Literature%20collected%20final.txt

2 Review Methodology

The research questions are addressed using the Systematic Literature Review (SLR) technique. Thomé et al. (2016) offer guidance on conducting and reporting SLRs. They present a rigorous approach with detailed step-by-step instructions, emphasizing an operations management perspective. This review adapts the Thomé et al.'s guidelines, including five steps: (i) planning and formulating the problem; (ii) searching the literature; (iii) data gathering and quality evaluation; (iv) data analysis, synthesis and interpretation; (v) presenting results and updating the review. Additionally, the PRISMA framework, which stands out as the gold standard for meta-synthesis and meta-analysis across various industries, including the supply chain domain (Naseem & Yang, 2021), is utilized for both data presentation and review revision.

Section 1 covered the first step in Thomé et al. (2016), i.e., planning and formulating the problem. This section describes the next two seps. Databases used for our review are Engineering Village (Elsevier), Scopus (Elsevier), ScienceDirect (Elsevier), Taylor & Francis Online, and Google Scholar. The following keywords and Boolean operators are employed for extracting the relevant scholarly articles (from 2010 to 2024) for our study:

(“physical internet”) AND (“artificial intelligence” OR “machine learning” OR “deep learning” OR “unsupervised learning” OR “supervised learning” OR “reinforcement learning”)

Due to the large volume of articles retrieved from Google Scholar, an additional keyword, *“hyperconnected”* is incorporated to refine the search, given that the initial number of articles approached 3,000. This decision aligns with Montreuil's characterization of the Physical Internet as “hyperconnected,” emphasizing the interconnectedness of its components across multiple layers and locations (Montreuil, 2015, Oger et al., 2018).

Figure 1 depicts the PRISMA flow map that includes the number of documents retrieved from each of the databases and the screening criteria. A total of 557 documents are recorded. After duplicate removal and keeping only English documents, 414 records are further screened on abstracts, keywords, and topic. This renders 123 records for full article assessment. Ten records are excluded after full article assessment, leaving 113 articles for bibliometric and in-depth content analysis. The last search was conducted on March 28, 2024.

3 Bibliometric exploration

Utilizing VOSviewer, a robust bibliometric analysis tool, we identify relationships among authors, terms, documents, and cited references. Known for its advanced features such as co-authorship, co-occurrence, bibliographic coupling, and co-citation networks, VOSviewer facilitates comprehensive analyses (Jan van Eck & Waltman, 2010). In this study, 113 records (including books, conferences, dissertations/thesis, and journal articles) are reviewed.

Bibliometric analysis comprises of five prime metrics: (1) Year, (2) Authors, (3) Keywords, (4) Types of journals, (5) Citations.

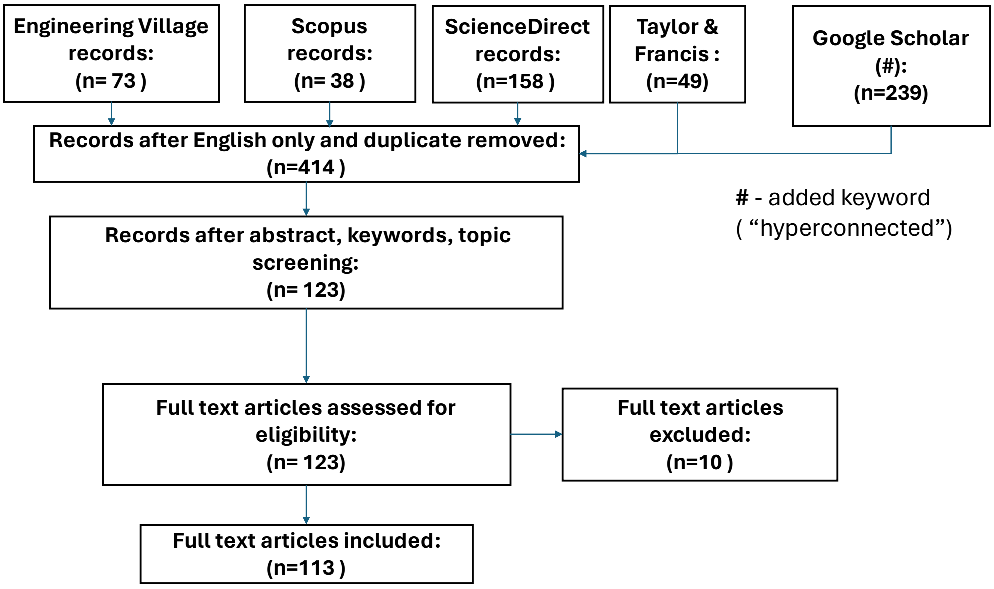

Figure 1 PRISMA flow map

3.1. Timeline trend

The number of publications and citations at various times are used in this study to show the research trend from 2010 to 2024. Accordingly, the first article mentioning some form of AI in PI is Meller et al. (2012), wherein, "a heuristic method, employing three rules to restrict the search, was proposed to determine the optimal modular container size for each product." The results reveal a substantial increase in the pace of publications in recent years, as seen in Figure 2. Following the publication of the paper on container standardization and selection in 2012, there was a relatively sparse amount of research conducted in that domain until 2017. Since 2017, there has been a noticeable increase in research interest in employing AI in PI research, evident from the linear trend line depicted in blue dotted line.

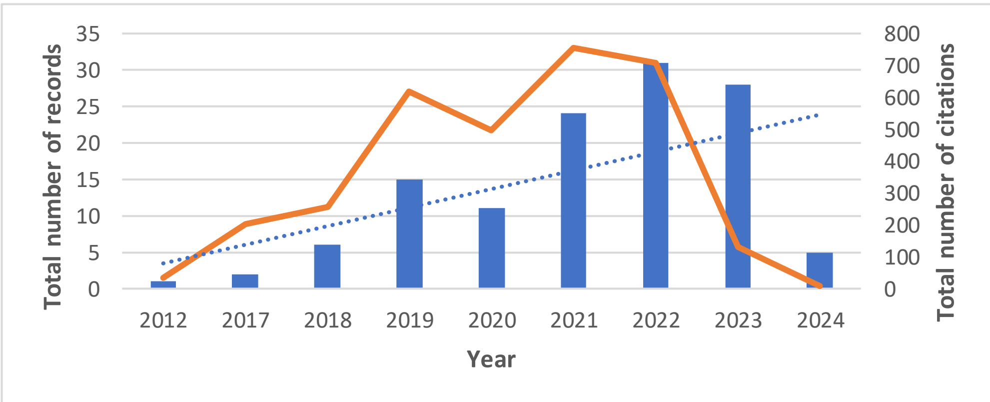

Figure 2 Number of publications and citations per year

3.2. Authors' influence

The top 10 most cited authors are depicted in Figure 3. With 381 citations, Klumpp, Matthias is the most referenced author. With 269 citations, Tran-Dang, H. is rated second, followed by Bruno, Giorgio; Giusti, Riccardo; Manerba, Daniele; Tadei, Roberto with 192 citations each. Klumpp, M authored three journal articles relevant to the scope of this SLR. The most highly cited among them is a solo-authored paper, which introduces a comprehensive multidimensional conceptual framework. This framework aims to distinguish between high and low-performing human-artificial collaboration systems in logistics, aiding in investment decision-making (Klumpp, 2018). The other two papers are co-authored with Hesenius, M; Meyer, O; Ruiner, C; Gruhn,V, and Zijm, H respectively. Tran-Dang, H closely follows with three articles, all co-authored with Kim, D. Additionally, two of these articles feature co-authors Krommenacker, N and Charpentier, P. These articles focus on the IOT and digitization era for PI.

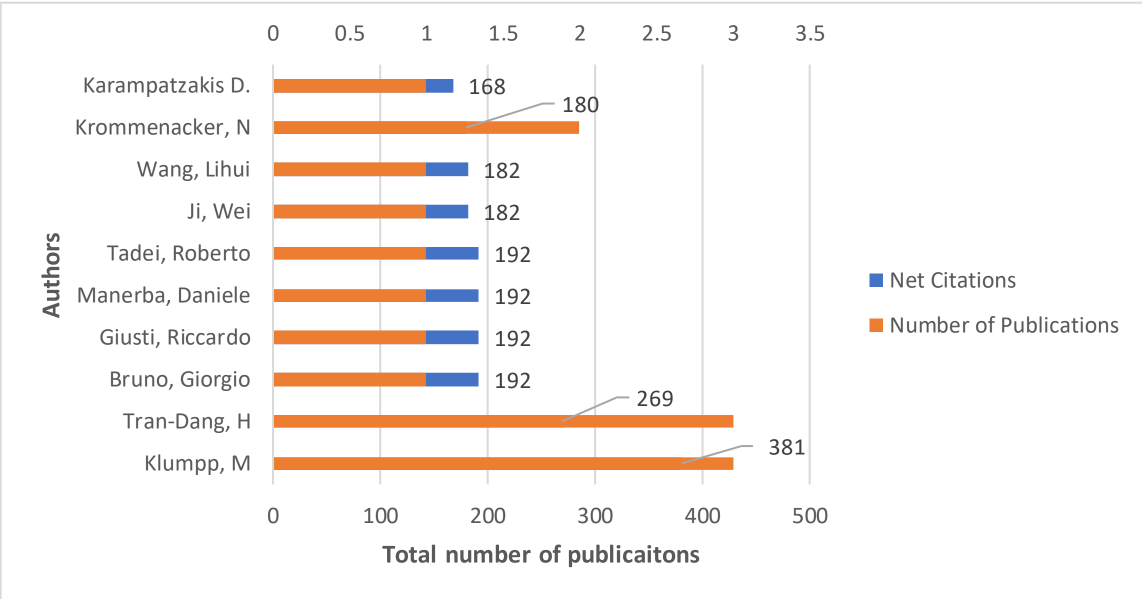

Figure 3

3.3. Keyword analysis

Keywords are nouns or phrases that represent the core content of a piece of literature. The existence of two terms in the same scientific article is referred to as co-occurrence. This study involves a total of 379 keywords. The co-occurrence threshold of keywords was set at 3. As a result, 36 items were inserted into visualization to demonstrate keywords co-occurrence (see Figure 4).

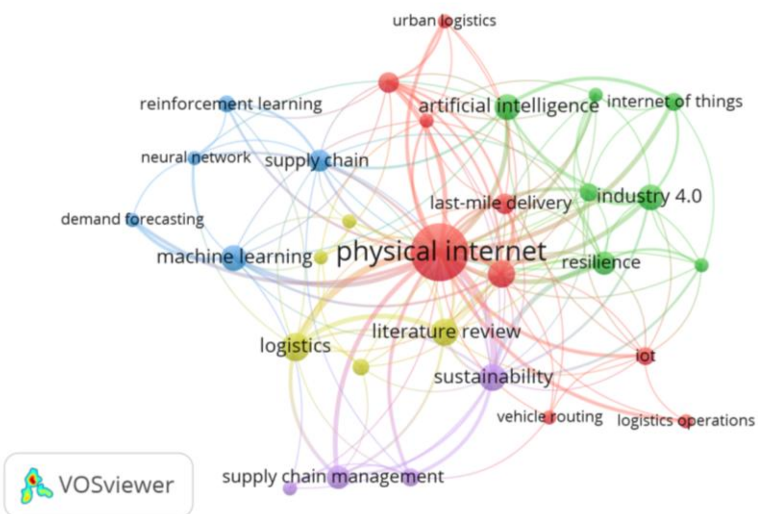

Figure 4

The data is segmented into five distinct clusters, each highlighting specific themes:

- Logistics Operations (red): Encompassing keywords such as “city logistics,” “last-mile delivery,” “optimization,” and “vehicle routing,” this cluster emphasizes the operational facets of logistics.

- Cyber-Physical Systems (green): Including terms such as “artificial intelligence” and “internet of things,” this cluster underscores the fusion of digital and physical systems within logistics, epitomizing concepts such as “industry 4.0” and “digital twin.”
- Data Analytics (blue): Featuring keywords such as “machine learning” and “demand forecasting,” this cluster accentuates the role of data analytics and machine learning techniques in enhancing logistical processes.
- Research trends and Methodology (yellow): Comprising terms such as “literature review” and “bibliometric analysis,” this cluster delves into the meta-level examination of logistics research methodologies and trends (“digitalization” and “omnichannel logistics”).
- Sustainability and Management (purple): Enriched with terms such as “sustainability” and “supply chain management,” this cluster centers on sustainable practices and management strategies within logistics operations.

The keyword trends for AI in PI showcase a strong focus on emerging technologies such as IoT, cyber-physical systems, digital twin, and industry 4.0. Optimization and simulation techniques are also prominent, suggesting efforts to enhance efficiency. Sustainability and resilience keywords reflect a growing concern for sustainable practices, while terms such as machine learning indicate a shift towards data-driven approaches.

3.4. Publication themes and metrics

The publications cover a diverse range of focus areas including operations research, logistics, transportation, environmental sciences, sustainable development, and manufacturing (see Table 1). This diversity caters to different disciplines and interests within the broader field of production and logistics. Gathered records include academic journals (85), conferences (18), books (6), theses (3), and dissertations (5). While both CiteScore and Impact Factor are measures of a journal's influence, they may vary due to differences in calculation methods. For instance, Computers in Industry has a relatively high CiteScore (21) compared to its Impact Factor (10), suggesting it might have received a significant number of citations recently. Journals such as International Journal of Production Economics, Journal of Manufacturing Systems, Journal of Cleaner Production, and Computers in Industry have relatively **high impact factors and CiteScores**, indicating their significance and influence in their respective fields. Journals like International Journal of Production Economics, International Journal of Logistics Research and Applications, and Transportation Research Part E: Logistics and Transportation Review have **high citation counts**, suggesting they are frequently referenced in academic literature. Journals such as IEEE Internet of Things Journal and The International Journal of Advanced Manufacturing Technology focus on niche areas such as IoT and advanced manufacturing respectively.

4 Content analysis

Literature reviews (LRs): The LR records are condensed into three thematic clusters relevant to AI and the PI, highlighting their application and impact on logistics and supply chain management (L&SCM). The first cluster focuses on the PI and digital transformation in logistics, exploring innovative frameworks, deployment strategies, and their role in enhancing resilience and sustainability (L’Hermitte et al., 2018; Tran-Dang & Kim, 2019; Tran-Dang et al., 2020; Pan et al., 2021; Fahim et al., 2021; Safwen et al., 2021; Chargui et al. 2022). The second cluster centers on the integration of AI and advanced technologies in logistics, including applications of machine learning, blockchain, drones, and the Internet of Things, showcasing the evolution towards smarter, data-driven logistics solutions (Giusti et al., 2019; Bekrar et al., 2021; Soebandrija et al., 2018; Kantasa-Ard et al., 2019; Nikitas et al., 2020; Taniguchi et al., 2020; Barykin et al, 2023; Agnusdei et al., 2022). The third cluster addresses digital twins, omnichannel strategies, and warehouse management, emphasizing the role of digital tools in optimizing supply chain operations, enhancing warehouse efficiency, and supporting sustainable urban logistics (Sampaio et al., 2019; Duong et al., 2022; Yu et al., 2022; Ferrari et al., 2022; Hübner et al., 2022; Bélanger et al., 2023;). These clusters illustrate the convergence of AI and the PI in transforming contemporary logistics practices and paving the way for future advancements.

Table 1 Summary of academic sources (top eleven based on publication counts)

Source	Impact factor	CiteScore	Count	Focus	Type	Citations
International Journal of Production Economics	12	19	7	Operations Research & Management Science	Journal	286
IFAC-PapersOnLine		1.8	7	Electrical and Electronic Engineering, Computational Mechanics, Control and Systems Engineering	Journal	80
International Physical Internet Conference			6	Interconnected freight transport, logistics and supply networks	Conference	7
International Journal of Production Research	9.2	18	5	Manufacturing, Industrial Engineering, Operations Research and Management Science	Journal	107
Dissertation			5		Dissertation	1
Transportation Research Procedia		3.2	4	Social science area of transportation research	Journal	114
International Journal of Logistics Research and Applications	6.6	10	3	Logistics And Supply Chain Management	Journal	280
Transportation Research Part E: Logistics and Transportation Review	10.6	15	3	Logistics and Transportation	Journal	272
Sustainability	3.9	5.8	3	Sustainability	Journal	117
Computers & Industrial Engineering	7.9	12	3	Computer Science, Interdisciplinary Applications	Journal	71

Conceptual frameworks: Within frameworks, two primary clusters emerge. The first cluster focuses on the PI and hyperconnected logistics systems, exploring frameworks and strategies for integrating the PI into city logistics, passenger air transport, last-mile delivery, and critical-product distribution (Kubek & Więcek, 2019; Suryavanshi, 2022; Kayikci et al., 2023). This cluster highlights the potential for enhanced performance, sustainability, and autonomous operations in logistics networks (Suryavanshi, 2020; Shaikh et al., 2023). The second cluster centers on the application of AI and automation in logistics and supply chain management, addressing human reactions, collaboration requirements, and the design of smart product-service systems. It includes conceptual frameworks for automation, innovative mobility concepts for smart cities, and the use of generative AI to optimize supply chain operations (Klumpp et al., 2018; Pan et al., 2019; Guo et al., 2021; Jackson et al., 2024).

PI problems and AI solutions: In the realm of PI logistics, addressing diverse challenges demands a spectrum of AI solutions. Leveraging Proximal Policy Optimization (PPO), joint replenishment problems can be efficiently managed through adaptive policy learning. Long Short-Term Memory Recurrent Neural Networks (LSTM RNNs) may prove indispensable for precise demand forecasting, ensuring optimized inventory management. Reinforcement Learning (RL) emerges as a versatile tool for dynamic tasks such as platoon organization, container and delivery trading, and self-organization, offering adaptable decision-making in real-time scenarios. Machine Learning (ML) techniques excel in joint order fulfillment and replenishment, harnessing historical data for predictive analytics. Meanwhile, the intricate dynamics of location service areas find resolution through a combination of Deep Learning (DL) models, metaheuristics, and active learning, enabling spatial optimization with efficiency and accuracy. For tackling the classic Vehicle Routing Problem (VRP), a plethora of AI approaches including AI algorithms, metaheuristics, and self-organizing systems offer diverse avenues for optimization.

5 Discussion

The outcomes derived from employing SLR are consolidated in this section through the development of a conceptual framework (akin to Cortes-Murcia et al., 2022). This framework serves to address RQ1-RQ3 by visually illustrating how AI technologies address PI problems. It does so by depicting PI components along the rows and AI solutions along the columns, providing a graphical representation of their alignment (see Figure 5).

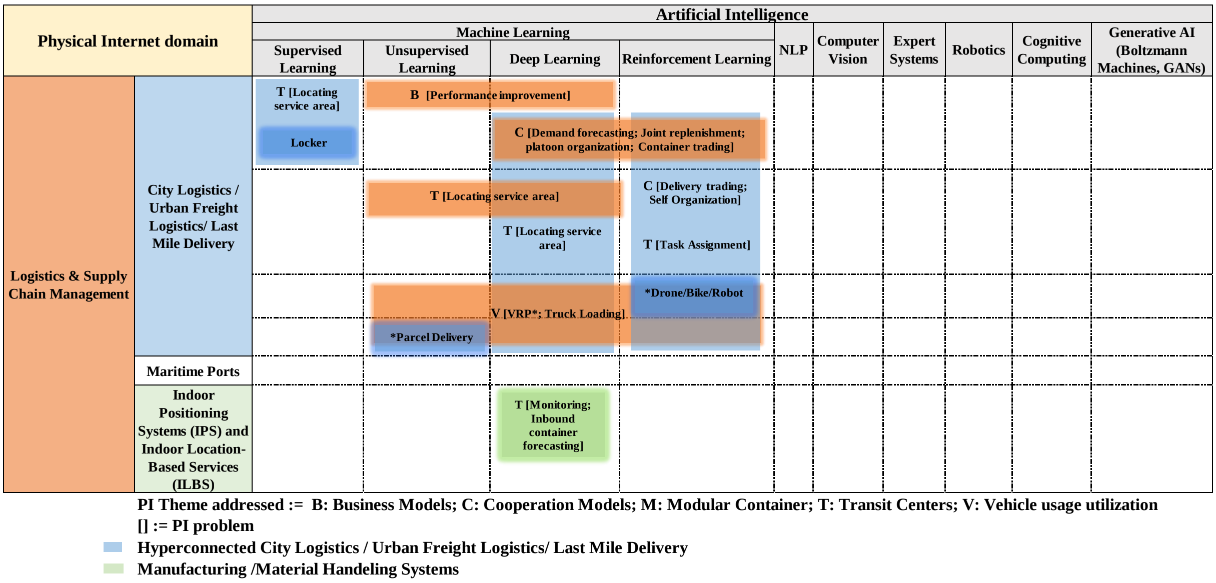

Figure 5 AI in PI conceptual framework

RQ1: What are the most prevalent AI methods?

In the context of the PI, the applications of AI methods are diverse. RL stands out as a prevalent technique, offering adaptive decision-making capabilities for tasks such as platoon organization (Puskas et al., 2020), container and delivery trading (Guo et al., 2021), and self-organization within PI networks. Alongside RL, metaheuristic algorithms play a significant role in optimizing various aspects of PI operations, from vehicle routing to location service area optimization and performance improvement (Meliani et al., 2019; Che et al., 2022). DL methods, with their ability to process vast amounts of data and extract intricate patterns, contribute to tasks such as monitoring (Liu et al., 2022), forecasting (Helmi et al, 2022), and optimizing truck loading (Bai et al., 2020) processes within PI systems. Additionally, ML techniques find utility in joint order fulfillment and replenishment (Leung et al., 2022), as well as active learning approaches within PI networks.

RQ2: What are some PI-Theme-specific AI enhancements?

Across different themes, provided by Treiblmaier et al. (2020), modular containers, vehicle usage utilization, transit centers, data exchange, cooperation models, legal framework, and business models, a range of challenges are identified. Within the context of modular containers, AI-driven solutions are instrumental in addressing challenges such as container packing and bin-packing, potentially revolutionizing container optimization processes. In terms of vehicle usage utilization, AI technologies such as deep learning algorithms and more traditional metaheuristics such as Tabu Search and simulated annealing/self-organization/solver algorithms (which can easily be converted into a RL setting; see Powell, 2011 & 2022), contribute to optimizing heterogeneous fleet vehicle routing, truck loading, and co-modality, enhancing resource efficiency, and reducing transportation costs. Transit centers, pivotal nodes in the PI network, benefit from AI advancements in location service area optimization, monitoring, and joint order fulfillment and replenishment, facilitated by techniques such as deep learning, machine learning, and metaheuristics. Cooperation models are enhanced by AI techniques such as reinforcement learning, which optimize processes such as platoon organization, container trading, and delivery trading, promoting smoother interactions and resource allocation among stakeholders. Furthermore, AI applications in legal frameworks and business models offer potential for innovative solutions, such as AI-driven route optimization and delivery scheduling, demand forecasting, and adoption modeling, ultimately enabling more agile and adaptive PI systems. The applications of AI in areas such as data exchange, legal frameworks and business models (Ji et al., 2023) indicate the need for further exploration and development in these domains.

RQ3: What are the potential AI methods for PI?

AI technologies such as NLP, Computer Vision, Expert Systems, Robotics, Cognitive Computing, and Generative AI hold significant potential for enhancing PI systems across various dimensions. NLP can facilitate seamless communication and information exchange within PI networks, enabling efficient coordination and decision-making. Computer Vision can aid in the automation of tasks such as object recognition and tracking, enhancing the efficiency of processes such as inventory management and package handling. Expert Systems can provide intelligent decision support, offering recommendations and insights based on complex data analysis and domain expertise. Robotics technologies can enable automation and autonomy in tasks ranging from warehouse operations to last-mile delivery, optimizing resource utilization and reducing operational costs. Cognitive Computing can enhance PI systems' adaptability and responsiveness by leveraging advanced reasoning and learning capabilities to interpret and respond to dynamic environmental conditions. Generative AI techniques such as Boltzmann Machines and Generative Adversarial Networks (GANs) can generate synthetic data for simulation and optimization purposes, facilitating scenario testing and decision-making in PI planning and operations.

AI can significantly enhance the implementation of the PI roadmap developed by the SENSE project (Ballot et al., 2020). By transforming Logistics Nodes into PI Nodes, AI can automate sorting and storage, optimize modular load unit use, and enable real-time tracking and digital service access. In logistics networks, AI-driven predictive analytics can optimize routes and schedules, while IoT sensors monitor goods in transit, ensuring timely and reliable deliveries. AI can integrate individual logistics networks by analyzing data to consolidate shipments and maximize transport asset use. For access and adoption, AI can provide simulation models and virtual assistants to support stakeholders in transitioning to PI concepts. In governance, AI can automate rule enforcement and enhance transparency through blockchain technology, ensuring a secure and compliant logistics environment.

6 Conclusion

The SLR presented here offers an assessment of recent studies (2010-2024), accompanied by an analytical discourse, synthesis framework, and suggestions for future research directions, highlighting the numerous contributions that AI brings to PI.

The potential benefits of AI for adopting the PI are substantial and multifaceted. AI can process and analyze vast amounts of data from numerous IoT devices, enabling seamless integration and real-time tracking across the supply chain(s), thereby enhancing transparency and efficiency. Predictive analytics employing AI and machine learning models can significantly improve demand forecasting, leading to optimized inventory management, reduced waste, and increased customer satisfaction. By automating routine tasks and providing advanced decision support amid complex logistics operations, AI markedly can boost the efficiency and resilience of the PI.

In conclusion, the exploration of the conceptual framework surrounding PI problems and AI solutions offers profound insights into the evolving landscape of logistics and supply chain management. Through this literature review, we have delved into the complexities of organizational challenges within the context of the PI, highlighting the diverse array of issues organizations face in modern logistics. Concurrently, the integration of AI solutions presents promising avenues for addressing these challenges with greater efficiency and effectiveness. By understanding the interplay between theory and practical applications in organizational settings, we uncover opportunities for innovation and optimization within the logistics and supply chain domain. As organizations continue to navigate this dynamic environment, the synergy between conceptual understanding and technological innovation will undoubtedly play a pivotal role in driving organizational success and resilience in the face of evolving challenges.

Future research must improve decision-making methods within the PI context. AI can enhance decision-making by leveraging real-time data, integrating diverse data sources, AI-enabled tools, and simulation models. Real-time information from IoT sensors and GPS tracking allows immediate operational adjustments, optimizing efficiency and responsiveness. AI's ability to integrate data across the logistics network provides a comprehensive supply chain view, revealing patterns and insights that lead to more informed decisions. AI algorithms can predict demand fluctuations, optimize routing, and anticipate disruptions, enhancing resilience and flexibility. AI-driven tools and simulation models help stakeholders evaluate strategies, ensuring efficient, adaptable logistics operations essential for the successful implementation of the Physical Internet.

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Gaia-X as an Enabler to Shape Interconnected Logistics in Europe

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Abstract: *While the interest in the research field of the Physical Internet (PI) has been growing over the last decades and simulations have been able to show significant efficiency potentials resulting in environmental and cost advantages, real-world applications are still in their early stages. This might be driven by the fact that establishing a PI system unlocks its full potential particularly when run at scale across company borders with many participants. Establishing such a system comes with its own set of challenges, not only on a technical level but also in regards of business and policy-related challenges. However, Gaia-X is a European initiative to create an open data infrastructure with strong emphasis on interoperability, trust and sovereignty. It promises to enable trusted decentralized digital ecosystems that allow participants to collaborate under a mutual set of policies and rules. With the Gaia-X specification released, we aim to investigate if and how Gaia-X fits as an enabler to interconnected logistics in Europe. The contribution of this paper is threefold. Firstly, we describe requirements for an open, cross-company PI based on use case diagrams. Secondly, we examine how the Gaia-X principles and components could be used to meet these requirements. Finally, we explore implications to potential business models.*

Keywords: *Physical Internet, Gaia-X 4 Future Mobility, Open Standard, PI Use Cases in Europe, Green Logistics*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☐ PI Networks, ☐ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☒ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

Targeted Delivery Mode-s*: ☒ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation*

1 Introduction

The Physical Internet (PI) provides a promising approach to significantly increase the efficiency and resilience of freight transportation. The increase in efficiency also reduces traffic while transport requirements remain the same. Hence, the PI concept makes a valuable contribution to protecting our environment, i.e. achieving the Paris Climate Agreement (ITF, 2018, 2021). In Europe, 77 % of freight transport takes place on the road (Eurostat, 2023), which means that vehicles on the road will play a key role. Despite expected potentials of approximately 30 % reduction in congestion, emissions and energy consumption from the transport sector (alice-etp, 2020), the implementation of this concept is still in its infancy. The European cloud initiative Gaia-X might be an enabler for the Physical Internet applications. In this paper, Gaia-X is considered to be both, a potential enabler for the implementation of PI use cases in Europe and a basis for further business models.

The remainder of the paper is structured as follows: In the second chapter we give an overview of the latest developments in regards of road-based PI (RBPI) concepts as well as a summary of Gaia-X and its adoption in the PI. In the third chapter we describe requirements of a cross-company PI with focus on private individual motor vehicles based on use case diagrams. We investigate if and how these requirements can be met by the Gaia-X principles in the fourth chapter. We summarize our findings and give an outlook into implications of potential business models in federated ecosystems in the fifth chapter.

2 Background & Related Work

The aim of the PI is to significantly improve the robustness and efficiency of freight transportation. Almost 77 % of transportation takes place on roads (Eurostat, 2023), of which 37 % are empty runs (KBA, 2023) and furthermore a large proportion are underutilized runs. In analogy to the Data Internet, the concept of the PI recommends a decentral approach for the routing of freight or freight components. For the road-based Physical Internet (RBPI) PI transporters are seen in the routing role (Kaup et al., 2020). The negotiation process for the transfer of goods is to be carried out either via distributed representatives of the PI transporters in kind of agents in a cloud system, which was designed in a reference model by Kaup et al. (2021) or a reinforcement learning approach based on vehicle-to-vehicle (V2V) routing (Lu et al., 2022).

A prototype implementation of the RBPI is aimed by the publicly funded project *Requirements and Application of Gaia-X in the Edge-Device Automobile* (Gaia-X 4 AGEDA[1]). This project focuses the design of an agreed and standardized interface for vehicles as edge devices to connect to a cloud infrastructure, in particular Gaia-X. Two major use cases have emerged in this project: firstly, *Collective Vision*, including the storage and consolidation of camera and sensor data from participating vehicles within Gaia-X and, as a second use case, *Green Logistics / Physical Internet*, using the RBPI approach based on Gaia-X. The motivation of Academia in the PI research field is primary to foster the intermodality and synchromodality of PI-Transporters, i.e. switching between different modes of transport such as road, rail, water or air (Lemmens et al., 2019). As an integral part of the PI-Roadmap, the aim of the AGEDA project is to design realistic solutions within the most important mode of transport, road, together with a practitioner community consisting of OEMs, suppliers and service providers in the transport sector. Outcome artifacts such as use case descriptions will be discussed both within and outside the project with experts and transportation scientists. One of these evaluation steps is the discussion of results at international conferences. As a next step, MVP’s and prototypes will be developed, which will be tested together with support of the Gaia-X infrastructure.

Originally introduced in October 2019 (BMWi, 2019) by members of the government of France and Germany, Gaia-X is an approach that aims to ’create the next generation of data infrastructure for Europe‘ (BMWK, 2024). While Gaia-X has since been transformed into a non-profit organization based in Belgium (the Gaia-X European Association for Data and Cloud AISBL[2]), community-driven hubs and cross-sectoral research projects work to transfer the concept into real-world applications. Gaia-X focuses not only on the underlying technical infrastructure but also takes transparency, legal compliance and interoperability of services into account (Federal Foreign Office, 2020). Although actual implementations are only starting to

[1] https://www.gaiax4ageda.de/
[2] https://gaia-x.eu/who-we-are/association/

become readily available[3], Gaia-X specifications are updated regularly[4]. In contrast to other standardization approaches, Gaia-X mostly refrains from dictating concrete technologies, making it both independent from specific implementations but also harder to grasp as there are multiple concurrent implementation approaches that are not fully compatible with each other. Although Gaia-X has been explored in greater detail over the last years in various aspects, its potential for the PI has not been analyzed widely.

Grefen et al. (2018) mention the Industrial Data Space (IDS; arguably a precursor of Gaia-X) as a potential basis for logistic processes that might enable federated platforms. Their work focuses on an outlook for future logistics and does not get into more detail on how such a system would meet PI specific requirements.

Dalmolen et al. (2018) describe the IDS and blockchain technology as enabler for trust in a multi-tenant logistic system. They spotlight the architecture of the IDS and roles of the individual components but keep their focus on the trust aspect and do not provide closer insights on how these technologies would benefit other PI requirements.

Hofman and Dalmolen (2019) continue their work by discussing the IDS with its communication protocol as potential enablers for interoperable platform services that would allow the implementation of the PI. While highlighting the need for such standardized platform services and pointing out how these services might be established, the benefits of the IDS for the PI are mostly out of scope of their research.

Klukas et al. (2021) mention Gaia-X in their report on the research project I²PANEMA but keep their focus on an Internet of Things solution for ports without getting into specifics on how Gaia-X mechanisms enable the use cases they present.

Hofman (2023) proposes a protocol stack to build a mobility data space that addresses technological as well as governance and legal aspects. While the paper gives valuable insights into high-level requirements for establishing a dataspace for the PI, use case specific requirements are out of scope.

In conclusion, previous research has mainly portrayed the IDS as an enabler for the PI but kept its focus on the trust aspect without exploring other potential benefits in greater detail. Gaia-X has briefly been mentioned before but a more detailed analysis is required to assess the suitability of Gaia-X for the PI. Therefore, we aim to investigate if and how Gaia-X might be used to establish a PI with a cross-company horizon in the following chapters.

3 Requirements of a Cross-Company Physical Internet

In this chapter, requirements for the underlying technology are established that enable a cross-company PI. The requirements are identified by means of use case modelling. The use case diagrams presented originate from the research project AGEDA. While the use case diagrams are mainly specified for an automotive application due to the nature of the project, a more generic approach with multimodal transport could be achieved with minor adjustments. Therefore, we see the use case diagrams suitable for extracting requirements.

We imagine the PI to be an open system in which multiple parties can provide their own implementations or instances of services, resulting in a cross-company PI. As such, **Trust** among the actors in the system is required (as discussed in Dalmolen et al. (2018)) and can be gained by secure **Identification & Authentication**. To ensure no one actor can take control

[3] https://dih.telekom.com/en/gaia-x-summit-shaping-trustful-digital-ecosystems-
[4] https://gaia-x.eu/media/publications/

over the system, **Federation of Decentralized Services** can safeguard from abuse, further strengthening the trust aspect. Finally, **Openness** to new actors is required under the premise that strictly **Enforced Policies** exist that ensure all actors follow rules decided on.

The use case diagram for the first use case is depicted in Figure 1. In *Parcel Drop-Off*, a sender is first selecting a provider that offers the services required for sending a parcel. As such, a form of **Service Discovery** with a mechanism to select a service provider is required. After selecting a provider, the parcel is registered at a *Registration GUI*. The parcel description might contain properties specifying the mode of transport that can be matched to the capabilities of transport vehicles, e. g. if cooled transport is mandatory. After registration, a trace entry for the parcel is logged. Therefore, **Immutable Logging** is required to achieve trustful tracing of parcel movements. Using the *Cloud Parcel Service*, the sender is then choosing a drop-off location, in this case a motor vehicle. This might be a parked vehicle without the driver at site. To be able to drop-off the parcel, the sender needs to unlock and open the vehicle. This permission is given by the *Cloud Parcel Service*. Since the permission should only be valid for this specific drop-off, this indicates the requirement for **Conditional Authorization**, preferable based on the trust mechanisms already established. The *Vehicle Parcel Service* running in the vehicle identifies and traces the parcel, thus concluding the *Parcel Drop-Off* use case.

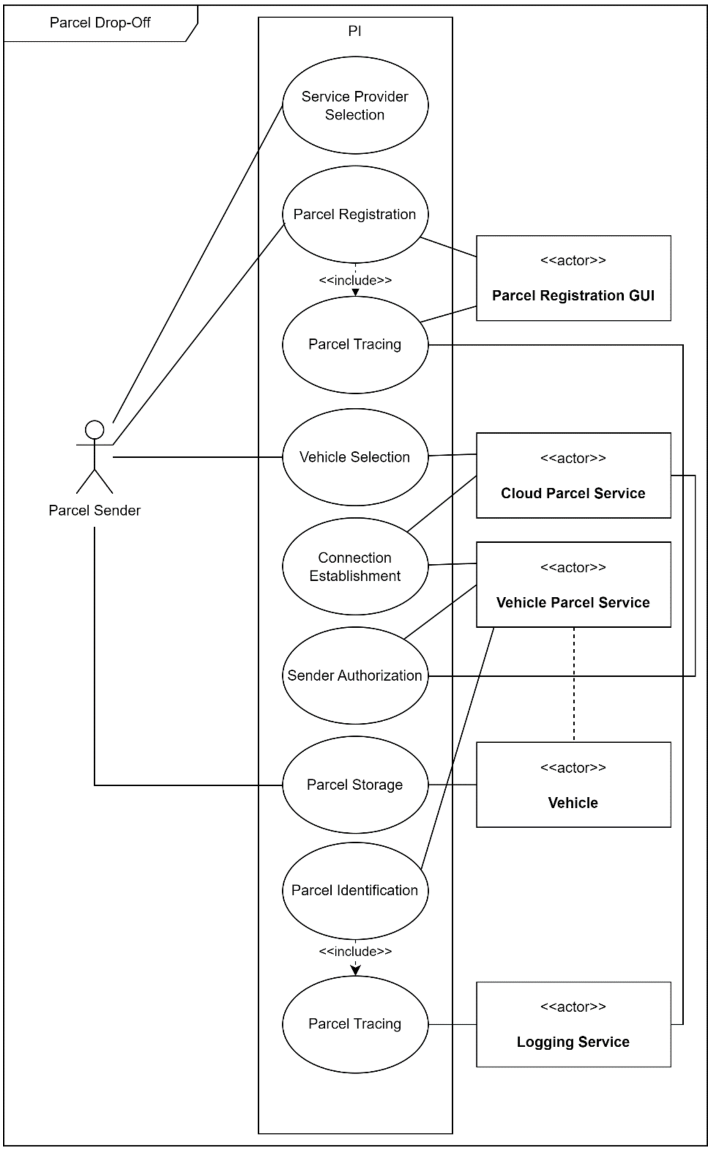

Figure 1: Use Case Diagram 'Parcel Drop-Off'

The use case diagram for the use case *Rendezvous* is depicted in Figure 2. In this diagram, the handover of a parcel from one vehicle to another is visualized. As a prerequisite, vehicles – represented by a *Vehicle Agent* – are periodically sharing their planned routes and vehicle characteristics with the *Infrastructure Hub* and receive potential transfer points in return. If the handover of a parcel becomes necessary, e. g. because of diverging routes of the vehicle and parcel, the *Vehicle Agent* searches for a potential rendezvous vehicle and initiates a negotiation with the corresponding *Vehicle Agent* to determine a possible location and time for the parcel handover. If both *Vehicle Agents* come to an agreement, this is also traced at the *Logging Service*. The negotiation process implies the requirement of a **Contracting Mechanism**. After agreeing on the terms, both vehicles meet, transfer the parcel and ensure the handover is traced accordingly, concluding the use case.

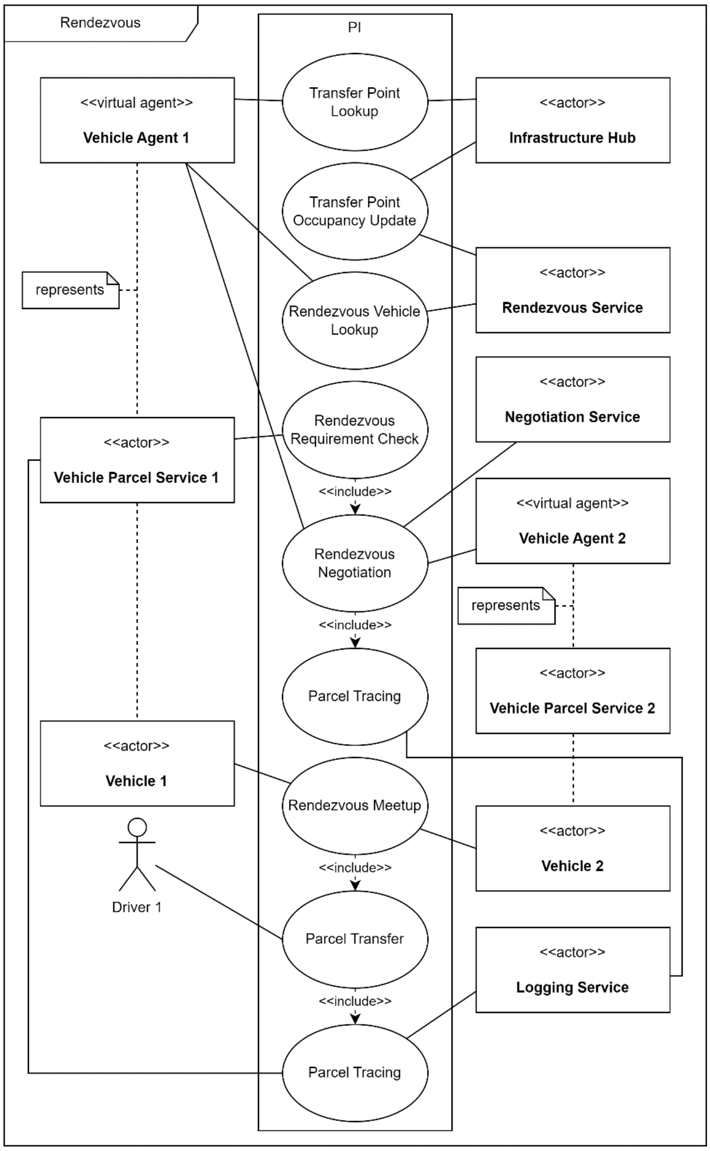

Figure 2: Use Case Diagram 'Rendezvous'

Based on the use case diagrams, we have identified the following nine requirements for the underlying technology that enables a cross-company PI: I. Trust, II. Identification & Authentication, III. Federation of Decentralized Services, IV. Openness, V. Enforced Policies, VI. Service Discovery, VII. Immutable Logging, VIII. Conditional Authorization and IX. Contracting Mechanism.

4 PI Requirements alignment to Gaia-X Principles

After having identified requirements for the implementation of the cross-company PI in the previous chapter, we assess if Gaia-X can fulfill the requirements in this chapter.

The Gaia-X documentation is publicly available in multiple documents.[5] The *Trust Framework* describes how an actor (called *participant*) can be part of the system by defining a set of rules each participant has to follow. Participants must provide a *self-description* (also called *Gaia-X Credential*) following the *W3C Verifiable Credentials Data Model*.[6] The *Trust Framework* specifies minimum requirements for **Identification** of participants, for example using extended validity certificates. The information is verified and signed and can be verified by participants using the *Notarization service*.

Data spaces are built on top (see Figure 3) of the *Trust Framework* and serve as a 'federated, open infrastructure for sovereign data sharing based on common policies, rules, and standards' (Reiberg et al., 2022). In the data spaces *participants* use their *Gaia-X Credentials* to provide and consume data from services. These services are published in a Gaia-X *Federated Catalogue* using *self-descriptions*. Since the *Federated Catalogue* can be queried, it provides capabilities for **Service Discovery**. Using *self-descriptions* serves the additional benefit of allowing consumers to verify that services follow policies by analyzing the attributes of the *self-descriptions*. For example, a policy might dictate that only services provided by participants who follow information security standards might be used. Participants could include their ISO 27001 certification as a claim in their *self-description* and have that claim signed. The consumer would then be able to check if the provider conforms to the policy by analyzing the *self-description*. Therefore, using *self-descriptions* fulfills the requirement of **Enforced Policies**. Since the attributes of *self-description*s required for compliance may be extended following domain specific rules, **Trust** can be achieved by defining, signing and verifying them.

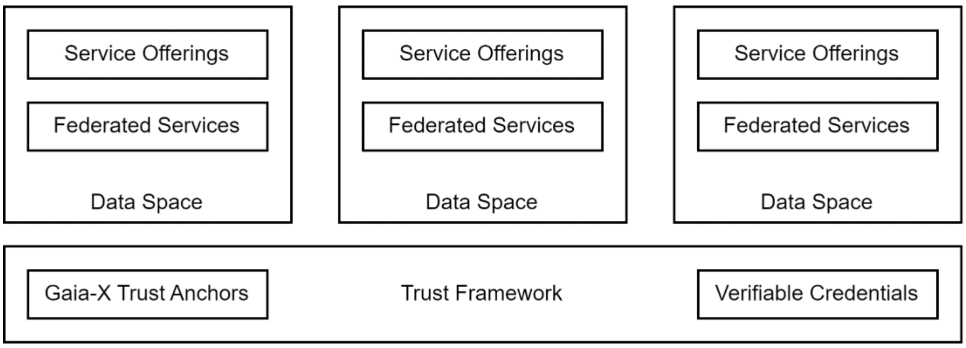

Figure 3: Gaia-X Trust Framework and Data Spaces

Since data spaces are federated by definition and meant to be interoperable, the requirement of a **Federation of Decentralized Services** is fulfilled. To achieve interoperability between service providers, attributes that define interface compatibility may be used. Reiberg et al. (2022) also mention **Openness** as a common concept of data spaces. While an open system allows new participants to join a data space, participants still maintain their choice of which other participants they want to interact with. Using policies based on the *Gaia-X credentials* as described ensures that **Trust** can be preserved even in open ecosystems.

Besides the catalog and trust components, Gaia-X also defines *Data Exchange Services* that allow negotiation and contracting between participants. While this fulfills the requirement for

[5] https://docs.gaia-x.eu/
[6] https://www.w3.org/TR/vc-data-model/

Contracting, it is important to note that these services are to be realized by each participant while the ecosystem may play a supporting role. Therefore, negotiating a contract is mainly to be implemented on the application level. Since agreeing on policies is part of the negotiation process, **Conditional Authorization** might be arranged. Mapped to the use case, this would provide the means to restrict the authorization for unlocking a vehicle to a short time frame.

As described in the Data Exchange Service Specifications, part of a contract might be the notarization and logging of the agreement in a federated *Data Product Usage Contract Store*, which realizes the requirement for **Immutable Logging**. While the Gaia-X specifications do not provide further details on how the contract store is to be implemented in order to guarantee immutable logging, this might be realized using blockchain technology as described in Dalmolen et al. (2018).

An overview of the participants and components that are part of a data exchange in a Gaia-X data space is given in Figure 4.

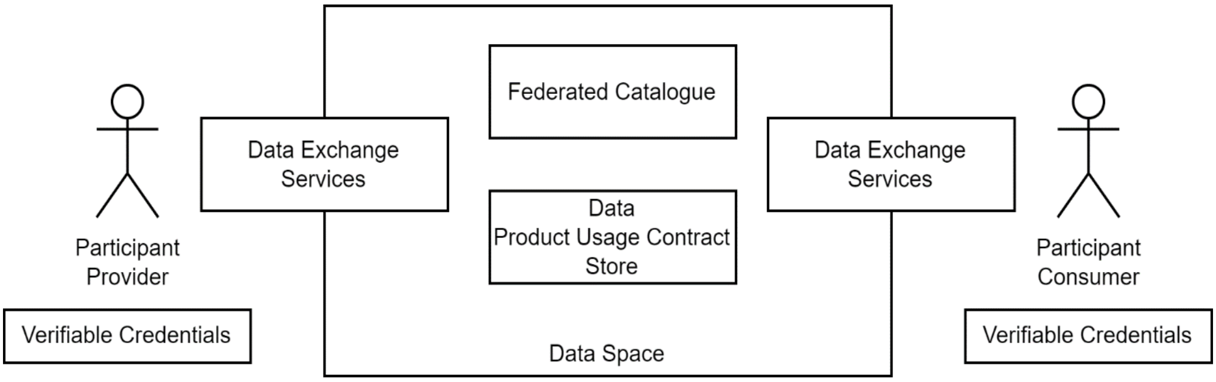

Figure 4: Participants in a Data Space

In conclusion, we found that Gaia-X addresses each of the identified requirements for the implementation of a cross-company PI. While the level of detail of the Gaia-X specifications leaves room for interpretation and the use cases presented are not all-encompassing and therefore additional requirements for underlying systems might exist, Gaia-X seems suitable for the implementation of the PI applications. While Gaia-X provides principles meeting the requirements as described, most of the logic for the use cases would still need to be developed in PI-specific components on the application level.

5 Conclusion & Outlook

The PI has the potential to greatly reduce inefficiencies in current freight transport when building a system in which many actors can participate. As we have shown, these actors have requirements for such a system, particularly in regards of trust. Gaia-X is a European use case independent initiative that specifies the building blocks for setting up open, distributed data spaces that provide mechanisms for gaining trust in automated fashion. The research project AGEDA aims to bring Gaia-X to the edge device automobile. Applying the Gaia-X principles then available in vehicles provides the opportunity to implement a system that meets the requirements of PI actors we identified based on use case diagrams. An interim alignment with concepts of other projects, i.e. of reconfiguration mechanism, has already taken place (Stötzner et al., 2024).

While we have explored the fit of Gaia-X to the PI from a technical viewpoint, participation in open data spaces has implications for intermodal mobility concepts as well. Understanding and addressing the complexity of these concepts is crucial for shaping interconnected logistics in Europe, particularly from an innovation management perspective. These concepts require careful consideration of the interests of various stakeholder and shareholder groups. Traditional business model modeling techniques often focus on direct 1:1 relationships between a solution provider and a specific target group, neglecting the diversity and interdependence of actors within the ecosystem and leading to a limited perspective on potential business models.

In a systems context, the modeling of use cases refers to a structured procedure that the system undertakes to generate a tangible and beneficial effect for involved entities. Standard practices for representing use cases typically involve visual diagrams, such as those prescribed by the ISO/IEC 19505 Unified Modeling Language (UML). Usländer and Batz (2018) note while these visual depictions serve as helpful tools for outlining system processes, their utility is limited without accompanying descriptive text that clarifies the diagrams' intent. The absence of a standardized method for integrating textual explanations can render the interpretation of these processes arduous and imprecise. At this point, more advanced methods such as the modeling of sub-use cases are suitable to explicitly capture the semantic layer of service descriptions.

Moving beyond those sub-use case models, which typically only map the conceptual requirements of a specific business case into technical requirements through requirements engineering, is essential. This approach risks overlooking unknown or unconsidered target groups, potentially resulting in a service offering that, based on specific data formats and ontologies, only partially meets the requirements of other domains.

To overcome this challenge, the particular interests of other domains must be integrated into the business analysis early on. This integration allows for the derivation of technical requirements that extend beyond purely technical aspects and support ambidextrous business models while including various target groups. Additionally, the interests of potential application groups in the further processing or refinement of data must be considered to achieve a critical mass in the usage of service offerings.

Furthermore, regulatory frameworks such as the Data Act must also be factored into the business modeling equation, ensuring compliance and capitalizing on the data governance structures they establish. The Data Act plays a crucial role by clarifying the usage rights of data holders as well as operators or users of devices. The potential for device operators to develop their own business models based on the data obtained must be considered early in the business modeling process (EU Regulation 2017/2394 and Directive 2020/1828). It is essential to resolve how participants in the presented Physical Internet use case, such as Parcel Senders, can be incentivized to share and process data. Additionally, under the provisions of the Data Act, manufacturers of vehicles are not granted the right to use and process data generated by the vehicle operator. To enable corresponding business models, the individual barriers to consent must be considered and overcome. This consideration promotes a mutually beneficial relationship, encourages the provision of data for further processing and refinement, and enables innovative Customer2Business business models.

In the realm of decentralized data economies, the potential for advanced business model techniques arises from their capacity to address the challenges of traditional approaches. Legacy models, limited by their focus on direct interactions and insufficiently detailed diagrams, fail to capture the complex interdependencies of modern, interconnected systems. The necessity for techniques that can interpret the semantic nuances of service descriptions and consider the broader spectrum of stakeholders is evident. By incorporating these advanced methodologies, business modeling can better accommodate the diverse needs of decentralized data economies, leading to more adaptable and encompassing service offerings.

In this context, Gaia-X can act as a catalyst to enable the shaping of interconnected logistics in Europe. By creating a secure and trustworthy data space, Gaia-X provides the foundation for the development and implementation of business models that consider the complexity and interdependence of the modern logistics landscape.

While this paper assessed the capabilities of Gaia-X as the underlying technology in the PI, future work needs to prototypically implement the system to demonstrate its capabilities while considering the current state of Gaia-X and elaborating on the border between Gaia-X and application-level components. Regarding the use case diagrams presented, more work needs to be done in further detailing interactions and expanding system capabilities. For example, the PI system should be capable of working in situations with limited network connectivity, i.e. using V2V communication. using V2V-communication. With respect to Gaia-X itself, we see additional work in further detailing the specifications as current implementations only provide limited interoperability. This might be a cornerstone for further establishing Gaia-X across the borders of Europe.

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The business model for federated data spaces to facilitate synchromodal logistics

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Abstract: *The logistics industry is undergoing significant transformations, where data sharing has become a critical factor for collaboration and sustainable logistics practices. This paper discusses the development of a taxonomy for business models of federated data spaces in the logistics industry, focusing on their application in synchromodal transport. This foundational study clarifies the operational and economic implications and serves as a basis for innovative business models. Our findings highlight the potential of federated data spaces for improving collaboration and value creation across logistics stakeholders. This study adds to the conversation on digital logistics by proposing business models that leverage data spaces for competitive advantage, implying that these are critical in transforming logistical operations into more efficient, adaptive, and financially viable systems.*

Keywords: *Business model, Data space, Physical Internet.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan:☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories),☐ Transportation Equipment, ☐ PI Networks, ☒ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☒ Access and Adoption, ☐ Governance.*

Targeted Delivery Mode-s*: ☒ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation*

1. Introduction

The connection between synchromodality and federated data spaces enhances dynamic freight transport planning, the ability to anticipate and manage interruptions or delays during transport, and the efficiency of rerouting or changing transportation modes (Pulido et al., 2024). It also opens avenues for innovative business models that have implications for different actors: those who aim to establish a data space and those who want to determine whether they should enter an existing data space (D'Hauwers et al., 2022). Business models can leverage data relationships among actors in synchromodality by developing new services, optimizing resource utilization, and creating value for stakeholders.

An important building block within a data space is aligning a heterogeneous set of inter-organizational partners who interact for a focal value proposition to materialize (Adner, 2016). From a business perspective, existing knowledge about value creation for the involved actors in the data space is limited. According to the IEDS project (2023), which surveyed 219 German companies, the most significant economic barrier to data sharing was the unclear benefit of data exchange, cited by 68% of companies. Additionally, 59% acknowledged the absence of a suitable business model. IDSA (2024)

A review of data space adoption within the IDSA (2024) radar reveals a diverse landscape. While various sectors are exploring and implementing data spaces, maturity levels differ significantly, with few projects reaching advanced deployment stages. Furthermore, a key challenge lies in aligning shared interests to develop business models. These models should prioritize strong governance, ensure seamless interoperability, and deliver value propositions for all participants. In this context, this research seeks to address the following critical question:

- What is the business model taxonomy for a data space for synchromodality?

By addressing the abovementioned question, this paper explores the business model related to the synchromodal data space concept from the perspective of the different roles involved: data consumers, data providers, and data space orchestrators.

2. Background on data spaces for transport

Data spaces are the foundational elements from which interested parties can obtain added services and solutions (Gawer, 2009, p. 54). The market is seeing an increase in the use of data spaces, which allow for the sharing of data and the provision of additional services and analytics (Schreieck et al., 2016; van den Broek & van Veenstra, 2018). Based on their intended use, data spaces can be implemented in two ways: federated, where data space operations are more decentralized, or centralized, where a single entity primarily manages data space.

The federated data space provides individual enterprises with tools to register and participate while concealing the complexities of data sharing (DTLF, 2022). Federated data space is a network of multiple platforms and a peer-to-peer solution utilized by the involved parties. According to Otto & Jarke, (2019) and Tiwana et al., (2010), it employs a "shared ownership" approach, meaning that it is not just applied in one central organization. As a result, a federated data space (DS) is scalable since it allows for involvement from other parties, even competitors. Sharing data with competitors can establish standards, while sharing data with suppliers helps optimize supply chains (De Prieëlle et al., 2020).

3. Business models landscape

A business model encompasses an organization's strategic framework to generate, deliver, and capture value in various social, economic, or other forms. In modern logistics, growing digitization and the significance of data sharing have influenced several business activities, resulting in new product and service offerings and creating new types of business relationships (FAN & ZHOU, 2011; Rachinger et al., 2019). Data space could serve as a solution, but adoption concerns such as unclear benefits, unclear cost structure, and a lack of trust in the system have been recognized as significant obstacles (Hutterer & Barbara, 2024). These obstacles indicate that to drive the development of such innovations and digital transformation, it is necessary to investigate new business model opportunities (Prem, 2015; Strandhagen et al., 2017). A shared understanding is also required to help scale the innovation element of the sector, allowing different players to explore new business opportunities.

There is extensive literature available on business models for big data (Katrakazas et al., 2019; Kim et al., 2016), centralized platforms (Abrahamsson et al., 2003), multi-sided platforms (Hoch & Brad, 2021), decentralized business ecosystem (Lage et al., 2022; Radonjic-Simic et al., 2017; Radonjic-Simic & Pfisterer, 2019; Tumasjan & Beutel, 2019; Wang et al., 2019) and open data ecosystems (Immonen et al., 2014; Kitsios et al., 2017). However, a specific focus on business models for data spaces facilitating freight transport remains underexplored, this highlights a research opportunity.

Establishing a taxonomy that encompasses different facets of business model development could be a fundamental step in this direction (Notteboom et al., 2017). The taxonomy seeks to identify the fundamental components of these business models and to provide a template for innovation based on the results of the study (Möller et al., 2020). Taxonomy for big data (Hartmann et al., 2016), data-driven business models (Dehnert et al., 2021; Engelbrecht et al., 2016; Möller et al., 2020), and data ecosystems (Gelhaar et al., 2021) are addressed well in the available academic literature. However, not much research has been done on defining the taxonomy for data space that supports synchromodal transport.

This approach can be instrumental in developing a taxonomy for business models in federated data spaces, facilitating synchromodal logistics by allowing for a comprehensive analysis of value creation, value delivery, value proposition and the scope of DS revenue (Lüdeke-Freund et al., 2019). These elements are crucial in ensuring that the business model not only meets the operational needs of synchromodal logistics, but also coincides with the logistics sector's overall goals of efficiency, sustainability, and innovation.

4. Designing the transport data spaces business taxonomy

Shared values and common interests are considered crucial success factors for data spaces (Vasilescu, 2023). However, despite existing sector-specific initiatives like the Catena-X Automotive Network (2022) and Fenix Network (2019), current practices and literature lack discussion on implementing data spaces for broader business value. This gap extends to finding shared interests that would enable expansion and the creation of a unified business framework across sectors. As this field is still relatively new, there's an opportunity to bridge this gap by either expanding existing initiatives or fostering collaboration to develop shared interests. We developed a taxonomy encompassing various components and characteristics to describe business models for data spaces in the freight transport sector based on Nickerson et al. (2013). This analysis captures the characteristics of data spaces relevant to the logistics industry, integrating them within the broader landscape of *digital business models* in data ecosystems. The framework enables stakeholders to consider a wide range of components and characteristics when designing or analyzing business models derived from data spaces in freight transport. It aligns with traditional transport concepts, such as multimodality and intermodality, and newly developed concepts, such as synchromodality.

The data used to develop the taxonomy is comprised of three main components. The first is a review of the literature related to business model taxonomies for data spaces; since this field is still in its early stages, we have included literature that pertains to data-driven and big data digital business models like IEDS project (2023), Schweihoff et al. (2022) or Wiener et al. (2020) as well as digital logistics business models such as Möller et al. (2019), Möller et al. (2020) or Mikl et al. (2021). The second component involves an examination of the current data spaces and the use cases developed for the logistics domain, as registered within the International Data Space Association (IDSA) radar. The third component is the concept of synchromodal freight transport, which ultimately is the intended application of the taxonomy. However, it is not restricted only to synchromodality.

4.1 Data Space Business Model Meta-characteristics

Following the taxonomy-building process, we determine the following meta-characteristics as the principal attribute from which all other relevant characteristics derive, ensuring coherence and relevance in the taxonomy (Nickerson et al., 2013). We aim to distinguish potential business models for data space for freight transport. The resulting taxonomy is presented in Figure 1 and is explained in the following subchapters.

4.1.1 Data Space Foundation

The **data space foundation** addresses the essential principles and frameworks that underpin the business model of data spaces. This is necessary as a data space is being developed, outlining the structure that a particular data space will follow. The first dimension concerns the nature of the data space's ***development***. The first type is the *Data Space,* which, according to IDSA (2024), is a decentralized system governed by rules that enable safe and reliable data exchange among its members, enabling trust and data sovereignty. It is implemented through one or more infrastructures and supports a variety of use cases. On the other hand, a *Use Case* is a specific scenario that demonstrates how the principles of data space are applied to share data to achieve a particular goal or outcome. The European strategy for data influences the ***perspective*** dimension, which aims to position Europe as a leading example of an economy empowered by data that makes better decisions—both in the private and the public sector (European Commission, 2020).

According to IDSA (2024), the ***maturity*** of each development is relevant to explaining the initiative framework, starting from an *Exploratory* level, which consists of identifying interest and feasibility within a specific domain by gathering stakeholders and discussing potential use cases. On the maximum levels, we find the *Operational,* where the data space is tested and launches its first market-ready use case, enabling data exchange and value creation, and *Scaling, where the* data space demonstrates market viability, sustainability, and growth, adapting to and attracting new members and use cases. Finally, the ***case pattern*** reflects the diverse motivations and goals driving ecosystem members to share data IDSA (2024).

4.1.2 Actor

The business models for a data ecosystem have implications for different actors: those who aim to establish a data space and those who want to determine whether they should enter an existing data space. Depending on their role, these actors may provide, receive data, or perform other activities (D'Hauwers et al., 2022). The **actor** element outlines the various stakeholders' roles within the data space, specifically focusing on the freight transport domain.

The ***Data Space (DS) roles*** are identified through an analysis of 64 use cases conducted by the IEDS project (2023). This approach provides an in-depth understanding of contemporary data-driven business models and ecosystems. The roles of the participants are closely related to ***Data Ownership***, which can be categorized as *Own Data*, *Derived Data with uncertain ownership*, or *Data owned by another entity* (Schweihoff et al., 2022). Regarding ***Transport Stakeholders***, this approach includes those in conventional hinterland transport, such as intermodality and the synchromodal stakeholder network. The latter encompasses the same actors but introduces additional roles, including the orchestrator role (Ceulemans et al., 2024) and roles related to software and technology (Pulido et al., 2024).

4.1.3 Value

The **value** dimension captures the essence of business models by representing the benefits and utilities generated by applications in data spaces. ***Value Creation*** refers to the key processes and resources (Mikl et al., 2021) the data space enables. The characteristics of this dimension were derived from the iteration of the data spaces development database in the logistics domain reported by IDSA (2024). These characteristics originate from the fundamental attributes of data spaces aiming to "enable the sovereign and self-determined exchange of data via a standardized connection across company boundaries" (Pettenpohl et al., 2022, p. 29).

	Dimension	Characteristics								E/N	Approach
DS Foundation	***Development***	*Data Space*	*Use Case* (1, 2, 3)							E	IDSA (2024)
DS Foundation	***Perspective***	*Private* (1, 2, 3)	*Public* (1)	*Mixed*						N	European Commission (2020)
DS Foundation	***Maturity***	*Exploratory*	*Preparatory*	*Implementation*	*Operational* (1, 2, 3)	*Scaling*				E	IDSA (2024)
DS Foundation	***Case Pattern***	*Shared Cost* (1, 2)	*Joint Innovation* (1, 2, 3)	*Shared Marketplace*	*Grater Community Good*					N	IDSA (2024)
Actor	***DS Roles***	*Service Provider*	*Data Trustee*	*Data-infrastructure provider* (1)	*App-Store Provider* (1)	*Data Provider* (2, 3)	*Data Consumer* (2, 3)	*Ecosystem Orchestrator* (1)	*Marketplace Operator*	N	IEDS project (2023)
Actor	***Data Ownership***	*Own Data* (2, 3)	*Derived data, ownership uncertain*	*Data owned by another entity* (1)						E	Schweihoff et al. (2022)
Actor	***Transport Stakeholder***	*Shipper* (2)	*Carrier* (3)	*Infrastructure Management*	*LSP*	*Authority*	*Terminal Operator*	*Orchestrator*	*Software and Technology* (1)	N	Ceulemans et al. (2024) Pulido et al. (2024)
Actor	***Stakeholder engagement***	*Data Sharing Agreements* (1, 2, 3)	*Partnership Models*	*Consortiums* (1, 2)	*Independent Operations*					N	Allen et al. (2014) OECD (2017)
Value	***Value Creation***	*Data Sovereignty* (1)	*Secure Data Sharing* (1, 2, 3)	*SC. Efficiency* (2, 3)	*SC. Responsiveness* (2)	*SC. Visibility* (2, 3)	*Sustainability Goals*	*Collaboration and Networking* (1)	*Digital Automation*	N	IDSA (2024) Logistics data spaces
Value	***Value Delivery***	*Provider & consumer matching* (1)	*Shared Digital Twins*	*Process Optimization* (2, 3)	*(Big) Data analytics/enrichment*	*Real-time visibility* (2, 3)	*(Smart) Contracts management*			N	Bastiaansen et al. (2020) Pulido et al. (2024) Möller et al. (2020)
Value	***Value Proposition***	*Selling data-based services*	*Optimization Services* (1)	*Selling data*	*Selling analysis*	*Data-driven improvements* (2)	*Data-enriched products & services* (3)	*Data-driven services* (1)		N	Schweihoff et al. (2022) Möller et al. (2020)
Value	***DS Revenue***	*Fees* (2)	*Pay-per-Use*	*Licensing*	*Commission*	*Subscription plan*	*Customized* (1)			N	Möller et al. (2019) IDSA (2024)
Resources	***DS Infrastructure***	*Data Ecosystem* (1, 2, 3)	*Marketplace*	*Hybrid*						E	Schweihoff et al. (2022) IEDS project (2023)
Resources	***Transport Mode***	*Truck*	*Rail*	*Ship/IWT* (1, 2, 3)	*Air*					N	Möller et al. (2020)
Resources	***Data Origin***	*Internal* (2, 3)	*External* (1)							N	Dehnert et al. (2021)
Resources	***Data Source***	*Self-generated data* (2, 3)	*Existing data*	*Restricted data* (2, 3)	*Freely available*	*Provided by user* (1)	*Acquired data*			N	Schweihoff et al. (2022)
Resources	***Service Flow***	*Manually driven*	*Predefined time steps*	*Event-driven* (1, 2)	*Data stream* (1, 3)					N	Dehnert et al. (2021)
Resources	***Source of Funding***	*EU*	*Government* (1)	*Private* (2, 3)	*Other*					N	IDSA (2024)

E: Exclusive dimension, N: Non-exclusive dimension, DS: Data Space, IWT: Inland Water Transport, LSP: Logistics Service Provider.

(1) Data Space developer (2) Shipper (3) Barge Operator

Figure 1: Morphological box of data spaces business model taxonomy for the freight transport sector

Value Propositions represent the business's offerings (Möller et al., 2019), encompassing primarily services derived from data spaces alongside products such as enriched data assets. In this case, the mechanisms established for ***Value Delivery*** address how these value propositions are delivered to customers (Lüdeke-Freund et al., 2019), such as data space participants. This dimension integrates logistics data-sharing infrastructure solutions with data-driven business models in the logistics sector, focusing on transport concepts like intermodality and synchromodality. Finally, we propose a ***Data Space Revenue Model*** designed to capitalize on the deployment of the digital infrastructure via participation in data spaces. These models are guided by relevant literature (e.g., Möller et al. (2019)) and the current deployment models in data spaces according to IDSA (2024).

4.1.4 Resources

The **Resources** dimension encompasses the tangible and intangible assets required to operate the data space, providing essential elements to benefit participants. In this context, the ***DS Infrastructure*** — serving as a *Data Ecosystem*, a *Marketplace*, or a *hybrid* of both — is the cornerstone of the data space, with the data itself being the primary resource. The dependency of resources on the actor dimension is significant; for example, the ***DS role*** of a ***Transport Stakeholder*** (e.g., a shipper) as a *Data User* or *Data Provider* significantly differs from their role when acting as an *Ecosystem Orchestrator* within the data space.

The ***Data Origin***, as introduced by Dehnert et al. (2021), represents whether the data input into the data space is *Internal*, meaning it comes from the data space itself, or *External*, meaning it comes from *Data Providers* regardless of their ownership. It is also necessary to identify the ***Data Source***, which refers to data *self-generated* by an actor; this can also be *restricted* or *freely available data*.

The ***Service Flow*** depicts how the offerings are delivered. For instance, according to Dehnert et al. (2021), the user proactively requests the service in a manually driven context. This differs from an *event-driven* context, where a trigger activates the service flow, or *predefined time steps*, where the service is delivered at intervals. In a *data stream* context, the data (or the service in question) is continuously offered, real-time or on time, wherever relevant.

5. Application of the taxonomy

Synchromodality, a concept that emerged around 2010, emphasizes collaboration among stakeholders to dynamically select the most suitable mode of transportation at any given moment, whether it involves a combination of road, water, or rail, to move goods within the infrastructure network (Tavasszy et al., 2010). This concept extends beyond traditional intermodal transport by integrating transport network planning that accommodates real-time modal shifts and flexible arrangements resulting from mode-free (a-modal) booking (van Riessen et al., 2013). To enhance data exchange, access, and reliability within synchromodality, Pulido et al. (2024) have integrated data space functionalities to enable the attributes of synchromodality, especially regarding visibility and flexibility in Inland Water Transport. According to the description of the data space, the use case represented in Figure 2 involves the implementation of data space principles within the freight transport context, integrating relevant real-time data from different stakeholders, such as inland barges voyage information, cargo-specific information, transit route status, and terminal statuses. With such information, it is possible to identify triggers for relevant actions, such as rerouting or optimizing barge transit.

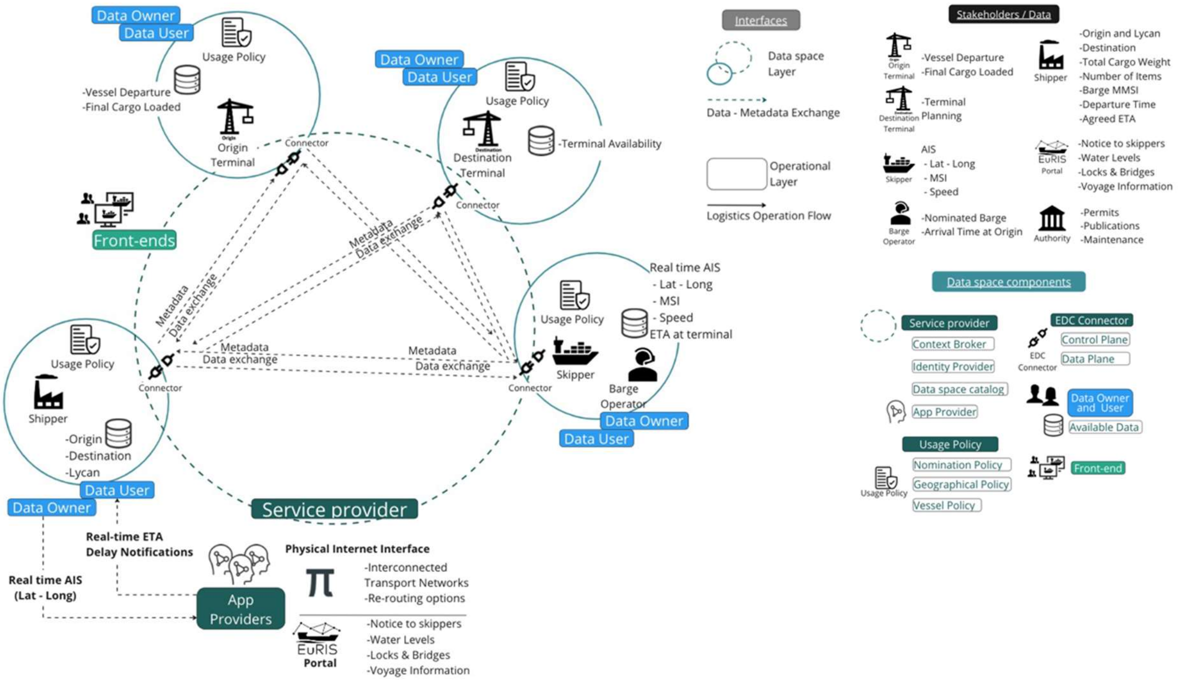

Figure 2: Synchromodal data space overview – Adapted from Pulido et al. (2024)

The morphological box displayed in Figure 1 captures the multidimensional aspects of the previously described synchromodal transport system's data space. Each dimension's subcategory is selected depending on the stakeholder's role in the data space and use case characteristics. The perspectives of the following three primary stakeholders are captured: the *data space developer* (green dot with the number 1) representing the interest of the data space, the *shipper* (orange dot with the number 2) being the entity facing challenges in their logistics process due to limited visibility on transport execution, and the *barge operator* (blue dot with the number 3), a company operating a large number of barges in Europe.

5.1 Business model for the data space for synchromodality

DS Foundation: The ***Maturity*** level is at an *Implementation* stage since the initiative has put its infrastructure and governance framework into practice. The first use case is functional, with data being exchanged between providers and recipients and the use case delivering its expected benefits (IDSA, 2024). It is worth highlighting the ***case pattern***, as it represents a *Joint Innovation* for the participants. This concept is based on the understanding that customer innovation can only be realized when ecosystem members work together since no single member possesses all the necessary data. On the other hand, for the *data space developer* and the *shipper*, there is a mutual interest in sharing data to cope with a shared requirement (*Shared Cost*) such as process efficiency and transparency, where every member saves money and time by sharing the burden. (IDSA, 2024).

Actor: The initiative centers on deploying digital infrastructure, indicating a system in which the *data-infrastructure provider* plays a fundamental role. Applications accessible through an *App Store provider* are vital for accessing or processing data. For example, in the synchromodal data space, applications help monitor incidents across the inland navigation ecosystem. They also provide event alarms when the estimated time of arrival (ETA) deviates from the planned schedule, thereby offering monitoring of ETAs and transparency for cargo in transit. *Data* *owned by another entity*, under the ***Data Ownership*** dimension from the data space developer, points to a model where ownership and control are distributed or assigned by other parties.

This frames the **DS role** of the *Ecosystem Orchestrator*, ensuring that all parties involved in the data space can participate and create value. It also identifies the different roles within the ecosystem and creates connections between them (IEDS project, 2023). ***Transport Stakeholders***, such as *shippers* and *carriers*, acting as both *Data Owners* and *Data Consumers* suggests their dual role in providing data from their operations and consuming enriched data or services derived from the data space to optimize transport efficiency and reliability.

Value: This dimension captures value creation, delivery, and value proposition within the data space. The *data space developer* generates a safe environment for *collaboration and networking* as means of ***value creation*** offering *data-driven services* as their ***value proposition***. This highlights a service model fueled by data analysis and insights. The *shipper* benefits from *real-time visibility*, vital for tracking and managing shipments efficiently. The *barge operator* seeks *data-enriched services*, indicating they can enhance their transport service offerings with data-derived insights by merging their data with the shipper's data for improved service.
The *data space developer* achieves the ***DS Revenue*** through a *customized* model that allows the developer to tailor services and solutions to the specific participants and their interest in data space. This approach enables the developer to charge based on the value delivered through these personalized services, potentially commanding a higher price for the added value of customization. Regarding the *Fees*, the *shipper* is charged yearly for participating in the data space as a data provider and consumer.

Resources: This section highlights how the *data space developer*, *shipper*, and *barge operator* acquire and utilize resources within a synchromodal transportation data space. All three stakeholders are integrated into a *Data Ecosystem*, leveraging necessary digital ***DS infrastructure*** in their operations. The *data space developer* integrates external data to create the baseline service for the data space, while both the *shipper* and *barge operator* primarily use internal data derived from their logistics activities to contribute to the ecosystem. The ***Data Flow*** for the *data space developer* and *shipper* is *event-driven* because, in synchromodality, responsiveness to situational changes is crucial. The *barge operator's* services are on a continuous *Data stream*, as real-time voyage information and status of barges are constantly shared, ensuring fast updates about events (triggers) and potential transport optimizations. Finally, the funding for the *data space developer* is sourced from government contributions, since the main initiative is generated from a government-funded project, contrary to the *shipper* and *barge operator*, which are private companies benefiting from the data space but paying a fee, as is the case for the *shipper*.

6. Concluding Discussion

The logistics sector exhibits a wide range of data sharing collaborations, creating diverse expectations for the supporting infrastructure such as data spaces. It is challenging to anticipate all potential uses, services or applications for such an infrastructure. However, well-designed data sharing ecosystems could give rise to new applications, products, and business models that have not yet been considered. (Bastiaansen et al., 2020).

Our research began with the identification of the business model building blocks for a data space dedicated to freight transport, where data exchange is crucial, such as in synchromodality, followed by the development of a baseline taxonomy. This taxonomy underscores the potential operational value of implementing data spaces from the perspective of transport stakeholders and outlines the potential sources of economic returns that the data space generates for its own development. A significant portion of the developments we analyze within the data space radar in the logistics sector are driven or incentivized by governmental initiatives, such as funding for research and development projects. It is from these projects that the data spaces then evolve into commercial data space entities.

Our contribution to academia is to provide a synthesis of the data space BM taxonomy, which, by combining its elements, can lead to new developments in transport services that have not yet been realized, although the components are available and identified. Additionally, the dimensions and characteristics of the data space dimensions serve as a starting point for further development of more digital-driven transport services, especially in the realm of synchromodality. This includes aspects such as provider and consumer matching, shared digital twins, process optimization, (big) data analytics/enrichment, real-time visibility, and (smart) contracts management.

Our research provides practitioners and stakeholders with shared interests in freight transport a valuable guide to explore the development of data spaces that are both sustainable and financially viable. Companies can assess their current digitalization efforts, data sharing practices (internal and external), and data-driven initiatives against the identified building blocks, with a special focus on intermodal and synchromodal transport strategies. Additionally, developing mechanisms to generate revenue for the data space is crucial, as a business model can only be sustainable in the long run if it produces enough revenue to cover its costs.

Future research on business models for data spaces in synchromodality should concentrate on exploring the cost structures that support these models. By analyzing the business models of various transport stakeholders—a dimension not fully explored in this study—and scrutinizing the differences in revenue generation, we can obtain deeper insights into their financial viability. Furthermore, identifying existing and emerging services enabled by data spaces, like predictive analytics or dynamic routing/pricing, will reveal new revenue potential.

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Toward a multi-dimensional resilience planning and assessment framework for a Physical Internet-based freight transport and logistics systems

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Abstract: *The Physical Internet (PI) offers a transformative vision for a sustainable freight transport future. However, the escalating risks of disruptions and extreme events threaten both freight systems and the communities they serve. We critically evaluate the state-of-the-art in Physical Internet and Hyperconnected City Logistics towards the objectives of addressing the dynamic and interdependent nature of logistics networks, as well as enhancing system resilience, especially within metropolitan urban areas. The study then proposes a multi-dimensional planning and assessment framework for resilience and sustainability research in freight and logistics, drawing on the performance concept (n-bottom lines, nBL) and systems science. Key R&D areas for future work are determined, including the need for an assessment framework that takes a comprehensive, multi-stakeholder perspective to ensure that future logistics networks are geared towards the environment and society as whole, alongside economic objectives. Research directions in complementary research fields are also identified, with implications for policy-making, stakeholder collaboration and industry practices.*

Keywords: *Physical Internet, Logistics Network Resilience, triple bottom line, n bottom line*

Physical Internet (PI) Roadmap Fitness: *Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☒ PI Networks, ☐ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

Targeted Delivery Mode-s: *☒ Paper, ☐ Poster, ☐ Flash Video, ☐ In-Person presentation*

1 Introduction

In recent years, several disruptive events have affected the world's logistics networks and supply chains in various locations and levels. Some examples are the COVID-19 lockdowns, the 2021 Suez Canal blockage leading to trade losses of up to USD 54 billion (Lee & Wong, 2021), and on a more small-scale context, major flooding events in various locations such as Queensland, Australia in 2022. This last event left several roads impassable due to flooding, disconnecting key points of the local supply chain. It was reported that six months after the disruption, there were significant economical losses, according to the Business Chamber Queensland's 2022 South East Queensland Floods Report. The frequency and intensity of these disruptions are only seen to increase in the coming years and decades, as the occurrence of extreme weather events has been becoming more and more common.

When the Physical Internet (PI) was first proposed (Montreuil, 2011) to achieve the high level of integration and connectivity exhibited by the digital internet in the physical setting of freight transport and logistic systems, it highlighted 13 unsustainability symptoms. Addressing these, dubbed as a *global logistics sustainability grand challenge*, required a reconfiguration of the logistics networks to be more integrated, collaborative and cost effective, among other objectives. Logistics network resilience is one of these identified problem areas, but research on this topic has been limited since.

System resilience is necessary to achieve sustainability. Bocchini et al. (2014) advocates for the integrated used of resilience and sustainability as additional dimensions for consideration of system performance. Rather than treating these two commonly-used measures as separate, that study proposes a methodology where these two are treated as complementary, and this concept would be transferable to logistics networks. A logistics network that is designed to be sustainable will be most effective when it is resilient at the same time, since system performance with respect to various metrics can be maintained even through disruptions. Coupling this with the PI concept and other innovations, we see that there is a big opportunity for future logistics networks in terms of achieving multiple objectives.

With these specific problems in mind, we look to the Physical Internet as one of the main avenues to achieve both sustainability and resilience in freight logistics. On the literature that deals with PI, underlying research areas have not yet been thoroughly explored, and there are only a small number that deal with resilience and/or sustainability. Thus, there is a need to firmly and clearly establish the current body of knowledge, and identify future directions to take. This paper aims to achieve these objectives by doing a systematic review of relevant research works and projects, then identifying key R&D areas to guide future research work and policy implementation.

2 Disruptions in PI-Enabled Logistics Networks

Throughout the remainder of this paper, we adhere to the definition of resilience from Hosseini et al. (2016), which is *the ability of an entity or system to return to normal condition after the occurrence of an event that disrupts its state*. Though this definition is for generic system resilience, it can be applied to the logistics context as well. In relation to this, we define robustness as the ability of the system to withstand a given level (of disruption), as stated in Shandiz et al. (2020) .

Disruptions in logistics networks can be classified in various ways. Network section affected, disruption intensity, frequency and warning time are some general disruption classifications that are used in literature. Logistics networks can be assessed with respect to resilience in this wide range of disruption classifications, but this paper focuses on select classifications that are deemed the most relevant to the core motivations of PI. Since PI leverages on high level of interconnection within the elements of the network, only disruptive events in this scope will be considered.

Short-to-medium term disruptions in network links

Road closures are one of the most common types of disruptions in logistics networks. Depending on the source of disruption, these can vary in extent/reach and duration, affecting one or more arcs in the network. Other studies focused on mathematically modelling the sustainability impacts of PI-enabled logistics networks. Labarthe et al. (2024) focused on connecting people and freight mobility through the joint usage of various transportation options, building on hyperconnectivity principles found within PI and HCL. The study proposed a model-based decision support approach for producing delivery solutions to multimodal transshipment problems, effectively reducing congestion levels and carbon emissions within urban areas. Xue et al. (2023) proposed a PI-enabled hyperconnected order-to-delivery system (OTD), which modelled the production-distribution system by multi-objective mixed-integer-nonlinear programming with economical, environmental and social impacts. It stated exploration of resilience metrics as one of the main avenues for future work. Ji et al. (2023) investigated the relationship between resilience and sustainability in PI-enabled supply-production-distribution networks. They were able to identify that PI-enabled networks were inherently more resilient and sustainable that the traditional counterpart.

Peng et al. (2020) focused on PI-enabled production-inventory distribution systems and formulated a multi-objective mixed integer linear programming model that covers economic, environmental and social sustainability. The study proved that PI can improve the identified distribution systems on all three sustainability dimensions. Guo et al. (2021) developed a Hyperconnected Physical Internet-enabled Smart manufacturing Platform (HPISMP), which they applied to production systems. The study was able to show that the resulting system was more efficient operationally and had a higher level of resilience and resistance against disruptions. Bidoni & Montreuil (2021) works with a previously-determined parcel routing model and generates different scenarios for demand and customer behavior through an AI-based application. The study allows for testing of several scenarios that may possibly happen in the real world, with objectives including efficiency, robustness and responsiveness of the hyperconnected logistics networks.

Short-to-medium term disruptions in network nodes

Similar to link closures, the operation of logistics network nodes can also be affected by disruptions. Peng et al. (2021) developed a two-stage stochastic programming model and a two-level heuristic algorithm to optimize both pre-event and post-event mitigation strategies in production-inventory-distribution systems. The study was the first to combine disruption risk management and the integrated production-inventory-distribution problem (IPIDP) in a PI-enabled system. Specifically, backup production, storage and handling capacities are considered for pre-event mitigation strategies and production capacity, storage and handling recovery, as well as product flow reconfiguration for post-event mitigation strategies. For post-event recovery strategies, Yang et al. (2017) investigated the resilience of a PI-enabled system by adopting a two-state Markov process as the system behavior. The study focuses on post-event minimization of disruptive events. Two PI-based dynamic and resilience transportation protocols were identified, allowing the system to react positively to different disruptive events, namely *risk avoidance*, which avoids all disrupted hubs for routing, and *risk-taking*, which considers still considers passing through disrupted hubs depending on the estimated penalty time of the hubs involved in the route. X. Liu et al. (2023) looked into the capacity deployment of logistics hubs in hyperconnected transportation networks to enhance resilience, and was able to show improved levels of economic and social performance objectives for hyperconnected networks. Ji et al. (2023) focuses on resilience and sustainability of supply chains under the PI context. A multi-objective mixed-possibilistic programming model was developed as a way to incorporate supplier resilience and sustainability into the network. Numerical experiments were done to show that PI-enabled networks allowed for significantly more efficient, resilient and sustainable networks.

Resilience through network structure design

A number of studies in PI investigate the network structure in order to address various objectives that include resilience. These involve looking at both nodes and links, and how they interact with and affect one another. Campos et al. (2021) proposes a high-level methodology for implementing a multi-tier hyperconnected network in the place of hub-and-spoke networks with the goal of achieving high levels of delivery speed, efficiency, system agility, sustainability and resilience. The study identified considerations when designing a service network geared towards achieving the objectives mentioned. These include clustering of the logistic zone, hub network design, service network design (at the operational level) and parcel routing, containerization and consolidation schemes. Kulkarni et al. (2021) and Kulkarni et al. (2022) studies the problem of designing resilient hyperconnected logistics hub networks. Using network topology measures involving paths and edges, the study is able to quantitatively measure resilience. Two integer programming-based solution approaches are proposed. Through a case study in China, the study was able to show that resilience can be achieved without significantly affecting system performance.

Mohammed et al. (2023) developed a methodology for designing a 2-tier supply chain network. Though the study was not done under the PI-context, similar considerations (i.e. high connectivity utilization) were used to achieve resilience through network design. Tordecilla et al. (2023) tackled the resilient supply chain network design problem under the context of PI. The study compares two setups: a basic setup, where at least one source node is connected to each destination node, and a hyperconnected setup, where each destination node is connected to all source nodes, with both models optimizing cost and resilience. The study measures resilience as the area under a recovery curve. Using a simulation-optimization approach involving three MIPs, the study was able to show that increased resilience was exhibited by the hyperconnected network setup. Kulkarni et al. (2023b) investigates network disruptions under the network interdiction problem for hyperconnected logistics networks. An exact solution methodology is developed, and its computational performance is assessed through numeric experiments. Performance of hyperconnected networks and their lean counterparts are compared, and it was determined that hyperconnected networks are more ideal in worst-case disruption scenarios.

Under a different type of network structure, Kulkarni et al. (2023a) focused on the relay logistics network design, targeting for network resilience through network topology. Computation experiment were done on a China-based parcel delivery company, it was determined that near-optimal solutions can be obtained within a reasonable amount of time. Kulkarni et al. (2024) extended this study through the proposition of a Capacitated Relay Network Design under Stochastic Demand and Consolidation-Based routing (CRND-SDCR) model, and was able to show, through numerical experiments, a high level of resilience under variability demand.

From the reviewed works, we see that studies within PI mostly focus on what are called pre-event measures, which technically pertains to robustness. Petitdemange et al. (2023) focuses on improving last-mile logistics in developing countries, with the goals of improving system efficiency, sustainability and resilience. A digital model-based approach is taken and has shown that significant improvements to lead time, carbon footprint and costs can be achieved. Nguyen et al. (2022) conducted a literature review on the Physical Internet/Digital Twin applications on the Supply Chain Management area, which included some insights on supply chain resilience. The study was able to surmise that recent works have been starting to explore supply chain resilience more, especially in the dawn of the disruptions due to the COVID-19 pandemic, but there is still a need to investigate more detailed problems involving supply chain disruptions in logistics routing, warehousing/manufacturing locating and supplier selection, among other aspects. These studies have explored what can conceptually be achieve in terms of improving system resilience once PI concepts are implemented in real-world systems.

3 Resilience Planning & Assessment Framework for PI-enabled Networks

Resilience has been studied and applied in various fields and industries, such as economics (Brown & Greenbaum (2017) , energy systems (Shandiz et al. 2020), organizations (Hillmann & Guenther, 2021), and even in supply chains (Pettit et al. 2010, Tukamuhabwa et al. 2015). A number of studies have already tackled this within freight logistics and the Physical Internet context, as discussed in the previous section. A high-level view is taken in the development of a resilience assessment framework for cross-referencing the previously reviewed works with proposed resilience metrics.

In order to further appreciate the resilience concept application logistics networks, we briefly examine the nature of disruptions and their effects. Upon the onset of a disruption event, system performance (with respect to various performance metrics) decreases until such a time that recovery strategies restore performance to the previous level (or in some cases, to a higher level), as seen in Figure 1. The magnitude of the deterioration of system performance depends on both the severity of the disruption and the ability of the system to resist this disruption. The duration for which the system operates at a level that is lower than normal depends on the initial dip in performance and how well the system is able to recover from the disruption event.

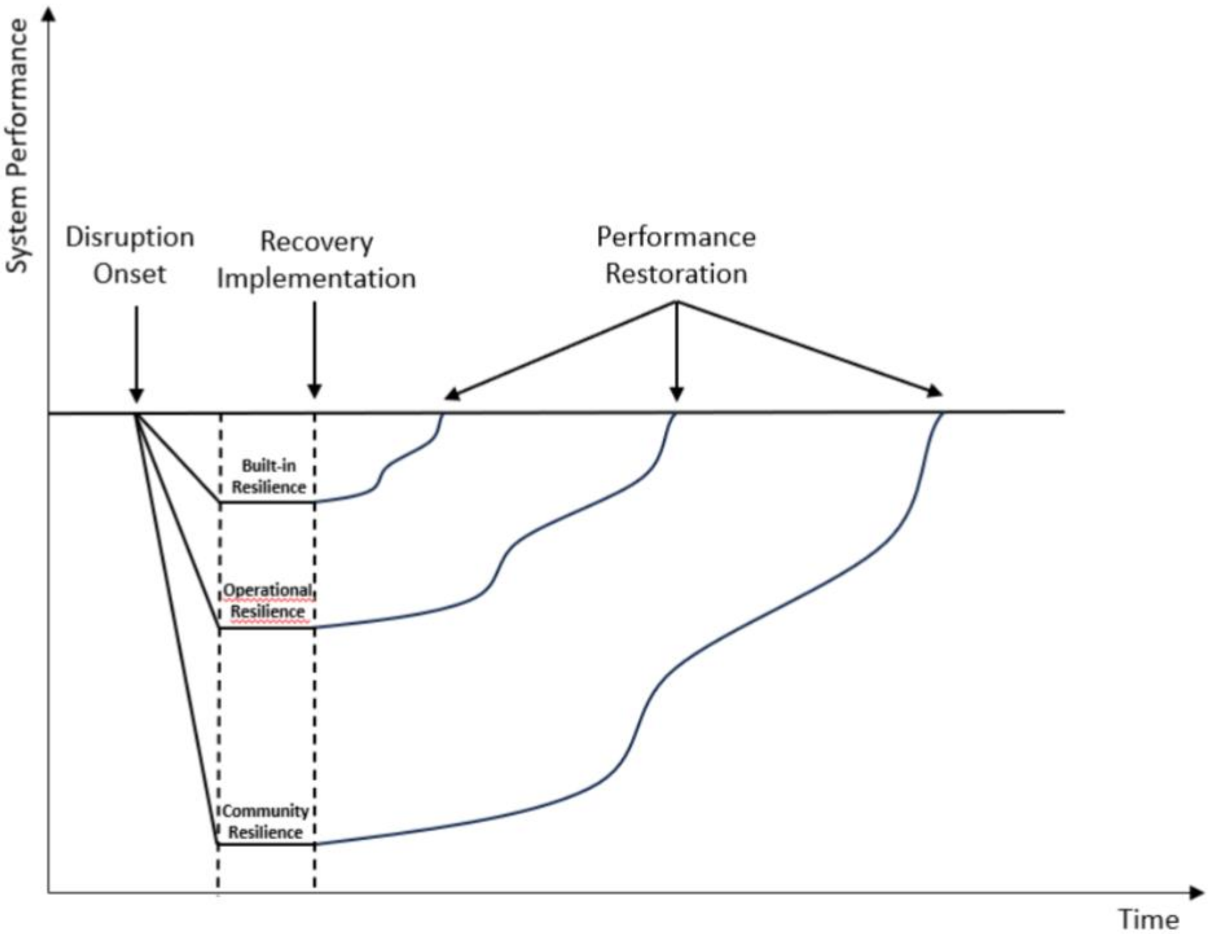

Figure 1 System performance over time during disruption and recovery.

As mentioned earlier, there are several different possible classifications of disruptive events, and Hasan & Foliente (2015) mentions that the type of disruption largely influences the impacts felt by the corresponding system. The same study categorizes hazards based on two main criteria: duration and warning time. Hazards such as earthquakes, bushfires and tornadoes are seen to occur without ample warning and time for preparation, while the other category of hazards, which include sea-level rise and chronic flooding are classified as having more warning time but would last longer. This categorization is summarized in Figure 2.

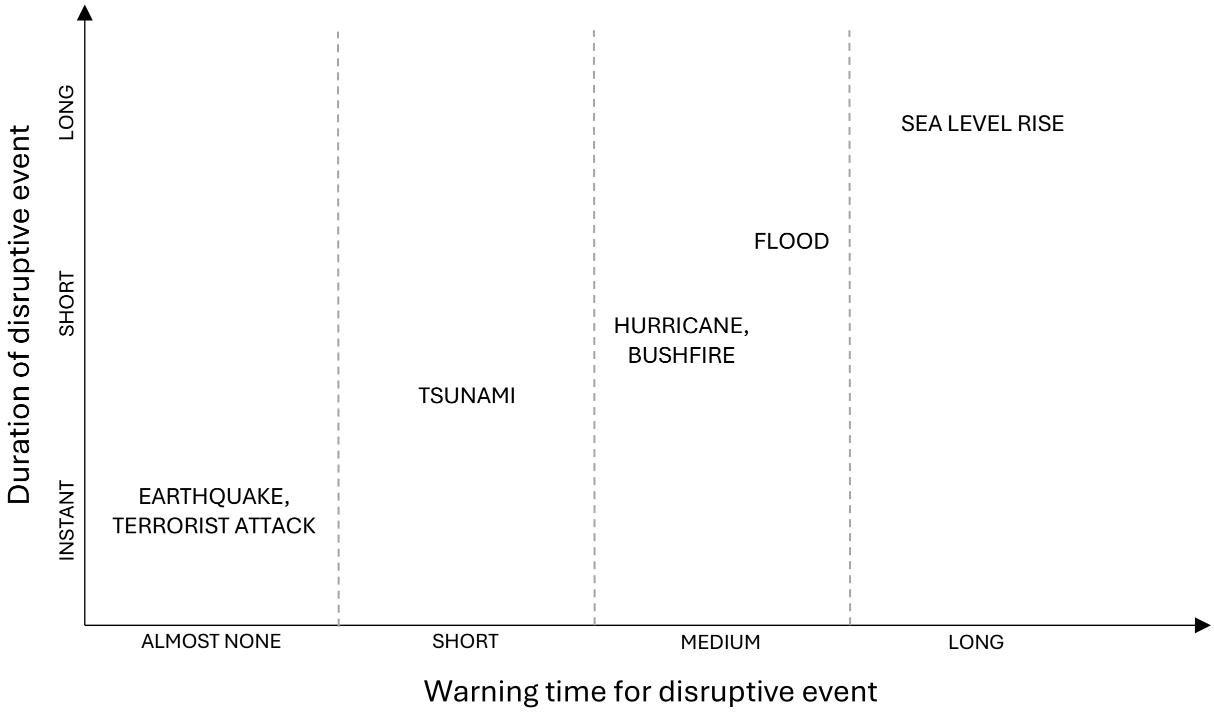

Figure 2 Classification of disruptive events according to duration and warning time, as discussed in Hasan & Foliente (2015)

With respect to the resilience exhibited within PI-enabled logistics networks, a multi-layered approach, as done by Shandiz et al. (2020) can be adopted to more accurately describe system behavior during disruptions. This approach involves three resilience layers, namely built-in resilience, operational resilience and community resilience. Upon the onset of a disruption, these three layers act together, either successively or concurrently, to work towards the restoration of system performance to the level its level before the disruption.

Designed/engineered Resilience

This resilience layer pertains to the inherent resilience that the system exhibits without any action or intervention. In the context of logistics networks, examples of this would be the hub and link redundancy provided in fully-interconnected and shared networks that are not present in traditional ones. In a shared network, a provider would have access to most, if not all, hubs and link in the network, and should some sections of the network fail, alternative sources of goods and paths would be available.

In PI-enabled networks, built-in/engineering resilience often involves the network structure, especially for hyperconnected mesh networks. The hyperconnected network design provides a high number of nodes and links, making the system inherently resistant to disruptions that involve a small portion of the network. The reviewed literature has offered various algorithms to implement this hyperconnected network structure, and actual implementation is seen to improve resilience.

Operational Resilience

The operational resilience layer consists of the actions and operations taken specifically to increase network resilience in anticipation of disruption. In logistics networks, this would often be in the form of the acquisition of redundant hub capacity, redundant inventory, and/or redundant transport channels. From the reviewed works, we can see that operational resilience is the layer that is discussed the most, as actions in this layer often required extensive modelling.

Both pre-event and post-event mitigation strategies would fall under the operational resilience category. This comes in the form of availing either backup capacity (for both nodes and links), or surplus in assets (i.e. inventory, fleet count), for both disruption effect mitigation and system performance recovery purposes.

Community Resilience

The third resilience layer in the multi-layer approach is community resilience, which pertains to the solutions that involve members of the community in restoring system performance. Depending on the extent of the disruption experienced, this type of resilience can extend to the larger-scale society-wide resilience, such as that experienced during the COVID19 pandemic in various systems such as health, social, and governmental. From the review conducted, we can see that the community resilience layer in the context of logistics has not been the focus of any of the studies so far.

Since the idea of the Physical Internet arose due to exhibited unsustainability symptoms, it is only natural that the slow but steady realization of PI concepts lead to more sustainable networks. In the literature reviewed in this study, we have seen commonalities in the multi-criteria evaluation of PI-enabled networks. Economic objectives are often quantified in direct profit, revenue and financial costs. Environmental objectives are most often evaluated in terms of greenhouse gas emissions. Societal objectives are often evaluated through reduction in traffic congestion, noise pollution reduction, or road safety improvement. System resilience is assessed against these performance metrics in order to evaluate logistics network resilience, as summarized in Table 1.

Table 1. Performance metrics used in PI-enabled logistics networks.

Main Objective	**Corresponding Metric**	**Objective Direction**
Economic	Financial Profit	Maximize
	Service Level	Maximize
Environmental	GHG Emissions	Minimize
Societal	Traffic Congestion	Minimize
	Road Crashes	Minimize

	Facilitation of Goods Transfer	Maximize
Socio-Economic	Network Uptime	Maximize

From these identified performance metrics, resilience is measures primarily in three aspects: magnitude of disruption, duration of disruption and rate of recovery. Table 2 lays out these metrics across the three identified resilience layers in the logistics network context.

Table 2. Resilience metrics across three resilience layers.

Built-in Resilience Metrics	**Operational Resilience Metrics**	**Community Resilience Metrics**
Degree of facility/channel sharing within network	Magnitude of disruption (Backup capacity activated)	Individual distribution of goods across network
	Duration of disruption (Duration of backup activation)	
	Rate of recovery (Original capacity restored)	

4 Key challenges

With the framework discussed in the previous section, we cross reference the reviewed literature to determine the gaps in knowledge on the multi-criteria assessment of PI-enabled logistics networks. Of the 13 studies that investigated resilience in PI-enabled networks, 11 have proposed pre-event solutions, through means such as acquisition of backup/redundant production capacity, inventory and/or transport channels. This strategy increases the robustness of logistics networks by drastically increasing network performance immediately before the occurrence of the expected disruption. For single major disruptive events that can be predicted (i.e. flooding due to typhoons), this can be done in a cost-effective manner as the exact time period for implementation of the pre-event solutions can be determined. However, for unexpected disruptive events (i.e. road/facility downtime due to earthquakes), a less targeted approach would be better, to minimize the cost of implementing these resilience measures.

Comprehensive assessment of PI-enabled networks

Examining these studies against the assessment framework, we see that the main focus of the studies are the economic objectives, which involves either maximization of company profits or minimization of company costs. The socio-economic effects of network disruptions has yet to be explored, and multiple reports have shown this to be very costly with respect to several perspectives. On top of this, there is currently no study that comprehensively addresses logistics networks through a multi-dimensional, multi-stakeholder perspective, which is what is needed in today's landscape. This includes system resilience, sustainability, as well as societal and environmental objectives, and finally, the integration of all these to a singular comprehensive assessment framework.

Network structure towards resilience

In line with PI's goal of interconnectedness, the hyperconnected logistics network structure provides an avenue for not just efficient but resilient networks. This structure has been explored by some studies, as previously identified. However, there remains a large area for future studies to expound on and improve the accomplishments of current works.

Tiering methodology – Previous papers have directly assumed a fixed number of tiers for the implementation of mesh network, without offering quantitative proof that the assumed number of tiers is the optimal number. Future work can be done to create algorithms that establish a tiering algorithm that would provide the optimal tier count given the characteristics of the implementation site.

Hub location – In determining the count and location of hubs within a specified tier of the mesh network, several algorithms have already been identified (i.e. clustering, greedy algorithms). Since the algorithms proposed previously are heuristics, there are opportunities to improve the accuracy and computational time of these heuristics. In addition to this, a larger gap exists in the resilience improvement of these mesh networks alongside economic objectives.

Incremental implementation – PI-enabled networks are meant to be implemented over existings logistics networks. However, there are no studies that address the methodology transitioning from a traditional logistics network to a PI-enabled one. Future work can look into determining the order network segments (i.e. specific nodes, links) to convert in order to achieve the best interim system performance, with respect again to multiple objectives such as economic, societal, environmental, and those concerning resilience and sustainability.

Resource and information sharing is also a rich area for achieving multi-criteria objectives in PI systems. This includes sub-sections such as real-time data management, data security measures, and resource sharing protocols. Increased efficiency across the entire network inherently leads to a lower operational level, which leads to less vehicles on the road, and ultimately lower network GHG emissions. This also allows a farther-reaching distribution of goods and more redundancy, both of which are direct contributors to system resilience. As such, research on achieving this fully-interconnected state is of utmost importance. Physical and digital interoperability issues in the real world need to be more intensively modelled, and solutions to these issues should be carefully planned to adhere to various real-world requirements.

5 Conclusion and Future Work

Toward a multi-dimensional resilience planning and assessment framework for a Physical Internet-based freight transport and logistics systems

The study has been able to strongly establish that there is an evident lack of works in PI that deal with logistics network resilience. Specifically, it was determined that the works that do address resilience only address a limited aspect, and a more comprehensive view on the subject needs to be taken. The study has thus been able to propose a resilience planning and assessment framework, to aid in the comprehensive evaluation of existing and establishment of future PI-enabled logistics networks. Additionally, key R&D areas are also identified within the field, including the development and expansion of a multi-dimensional assessment tool that takes into consideration a multi-stakeholder perspective, in order to ensure that future logistics networks are not just profit-driven but are beneficial to the environment and society as a whole. It is also important to develop research in complementary fields, such as resource and information sharing, and alternative last-mile delivery modes, especially under the multi-dimensional perspective, as these would provide concrete methodologies for meeting the multiple objectives of these systems.

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A protocol for node-to-node transshipment in the PI analogizing from Internet principles

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Abstract: *This paper introduces the PI-link protocol, a novel process inspired by the operational principles of the Internet, to address node-to-node transshipment within the Physical Internet (PI). Recognizing the critical need for efficient, standardized protocols to manage the complexities of logistic flows in the PI, we propose a simple, adaptable protocol designed to facilitate seamless collaboration among diverse logistics service providers. By drawing analogies to the TCP/IP model, our protocol emphasizes streamlined processes for dynamic and static information exchange, analogous to the Internet Protocol (IP) ensuring and supporting effective shipment processing, routing, and monitoring across interconnected logistic networks. The technical operations of the protocol are clearly demonstrated through pseudocode, providing a detailed blueprint for its implementation. This exploration aims to contribute to the ongoing development of the PI, by providing a first step towards a simple baseline protocol stack, as TCP/IP for the Internet.*

Keywords: *Physical Internet, Protocols, Protocol Stack, Nodes, Operationalization, Internet, Framework, TCP/IP.*

Physical Internet (PI) Roadmap Fitness*: ☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☒ Governance.*

Targeted Delivery Mode-s*: ☒ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation*

1 Introduction

The Physical Internet (PI) has gained considerable interest within the last few years and is meant to fundamentally change the transport sector to tackle its inefficiencies and environmental impacts. Even though implementation is urgently required, scalable and overarching concepts on the operationalization of the PI remain scarce. Managing several stakeholders in collaborative and seamlessly connected networks of networks requires efficient, effective and easy to run protocols similar in effect to protocols used for managing data exchange on the Internet (Dong & Franklin, 2021).[1] Establishing a network-of-networks requires, amongst others, a protocol that controls the connection between individual networks, i.e. the connection from node-to-node. Hence, as a first step towards a network-of-networks, we are developing the PI-link protocol.

[1] A protocol is defined as a system of rules that explain the correct conduct and procedures that should be followed in a formal situation.

This paper is centered around the central question of "How to operate the PI?". It is aiming to combine two areas of research into one. Particularly, the areas of logistics transportation management and information systems. Extensive research has shed light on the conceptual aspects of the PI (e.g. Dong & Franklin, 2021; Montreuil, 2011; Montreuil et al., 2018) and its assessments (e.g. Briand et al., 2022; Sarraj et al., 2014), revealing promising prospects. Introducing a protocol stack aligned with the OSI model, Montreuil et al. (2012) laid the groundwork for PI protocols, while Dong & Franklin (2021) highlighted the relevance of the DoD model. Technical attempts to design protocols for the PI were made by some authors addressing primarily the optimization of node internal structures such as consolidation or routing (Briand et al., 2022; Gontara et al., 2018; Sarraj, Ballot, Pan, Hakimi, et al., 2014; Shaikh et al., 2021). However, most protocols discussed in the context of the PI provide limited operational guidance for managing goods flows across a set of networks-of-networks. Here, the Internet serves as a valuable model that employs protocols that provide guidance for developing PI focused protocols based on physical rather than digital flows. The design principles of the Internet's protocols emphasize simplicity and openness as guiding factors that shape all system-level protocols and controls (Phillipson, 2021).

In keeping with the minimalist philosophy of the Internet, the protocols envisioned for the PI should also embody a straightforward design that specifies standard processes for managing and controlling flows across the PI. Following standardized processes fosters interoperability and represents an important element for the implementation of the PI (Münch et al., 2023). The Internet specifies these standard processes for various protocols via RFCs[2] (Requests for Comments) that are developed collaboratively and are continuously reworked and updated.

While the protocols of the Internet have grown in complexity over time, the PI should aim to begin its journey with a simple protocol structure. This strategy allows the system to organically adapt its control processes in response to specific circumstances, mirroring the adaptive evolution of the Internet's protocols over the years. Hence, we make reference to the foundational TCP/IP protocols, constituting the fundamental protocol suite operating and controlling the Internet (Montreuil et al., 2012). We define the standards and showcase their functionality, enabling diverse actors in the PI to leverage them. Taking a cue from the Internet's TCP/IP model, we can consider a thought experiment in structuring PI-protocols that involve Sender-Receiver transfers (akin to TCP) and Node-Node transfers (comparable to IP) and therewith build a framework to operate the PI. This paper focuses on the inter-node (link) management of flows in the PI and defers discussion of the end-to-end management of flows (the TCP analog) for future research.

The overall objective of this research is to develop and test a protocol that addresses the collaborative transshipment of freight between two nodes involving different logistics services, executed by different LSPs. This objective is composed of three goals. First, we are aiming to develop a generalizable protocol artifact for inter-node flow management in the PI, analogous to the Internet Protocol (IP) that was developed by the Defense Advanced Research Projects Agency (DARPA) in 1973 (Clark, 1988). Second, we will demonstrate the protocols' feasibility and resilience by testing it in different situations and by introducing uncertainties in a simulation environment, using actual distribution center data (next steps). Being able to demonstrate that the protocol works shows practitioners that a collaborative network-of-networks like the PI is implementable. Third, similar to the development of the Internet where the TCP/IP protocols laid the groundwork and influenced the creation of more sophisticated protocols (Clark, 1988), our goal is to establish a simple and generalizable protocol structure

[2] » RFC Editor (rfc-editor.org)

that is intended to serve as a basis for the development of more sophisticated protocols that can address specific issues in various contexts.

In this paper, we discuss collaboration in logistics, the PI and Internet protocol models (Section 2), and then explain the framework and mechanics of our protocol with pseudocode examples (Section 3). We conclude with our findings and future research directions.

2 Literature review

2.1 Logistics collaboration

Collaboration in supply chains can be defined as “the ability to work across organizational boundaries to build and manage unique value-added processes” (Fawcett et al., 2008, p. 93). When the advantages of collaborative work surpass its drawbacks (Terjesen et al., 2012), companies might endeavor to merge complementary capabilities to generate value beyond what they could attain individually (Barratt, 2004; Daugherty et al., 2006). As a result, collaboration in supply chains is recognized as one of the most effective ways to improve freight transportation efficiency in the pursuit of sustainability (Goldsby et al., 2014).

Supply chains encompass various levels and hierarchies, but collaboration within this framework can be categorized into two forms: vertical and horizontal collaboration (Mason et al., 2007). Vertical collaboration focuses on the beneficial interaction between vertically integrated actors on different levels within a supply chain. This facet has been extensively explored in the literature, including studies by Barratt (2004), Power (2005) and Stadtler (2009). More recently, horizontal collaboration has gained traction which focuses on the interaction of companies that are operating on the same level of the supply chain, e.g., shippers, logistic service providers (LSPs), or customers (Mason et al., 2007; Pan et al., 2019).

In freight transportation, horizontal collaboration has grown both industrially and academically. Industrially, initiatives such as the European carrier association ASTRE have facilitated cooperation among independent carriers (Pan et al., 2019). Companies are seeking greater synergies to reduce inefficiencies, leading to extensive and efficient collaboration across supply chains in terms of lower delivery costs (Cruijssen et al., 2007), fewer carbon emissions (Karam et al., 2020), increased service levels (Chabot et al., 2018). Additionally, successful cases, such as the collaboration of four manufacturers in France (Mars, UB, Wrigley and Saupiquet), illustrate its effectiveness. Academically, horizontal collaboration is an evolving field that is witnessing the emergence of new concepts, methodologies and models that promote collaboration from the carrier level to the supply network level.

On the carrier level, Pan et al. (2019) classified horizontal collaboration schemes into six categories, such as Carrier Alliance and Coalitions, Transport Marketplaces and, amongst the others, the Physical Internet (PI). In most collaborative scenarios, partner companies are required to share information about their transport orders and delivery vehicles with a central coordinator, such as a logistics service provider (Karam et al., 2021). This shared information is then used by the central coordinator to identify collaboration opportunities, formulate a joint delivery plan, or propose freight exchanges between partners.

However, the practical implementation of horizontal collaborative transportation networks is rarely observed. This is mainly due to the fact that the collaborating partners are often competitors, which raises concerns about establishing a trustworthy partnership (Basso et al., 2019). Providing the power over operations and customer information to a central coordinator would neither eliminate trust issues nor necessarily be compliant with competition law (Karam et al., 2021).

Nonetheless, there is the concept of the PI, which stands somewhat apart from the other horizontal collaboration schemes as identified by Pan et al. (2019). The PI circumvents the challenges linked with a central coordination entity by embracing Internet principles that employ distributed governance across a collaborative network-of-networks (Montreuil, 2011).

The Internet, which the PI concept originates from, provides a standardized approach for the distributed management of the transmission of data packages within the largest system ever created by mankind (Dong & Franklin, 2021). It connects billions of devices, networks and subnetworks transmitting data packets from source hosts to destination hosts, which is analogous to what the PI aims to accomplish. To enable such services, the Internet applies protocols, incorporating rules, guidelines and governance mechanisms that support the sharing of resources across networks. Internet -like protocols are also required for the operationalization of the PI.

2.2 Physical Internet protocols

We see the development and implementation of protocols addressing the management and organization of logistics flows in the PI as a central prerequisite for the implementation of the PI. The requirement for protocols comes from the different entities and actors involved in the PI. As the PI consists of a network-of-networks that incorporates nodes, lanes, carriers, shippers and shipments, the requirement for protocols addressing different purposes is fundamental (Montreuil, 2011). What is required are fast and reliable protocols like those employed in the Internet that are able to process large numbers of loads (Briand et al., 2022). Standard optimization techniques require either enormous computing power or significant calculation time to deal with the dynamic nature of the PI. Therefore, it is crucial to take one step back and look at the first Internet-analogous conceptualizations for a protocol stack.

Montreuil et al. (2012) proposed the first protocol stack taking into consideration the seven-layer OSI model. Other authors have used the five-layer Department of Defense (DoD) model as an example since it is the model upon which the Internet is built (Dong & Franklin, 2021). The DoD model is like the OSI model but consolidates three OSI layers into one.

First attempts to design technical protocols for the PI were made by Sarraj et al. (2014b) They laid the foundation for protocols by referring to Internet protocols and assessed PI performance based on a stylized case that validated the benefits of the PI. The transfer between Internet and PI protocols was conceptually further developed in Kaup et al. (2021) by a detailed comparison between these protocols relying heavily on the seven-layer OSI model.

In Sarraj et al. (2014a) they further proposed a structure for protocols, incorporating containerization, consolidation for efficient asset utilization and routing through the PI in combination with a clear assessment of the usability of the protocol. The results show a significant improvement in fill rates, reduction in CO_2 emissions and lower costs. However, the approach lacks dynamism and scalability. The first scalable routing protocol is proposed by Gontara et al. (2018) taking advantage of the Border Gateway Protocol (BGP) used in the Internet for routing between neighboring networks, so called Autonomous Systems (ASs). They highlight the reliance on information exchange between ASs for their protocol that supports dynamism in the logistic network, especially when it comes to disruptions on lanes, e.g., congestion. Their protocol solves relevant problems in terms of container filling, flow routing and consolidation.

Dong & Franklin (2021) address the dynamism issue by considering the operationalization of Internet networks. They consider metrics such as cost, time, schedule, emissions and capacity that must be dynamically optimized for effective and efficient operationalization of the PI. To address these issues, standard optimization processes face scalability problems in a dynamic environment like the PI. Briand et al. (2022) propose a fast, reliable and resilient mechanism for routing and assignment of Full Truck Loads (FTL) that is scalable and based on an auctioning mechanism. Their approach is among the first that considers the competitive interaction of stakeholders in the PI. They show by simulation that their protocol leads to a significant reduction in cost as well as environmental impact in terms of reduction in empty milage. In addition to Briand et al. (2022), Lafkihi et al. (2019) consider an auction-based optimization protocol for a PI-like network. Their protocol takes incentive mechanisms and collaborative rules into account for the management of shipper-carrier relationships and routing across the network.

Apart from routing, other protocols are required for the PI. Shaikh et al. (2021) developed protocols for fast and efficient dynamic consolidation of PI containers at hubs under the assumption of on-demand transportation services being available. They propose the idea of using maximum latency to adjust waiting times at nodes and schedule flexibility based on upstream visibility. In the context of parcel logistics Orenstein & Raviv (2022) proposing the design and operation of a Hyperconnected Service Network for parcel delivery considering a routing mechanism and math heuristic for routing and scheduling at service points where vehicles are arriving and leaving according to fixed schedules.

Protocols focused on tasks such as auction logistics scheduling for perishables (Kong et al., 2016) and truck/container scheduling at road-rail hubs (Chargui et al., 2020) provide operational value, but don't fully align with the Physical Internet (PI) concept, which aims to optimize load flows between nodes. While most PI protocols differ significantly from digital ones, our approach, inspired by Internet studies, may evolve to address the physical-digital divide, as discussed by Dong & Franklin (2021)

2.3 Internet protocol suite

Since the PI takes its name and functionality from an analogy to the Internet, we focus on this analogy and the functionalities of the Internet to assist in organizing our thoughts concerning the development of protocols for the PI. It is, therefore, important to understand some key considerations of the Internet and its protocols before we take the Internet analogy into consideration for the PI protocols.

In the early 1970s, research on packet-switched networks aimed at sharing computer resources laid the groundwork for the Internet's protocols (e.g., Heart et al., 1970; R. Kahn & Crowther, 1972; R. E. Kahn, 1972; Roberts & Wessler, 1970). Unlike earlier efforts that focused on intra-network communication, Cerf & Kahn (1974) introduced a framework for sharing resources across networks, detailing an architecture that included hosts, packet switches, and their interconnections. They addressed the need for standard protocols, such as TCP/IP, to handle network variations, including packet sizes and error handling. Their work also emphasized the importance of "gateways" for connecting independent networks and facilitating process-to-process communication under varying network conditions.

TCP, as first described by (Cerf & Kahn, 1974), governs the division of data or messages into transmittable packets, oversees the transmission of these packets over the Internet, and guarantees the successful delivery of the transmitted data to its intended destination. In fact, TCP represents the start and the end of the transmission of the data packet. In the physical freight industry, TCP is analogous to a freight forwarder responsible for ensuring and regulating the reliable end-to-end delivery of goods. However, the Internet is constructed from interconnected networks, with routers serving as pivotal connection points between these networks (Clark, 1988). Within this framework, IP manages the transmission between routers and establishes rules for packet routing and addressing, enabling routers to direct packets from router to router seeking to reach their designated destination hosts. This is what freight/carrier companies are intended to do in the physical world.

The protocols utilized on the Internet serve as a robust starting point. Consequently, we consider the information systems literature with a focus on what was published on networking protocols as a relevant source to inform our research. Specifically, the early literature on the Internet Protocol (IP) is of great importance for our research, given that we are developing inter-node protocols in this project, similar in their requirements to the requirements that resulted in the IP.

2.4 Internet protocol

The first official specification of the IP was made in 1981 by Jon Postel. In general, he specified the IP as crafted for application in interconnected systems of packet-switched computer communication networks (Postel, 1981). The IP facilitates the transmission of data blocks, known as datagrams, from sources to destinations. These sources and destinations are hosts identified by fixed-length addresses. Additionally, the IP accommodates the fragmentation and reassembly of lengthy datagrams when needed (similar to deconsolidation and reconsolidation in logistics networks), ensuring seamless transmission through "small packet" networks. Fragmentation is especially necessary when the bandwidth of a network is not sufficient for the size of the datagram (or the capacity of a transport mode is small compared to load size). It is important to mention that the IP is limited in its functions. It does not incorporate end-to-end data reliability mechanisms, sequencing, flow control or other mechanisms that are commonly found in host-to-host protocols like e.g., TCP. However, the IP relies on the services incorporated in its underlying networks by providing information for handling a message transmission and consuming information based on transit parameters. The IP sits between the layers of the host-to-host protocols, such as TCP and local network protocols. IP is called on by TCP and calls on local network protocols to carry the datagram to the next node. We refer interested readers to Postel (1981) for a detailed elaboration on the specifications and operation of the IP.

3 The PI-link protocol

3.1 Integration into the overall frame

The PI-link protocol is designed to facilitate the movement of shipments across a network of interconnected nodes. This involves transferring shipments from one node to another until the destination is reached. Therefore, the PI-link protocol specifies the operational node-to-node information-exchange for the link layer. This information exchange can be distinguished into two types of information. Static and dynamic information. Static information refer to shipment specifications that are set at the beginning of the journey and are passed from link to link without any changes. They serve as inputs for nodes to process, route and assign shipments in a productive way. In contrast, dynamic information refer to shipment state information and is encrypted into each link at the beginning of each link journey by the nodes. Shipment state information is collected along the link, handed over to the node at the end of the link and then purged for that link. Nodes push this state information to the control layer, where they are processed and monitored. Figure 1 illustrates this process visually. Based on this information the control layer can control the shipment and make decisions that inform the nodes about how to behave (route, assign or handle the shipment). However, the control layer and its respective protocol is subject to future research. This paper focuses on the link layer and its governing PI-link protocol and assumes inputs from the control layer are provided to the nodes in a "black-box" fashion.

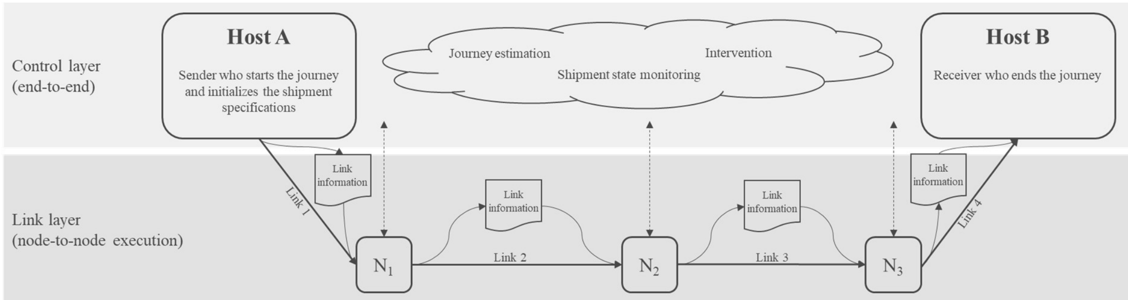

Figure 1: Shipment journey operations on two layers

3.2 Information management

As mentioned, the PI-link protocol specifies the sharing of two types of information: **Information about shipment specifications** and **information about the shipment state**.

Shipment-specifications are generally static on a single link, they remain the same over time. However, they can be changed by nodes when starting out on to a new link, but then stay static until at least the next node. Static information includes (a) Addresses (origin -destination, prior node, subsequent node), (b) Shipment specification (order number, number of packages/items, dimensions and weights of packages, ability to break shipment up, belonging to larger shipment, time window of promised delivery), (c) Journey initiator (freight forwarder, shipper, PI), (d) Service requirement (careful handling for fragile goods, cooling for perishable goods) and (e) Priority (indicates that the shipment is to be handled in an expedited manner). Priority can be increased by nodes as it becomes clear that a shipment may run into a delay. Additionally, the (f) Service provider (carrier and transport mode used) must be specified for the link. The service provider is an outcome of the routing and load allocation procedure undertaken by the nodes. What comes along with this are the (g) Estimated "cost" for a link that must be encrypted into the link (costs are not limited to monetary costs but also to time elapsed on the link or emissions emitted)[3]. These costs are a planned target the link aims to achieve.

In contrast, shipment states are rather dynamic, they change along the journey of the shipment over a link. Shipment states are primarily focusing on the (h) Cumulative "costs" occurring on the link between two nodes (e.g., actual distance traveled, actual time traveled, etc.). These costs are collected so that comparisons of actual versus planned costs can be made. Nodes (using internal protocols) evaluate for inbound shipments the cumulative costs that occurred on the last link against the targeted costs specified at the start of the link journey. Deviations between current and target values will be conveyed by the node to the control layer which takes action based upon this information. This concept is inspired by the "Time to Live" trigger specified by the IP (Postel, 1981).

It might be questioned whether payment-related information is within the scope of the protocol. However, we argue that resolving payments for a shipment and associated services throughout the journey is a task for a comprehensive protocol that governs the end-to-end journey (the control layer), not just the node-to-node transfer and falls therewith out of the scope of this protocol. However, the PI-link protocol accumulates costs incurred along each link and communicates them to the higher-level protocol that performs total shipment cost calculation.

[3] The concept of cumulating costs per "hop" has also been suggested for predetermining a price for a connection on the Internet(Stiller & Reichl, 2001).

3.3 Model of operation

It is important to mention that the PI-link-protocol process is an information-sharing process. The protocol uses the services of its link origin-destination nodes but does not specify how they should use or process the information it carries (e.g., the node's internal systems are responsible for routing the shipment to a specific $d \in D$ based on certain decision parameters or algorithmic results). Nevertheless, it is responsible for exchanging and providing the relevant information based on which node-internal mechanisms can, for example, determine the optimal route. In line with Postel's (1981) description of the operations of the Internet Protocol, the PI-link protocol implements two basic functions: shipment data sharing and shipment state monitoring on a specific link. In addition to that, the nodes (in our model the T) implement mechanisms that process the information provided by the PI-link protocol and respond in a stochastic fashion. It is important to mention that these functions are not part of the PI-link protocol but are the responsibility of the node's internal management system. Table 1 provides an overview on the notations used in the following sections to describe the protocol.

Table 1: Notation of parameters used

Node parameter		**Load parameter**		**Link parameters**	
Upstream Node	$u \in U$	Load	$a \in A$	Link	$l \in L$
Downstream Node	$d \in D$	Request	$r_a \in R$		
Transfer Node	T	Load specification	$spec_a$		
		A cumul. cost ul	cc_a^l		
		A target. cost ul	$cc\_tar_a^l$		

To model the PI-link protocol we consider a section of a logistic network where several Upstream Nodes $u \in U$ generate loads $a \in A$ that are sent on a set of Links $l \in L$ connecting each u to an intermediate Transfer Node T and further downstream T to Downstream Nodes $d \in D$. The PI-link protocol will be implemented for each $l \in L$. Protocol supporting functions are implemented in the T. In a whole PI-network the PI-link protocol would be implemented for each link in the network. However, for explanatory simplification, we confine our discussion to the transmission of a shipment from an upstream node to a single intermediary transfer node and onwards from the transfer node to a downstream node. Figure 2 illustrates the operational interaction scheme specified by the protocol between nodes.

In general, the process specified by the PI-link protocol can be subdivided into three separate processes, namely (1) outbound dispatch, (2) link monitoring (3) inbound receipt.

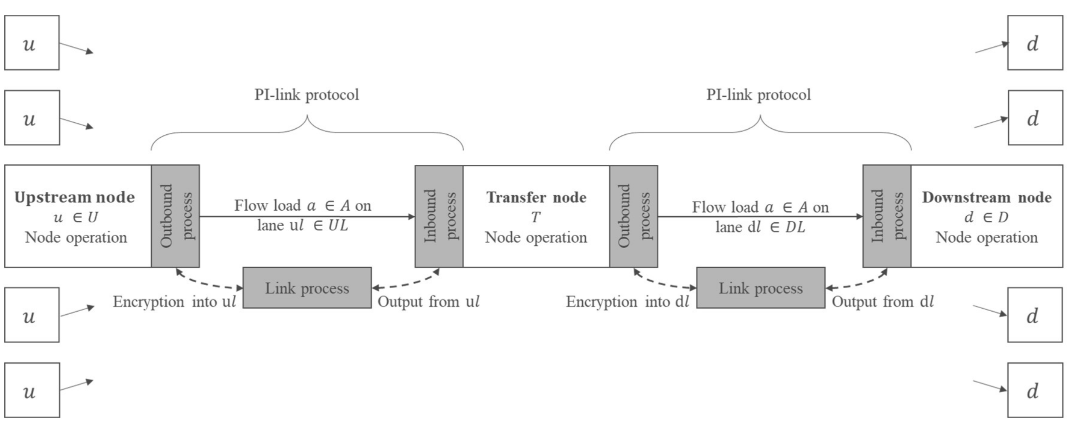

Figure 2: Schematic interaction model of the protocol

In our model, we assume the loads $a \in A$ to be generated at the upstream nodes $u \in U$ and to be assigned by an assignment mechanism (e.g., an auction as proposed by Briand et al. (2022)) to a link l. The prerequisite for an assignment of a load is that it is not in a ratention status. Retention can be initiated if a load faces an issue, such as excessive costs at a previous link or damage, that requires a decision from the responsible journey initiator. A successful assignment is indicated by an upstream request for assignment $r_a \in R$. Process 1 illustrates the outbound dispatch process after a succesfull assignment.

Upon receiving an assignment request $r_a \in R = 1$, including the load specifications $spec_a$, target cost $cc\_tar_a^l$ and the dedicated link $l \in L$ from a node $u \in U$, the protocol proceeds to encrypt the shipment specifications and the target cost in the link $l \in L$. In this context, the specification serves as a repository/carrier of shipment information (as discussed earlier). These details typically include factors like load weight, dimensions, or cooling requirements. The encryption establishes the link by providing the relevant information and conditions to the carrier operating on the link prior to dispatch. This is important for the carrier to plan operations accordingly. Thus, the encryption process prepares the journey of the load to the next node that is started when the node releases the load as an outbound shipment. Process 1 technically demonstrates this process.

Process 1: Outbound dispatch

```
Input: Receive r_a ∈ R = 1 including spec_a, cc_tar_a^l and l ∈ L from u ∈ U
for r_a ∈ R = 1 do
        encrypt spec_a into l             // journey static shipment specification encryption
        encrypt cc_tar_a^l into l         // link static cost target encryption
Output: Encrypted link l                  // link established
end for
```

Once a load $a \in A$ is dispatched and begins its journey on a link $l \in L$, the protocol actively tracks the load's progress. As a result, the costs cc_a^{ul} associated with the link are calculated and updated. This means that the collective cost factor cc_a^l, which incorporates a variety of cost such as money, time, and emissions, grows steadily as the load progresses on the link. Emission costs, for example, are determined using specific calculation methods that take into account the distance traveled and the mode of transportation used. This procedure is defined by process 2.

Process 2: Link monitoring

```
Input: Encrypted link l
for a ∈ A on l ∈ L do
        accumulate cc_a^l                 // accumulation of cost along the link
end for
```

As a load $a \in A$ arrives at at a destination node, e.g., node T, the inbound process (process 3) starts its action. This is a process for handling and analyzing load-related data carried and collected by the link.

Initially, the node receives a load, denoted as a, from a set A, which comes from an upstream link ($l \in L$). For each load a, the protocol specifies the decryption of several pieces of information: the load specification $spec_a$, the target cost $cc\_tar_a^l$, and the actual cumulative cost cc_a^l. These encrypted parameters represent the detailed shipment information, the cost goals set for the load and the specific link, and the actual costs incurred on that link, respectively. Upon receiving these parameters, the node T performs a critical comparison between the actual cumulative cost cc_a^l and the target cost $cc\_tar_a^l$.

If the actual cost exceeds the target, indicating a discrepancy or inefficiency in handling the load, the node notifies the control layer about the discrepancy. When the total cost incurred exceeds the target cost the node communicates the actual cumulative costs cc_a^l to the control layer for additional actions or analysis. Conversely, if the actual costs cc_a^l do not exceed the target, the actual cumulative costs are simply communicated to the control layer without the need for special attention.

Process 3: Inbound receipt

```
Input: Receive a ∈ A from l ∈ L
for a ∈ A on l ∈ L do
        decrypt spec_a from l ∈ L            // handover of load specification to node
        decrypt cc_tar_a^l from l ∈ L        // handover of target cost to node
        decrypt cc_a^l from l ∈ L            // handover of actual cumulative cost to node
        Input: Receive encrypted parameters spec_a, cc_tar_a^l and cc_a^l
        if cc_a^ul > cc_tar_a^l then         // target-performance comparison
                retain a                     // retention of problematic load
                Output: Inform control layer on cc_tar_a^l exceedance
                        Broadcast cc_a^l to control layer
        else
                Output: Broadcast cc_a^l to control layer
        end if
        purge cc_a^l
end for
```

After handling the comparison and necessary communication with the control layer, the PI-link information for the shipment is purged and the PI-link protocol for that shipment on the link is terminated. This cycle repeats for each load a within A received from the links l, ensuring each load is evaluated and managed according to its performance relative to cost targets.

4 Conclusion

In conclusion, this paper has laid the foundational framework for the PI-link protocol, drawing parallels with the Internet's operational principles to enhance the PI node-to-node transshipment processes. Our research delineates a comprehensive structure for managing and controlling logistic flows, emphasizing the significance of streamlined, standardized protocols akin to those that have revolutionized digital communication.

Our findings underscore the critical role of simplicity, interoperability, and standardized processes in facilitating seamless collaboration across diverse logistics service providers (LSPs). By analogizing from the Internet's TCP/IP model, we have outlined a protocol framework that not only facilitates efficient and resilient transshipment between nodes but also sets the stage for future advancements in end-to-end logistics management. The IP equivalent PI-link protocol emphasizes the importance of managing dynamic and static information exchange between nodes, ensuring that shipments are processed, routed, and monitored effectively across the network.

Future research directions are pivotal, with a particular focus on simulation and testing of the proposed protocol in varied and uncertain environments. These steps are essential to validate the protocol's adaptability, efficiency, and resilience, demonstrating its practical applicability and effectiveness in real-world logistics scenarios. Such empirical testing, using real world data, will not only affirm the protocol's theoretical underpinnings but also provide invaluable insights into its operational impact, fostering a more collaborative, sustainable, and efficient logistics network in line with the overarching goals of the Physical Internet.

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Optimization Model-Driven Adaptation in Interconnected Manufacturing Networks

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Abstract: *In an ever-evolving market landscape, companies often excel at spotting opportunities within their existing product range but struggle to identify opportunities for new product lines. This gap underscores that traditional approaches, often siloed and focused on singular manufacturing systems, fall short in exploiting the full spectrum of capabilities that an interconnected, ecosystem-wide perspective offers. This research proposes to bridge this gap by extending the adaptability analysis from isolated systems to an interconnected network framework by manufacturing potential collaborative efforts. The study introduces an optimization model designed to accurately give adaptation recommendations based on shared capabilities. It capitalizes on our results of an ontology-based matchmaking process to effectively map identified manufacturing service providers candidates. The model encapsulates a decision-making process in an enterprise's location and operation allocation network, aiming to map out the identified candidates, explore feasible task allocations, and ultimately select an optimal configuration that meets the manufacturing requirements. An illustrative case involves a stroller manufacturer branching into folding bicycle production. This scenario serves as a validation of the model, showcasing its ability to enhance company adaptability and resilience. Through interconnected production networks, the model helps seizing new production opportunities and accurately estimate co-production costs.*

Keywords: *Interconnected Production Networks, Optimization Model, Physical Internet, Resilience, Adaptability.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☒ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

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1 Introduction

Over the past few years, the paradigm of traditional manufacturing planning has increasingly shifted towards optimizing collaborative efforts at the inter-enterprise level, a strategic pivot in response to the challenges and competitiveness demands of emerging markets(Andres et al., 2021). Historical examples like the collaboration during World War II among companies such as Ford, Douglas, and Convair, as well as the partnership between GM and Philips for the HOPE ventilator project during the COVID-19 pandemic, showcase the effectiveness of this evolution. Similarly, Ford's initiative with the Mustang Mach-E electric SUV demonstrates the same collaborative spirit driven by strategic market expansion, not just the need for crisis management.

However, the rapid changes in market demands and advancements in production technologies have made it increasingly difficult for a single enterprise to effectively respond on its own(Hu et al., 2020). Today, a collaborative network of partners, leveraging shared capabilities and resources, is crucial to mitigate the environmental and social impacts of operational expansion. This approach aligns with Virtual Enterprise concept (Polyantchikov et al., 2017), where the outsourcing of manufacturing tasks goes beyond transactional exchanges and into strategic interconnected production networks. Collaborative manufacturing partner selection for a product in a collaborative environment is a complex decision-making problem that requires comprehensive consideration of multiple attributes of candidate partners(Moghaddam and Nof, 2018). Yet, current research often overlooks crucial factors such as the degree of alignment between a partner's manufacturing capabilities and the overall financial consideration(Li et al., 2021). This gap highlights the need for an integrated approach, leading to a fundamental research question: *How can enterprises strategically select partner candidates to optimize the configuration of a Virtual Enterprise and effectively capitalize on new production opportunities?*

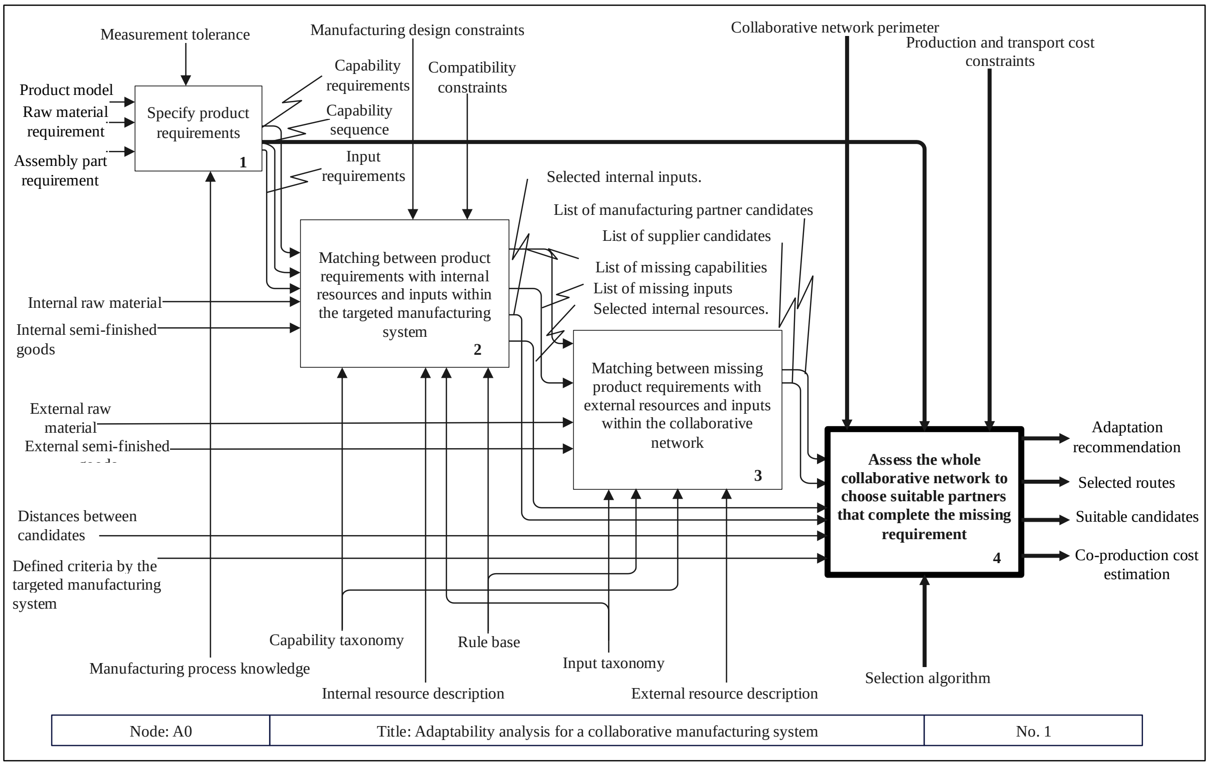

Figure 1: Adaptability analysis framework for a new production opportunity in an interconnected collaborative manufacturing network(Ferhat et al., 2023).

Building on our previous work, we have developed a framework for adaptability analysis within collaborative manufacturing systems, as depicted in Figure 1. This framework consists of two main objectives: initially, identifying potential partners through a matchmaking sub-process that aligns resources with operational requirements; subsequently, the selection of suitable candidates from this pool, which forms the crux of this research (sub-process 4 in bold on figure 1). The core challenge addressed in this paper is the Partner Selection Problem (PSP), focused on selecting optimal partners within a a production network. Addressing our research question, this process ensures that strategic alignment and financial considerations are at the forefront of partner selection decisions, aiming to optimize both operational efficiency and production network resilience.

This paper introduces an illustrative case study involving a leading folding stroller manufacturer that plans to expand into folding bicycle production using the Partner Selection Problem (PSP). This example primarily demonstrates the practical application of our optimization model, which estimates the co-production costs—including manufacturing and transportation expenses. Such insights are critical for leaders in making informed decisions about new manufacturing opportunities and underscore the significance of cooperative innovation in interconnected markets.

The paper first explores the theoretical background, followed by a discussion of our contribution, including the PSP implementation. It then moves into the context of an illustrative case study, examining the implications of our findings. The final section draws conclusions and suggests directions for future research, offering a comprehensive look at both the theoretical and practical aspects of partner selection in modern manufacturing environments.

2 Theoretical background

2.1 Production network

Over the past two decades, considerable scientific research and numerous projects have focused on production and manufacturing networks (Mladineo et al., 2018). These studies, highlighted by researchers such as (Müller, 2006) and projects like those by (Markaki et al., 2013) have employed various terminologies to describe types of production networks. These include "global production networks" (Jaehne et al., 2009), reconfigurable collaborations" (Schuh et al., 2008), "dynamic manufacturing networks" (Markaki et al., 2013), "virtual enterprises" (Camarinha-Matos et al., 2009) and “universal manufacturing systems”(Kusiak, 2022). Virtual enterprises are particularly notable as dynamic, opportunity-driven networks established to seize specific business opportunities within a limited timeframe.

A significant challenge in managing these networks is partner incompatibility, which often leads to the failure of collaborative projects (Dacin and Hitt, 1997). It is crucial for organizations, regardless of size, industry, or location, to select partners that not only align with their objectives but also bring the necessary skills and strategic orientations that complement their own operations(Emden et al., 2006). This needs to form a production network with suitable partners brings us to a critical inquiry:

R.Q: How can enterprises strategically select partner candidates to optimize the configuration of a Virtual Enterprise and effectively capitalize on new production opportunities?

2.2 Partner Selection Problem

Effective partner selection is critical to successfully capitalize on market opportunities. Known as the Partner Selection Problem (PSP), this issue arises when the production process requires integration of various technological operations that different enterprises within the network can perform. Addressing the PSP involves assessing potential partners' capability to meet production demands efficiently.(Huang et al., 2018; *Production Networks meet Industry 4.0*, 2020; Tao et al., 2012; Wu and Su, 2005).

Partner selection problem in production networks has been a recurring issue in various studies. (Han Zhao et al., 2006)proposed a method of rough production planning based on case-based reasoning to address partner selection and task assignment in extended enterprises. (Wu and

Barnes, 2011) discussed partner selection and production-distribution planning in defective supply chain network systems, showing that the proposed approach outperformed existing methods. (Veza et al., 2015) highlighted the importance of evaluating enterprise performance to solve the partner selection problem in production networks. (Mladineo et al., 2017)introduced the HUMANT algorithm to solve partner selection problems in Cyber-Physical Production Networks. (Polyantchikov et al., 2017)focused on sustainable partner network solutions for virtual enterprise formation. (Guo et al., 2019) proposed a Distributed Approximation Approach to solve the sustainable supply chain network design problem by dividing it into partner selection and transportation planning sub-problems. Overall, these studies emphasize the significance of effective partner selection methods in optimizing production network. These studies underscore the importance of developing robust partner selection methodologies to optimize production networks effectively and efficiently. Researchers concur that decomposing the complex problem of partner selection into manageable sub-problems allows for more focused and effective solutions (Wu and Barnes, 2018).

3 Contribution

3.1 Problem Description

In this study, we propose an Integer Linear Programming (ILP) model to address the (PSP) within a production network. The model aims to minimize total production costs, encompassing both manufacturing expenses for each operation and transportation expenses between enterprises by proposing a new Virtual Enterprise configuration. It facilitates strategic enterprise selection and precise determination of operation and transport quantities that align with the product's nomenclature and manufacturing process. Our approach builds on a foundational ontology-based framework and enhances decision-making by integrating enterprise selection with optimal path determination within the network. This dual focus enables a comprehensive allocation of tasks across selected enterprises, accounting for both their unique production capabilities and the logistical intricacies of the production sequence.

In Figure 3, the diagram represents a product that requires five distinct operations for its manufacturing process. These operations are mapped out across a network consisting of three pre-identified manufacturing systems, each capable of performing some of the required operations. Our objective is to determine the optimal configuration of a new VE, effectively aligning each required operation with the most suitable manufacturing system. Through this approach, we aim to enhance the coordination within the production network, selecting the best partners and their corresponding operations to streamline the manufacturing of the product.

Despite numerous studies on partner selection within production networks, there remains a significant gap in dynamically adapting these strategies for Virtual Enterprises, particularly in environments characterized by rapid market fluctuations and swift technological progress. This study aims to bridge this gap by devising a responsive partner selection methodology tailored for Virtual Enterprises, enhancing their agility and effectiveness in capitalizing on emerging opportunities, as directly addressed by our research question.

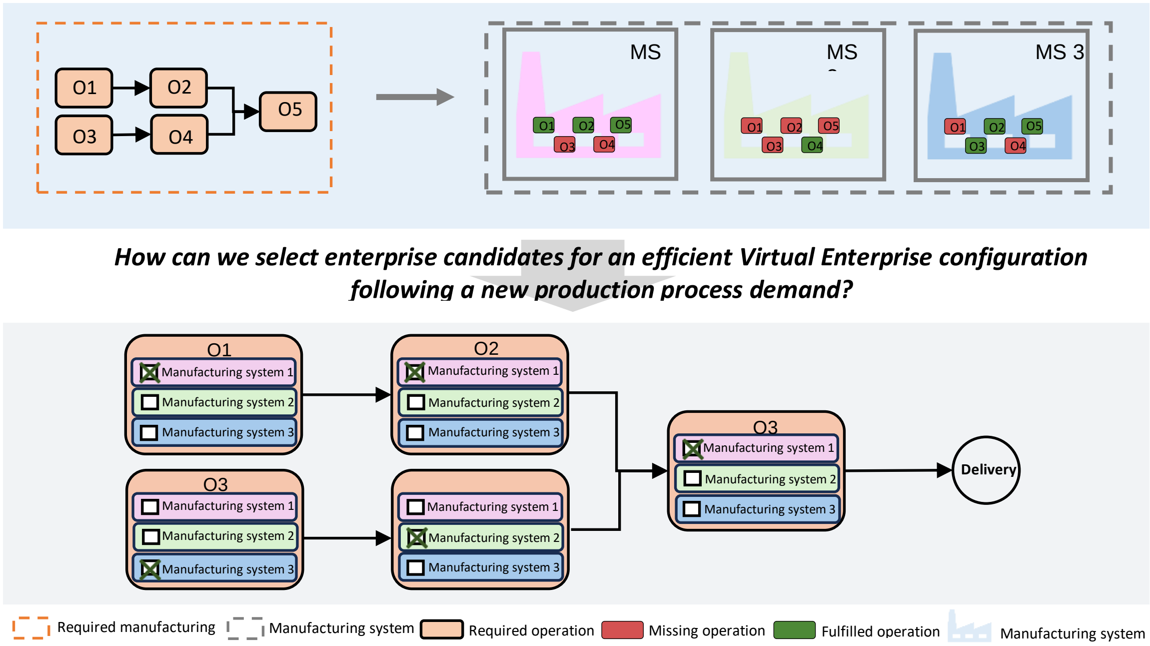

Figure 3: Partner selection problem application within a production network for a new production process.

3.2 Model Assumptions

Manufacturing enterprises can share their capabilities within the network to fulfil a new production demand, but it is crucial to select optimal agents (enterprise) for each activity (operation) to achieve the new production requirement with a reasonable manufacturing and transport cost. To navigate this challenge, we establish the following assumptions:

Hypothesis 1 (H1): Exclusive Operation execution

We suppose that each required operation is executed exclusively by a single enterprise, precluding the co-production of any part of a product by multiple enterprises.

Hypothesis 2 (H2): Single Output Provision

We posit that each operation undertaken by any enterprise resource results in a single output.

Hypothesis 3 (H3): Leadership and Opportunity Offer

This hypothesis posits that a leading enterprise within the network spearheads new production opportunities, making pivotal decisions based on global production costs and partner bids. This leader assesses partner proposals against cost-efficiency and strategic fit, ultimately determining the network's engagement in a co-production partnership.

3.3 Objective function

$$min \sum_{i}^{I} \sum_{j}^{J} \sum_{k}^{I} C_i^j \, . Y_{ik}^j \; + \sum_{i}^{I} \sum_{k}^{K} \sum_{j}^{I} t_{ik} \, . Y_{ik}^j$$

This objective function aims to minimize the total co-production cost for a demand D. The cost includes the manufacturing cost for each resource of each enterprise selected and the transportation cost inter-enterprises.

3.4 Variables

- $\boldsymbol{Y_{ik}^{j}}$: Quantity produced by enterprise i for operation j, which then serves as the input for enterprise k to carry out the subsequent operation.

3.5 Parameters

- C_i^j : Manufacturing cost of operation j by company i.
- t_{ik} : Transport cost between company i and company k.
- $a^{jj'}$: Operation sequence indicating if operation j must precede operation j'.
- *D:* Final product Demand.
- n^j: Base unit demand for operation j (nomenclature description).
- Cp_i^j: Production capacity of enterprise I for operation j.
- I: Set of enterprises, indexed by i.
- J: Set of operations, indexed by j.

3.6 Constraints

Constraint 1: "Demand fulfilment"

Ensure that the total production for each operation matches the demand.

$$\forall j \in J : \sum_{i}^{I} \sum_{k}^{I} \boldsymbol{Y_{ik}^{j}} = \boldsymbol{D} * n^j$$

Constraint 2: "Sequence of operations"

Enforce the sequence of operations according to $a^{jj'}$.

$$\forall j, j' \in J : such\ that\ a^{jj'} = 1, then\ \forall k \in I : \sum_{i}^{I} \boldsymbol{Y_{ik}^{j}} \geq \sum_{l}^{I} \boldsymbol{Y_{kl}^{j'}}$$

Constraint 3: "Exclusive Operation Allocation"

Ensure that each operation j is procured by only one enterprise i with its required demand.

$$\forall j \in J, \forall i, k \in I : \boldsymbol{Y_{ik}^{j}} = \boldsymbol{D} * n^j$$

Constraint 4: "Enterprise Operational Capacities"

Production quantities must not exceed the production capacities of each enterprise.

$$\forall j \in J, \forall i \in I : \sum_{k}^{I} \boldsymbol{Y_{ik}^{j}} \leq Cp_i^j$$

4 Illustrative case

4.1 Context

In our illustrative case, we examine the strategic expansion of a leading folding stroller enterprise into a new production opportunity: folding bicycles. The manufacturing process for folding bicycles, as detailed in Figure 4, encompasses five distinct operations outlined in the nomenclature located in the upper left of the figure. This process constructs the bicycle using the following components: a frame, a pair of wheels, a front set, a saddle, and a transmission instrument. Central to this study is an analysis focused on the semi-products—those that have undergone specific operations—denoted by numbers 11, 12, 13, and 14, leading to the final product marked as 15. It is these intermediate forms, the semi-products, that hold particular significance in our research, providing critical insight into the efficiency and effectiveness of the production network.
As depicted in the right side of figure 4, the market expansion of the stroller enterprise to a folding bicycle production is supported by a pre-established network of seven enterprises, identified from a larger candidate pool through an ontology-based matchmaking process refined from our initial knowledge graph.
The goal is to select an optimal subset of partners and pathways within this network that minimizes co-production costs. Each selected enterprise contributes distinct resources required for the operations, with unique manufacturing costs and transportation expenses influenced by their geographical distances. The initial production target is set at 50 folding bicycles. By calculating the total production cost, which includes both manufacturing and transportation expenses, we provide the enterprise leader with a co-production cost analysis. This analysis is crucial for making informed decisions about this new production opportunity.

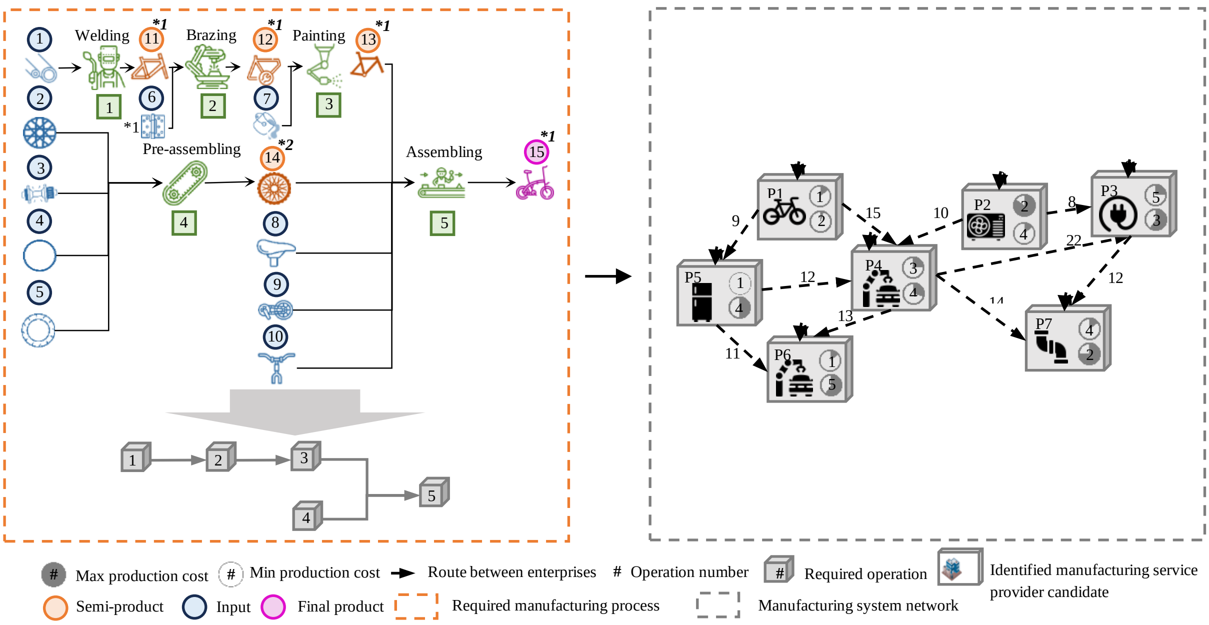

Figure 4: Folding bicycle production requirement for a production network.

4.2 Results

The optimization model has been solved using (IBM ILOG Cplex Optimization Studio). It provides an approach to evaluate stroller company's expansion into the folding bicycle market.

It does so by integrating diverse operational and logistical variables to establish a cost structure. Specifically, the model predicts that adopting this new manufacturing strategy would result in a production cost of 1800 euros for the required demand of 50 folding bicycles. This estimation is foundational for the company, guiding investment decisions and setting a benchmark for financial sustainability in this new market foray (see figure 5).

As illustrated in figure 5, the model proposed anew VE configuration.Enterprise P1 is the starting point, handling Operations 1 with the production of 50 welded frames (semi-product 11) for the folding bicycle. It also executes Operation 2, procuring 50 outputs of brazed folding frames (semi-product 12). The continuation of the manufacturing process sees the semi-finished product 12, with a transport quantity of 50, moving to Enterprise P4P4's handles simultaneously the parallel execution of Operations 3 and 4, producing 50 painted folding bicycle frames (semi-product 13) and 100 wheels (semi-product 14), respectively. Both semi-products 13 and 14 are transported to the next enterprise with a transport quantity of 150 to be assembled within the last enterprise 6. Enterprise P6 is depicted as the final assembly point for Operation 5, where all components come together to complete the folding bicycles (see table 1).

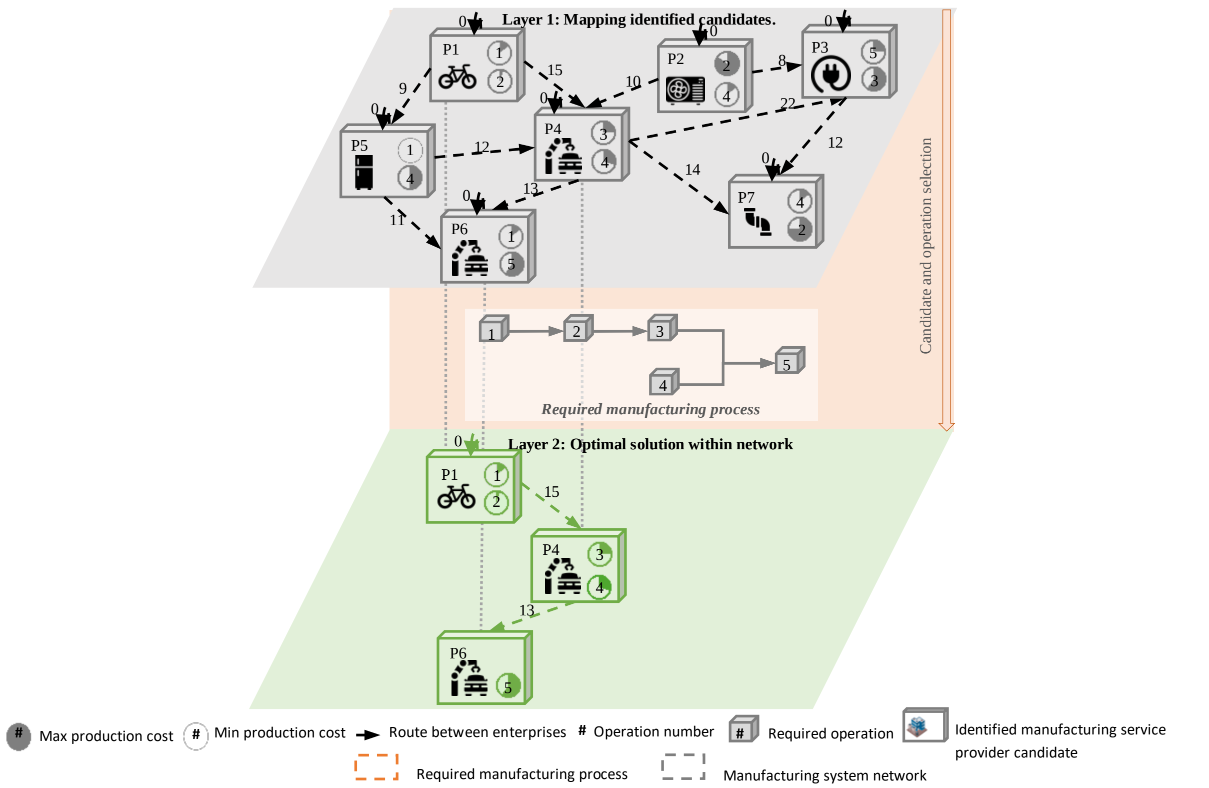

Figure 5: New Virtual Enterprise configuration of the production network for the folding bicycle production opportunity.

The estimated co-production cost and the detailed production path underscore the model's utility in identifying and mapping out the most cost-effective and operationally efficient pathway for the new production opportunity. The leading enterprise of folding strollers can use this detailed financial analysis and the optimized network configuration to make informed decisions about the economic viability and strategic direction of expanding into the folding bicycle market.

Table 1: Operation-enterprise production quantity allocation.

Depart enterprise	*Affiliated operation*	*Following enterprise*	*Production quantity*
1	1	1	50
1	2	4	50
4	3	6	50
4	4	6	100
6	5	6	50

5 Conclusion and perspectives

In the landscape of modern manufacturing, enterprises are frequently compelled to seek partnerships within a production network when new production opportunities arise. This necessity is often driven by limitations in capacity, capability, or financial resources. The critical challenge in such scenarios is to select the most suitable partners who can collaboratively form a new Virtual Enterprise, one that meets the specific criteria set forth by the decision-maker. Addressing this challenge, our research introduced an optimization model tailored to the Partner Selection Problem (PSP). This model is adept at estimating co-production costs, encompassing both manufacturing and transportation expenses, to provide enterprises with the comprehensive financial insights necessary for strategic planning and decision-making. Specifically, our illustrative case demonstrates the model's practical application, as it maps out the production of 50 folding bicycles, selecting partners and pathways to optimize co-production costs, and ensuring an efficient allocation of production quantities. This model not only aids in evaluating the feasibility and viability of the stroller company's expansion into folding bicycles but also serves as a benchmark for production cost comparison in similar industrial applications.

To enhance this proposed PSP model, we recommend these following perspectives:

- Encompassing dynamic variables such as production timelines and batch sizes can be added to expend the model to a job-shop scheduling problem for an operational application.
- Further explore reconfiguration implications, particularly the financial impact associated with modifying production lines, including layouts and machinery, to accommodate new manufacturing ventures.
- Expand the model's capabilities to allow multiple enterprises within the network to undertake an operation procurement. This will provide a more flexible and comprehensive approach to operation allocation across the production network.

These recommended expansions are not solely theoretical; they call for empirical validation and testing. Future experiments could involve applying the model in varied industrial environments to assess its robustness, adaptability, and scalability. Moreover, case studies involving real-time production settings could validate the model's effectiveness in dynamic scenarios, providing deeper insights.

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Demand estimation adapted to hyperconnected transport systems in regional areas

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Abstract: *Regional transportation systems face multiple challenges, including inadequate service quality and scarce and geographically dispersed demand. The Physical Internet (PI) concept offers potential solutions to these issues, yet its focus has primarily been on urban and freight-oriented contexts, overlooking the unique challenges of regional transportation. Moreover, the limited analysis of regional transportation has resulted in a lack of detailed understanding of demand dynamics and difficulties in aligning supply capabilities with demand expectations. To address these issues, this paper proposes a methodology for analyzing regional transport demand, that embraces the PI concept by treating both freight and passenger demand within a unified framework. The methodology defines user profiles, characterizes demand in terms of volume, time, and space, and identifies the factors influencing transportation use. An experimental study using the ECOTRAIN project validates the effectiveness of this approach. This case study not only shows the applicability of the methodology but also highlights its potential to guide the development of tailored transportation solutions suited to regional areas.*

Keywords: *Hyperconnected, Physical Internet, Demand estimation, Regional, Transportation, Supply Chain management.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☐ PI Networks, ☐ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☒ Access and Adoption, ☐ Governance.*

Targeted Delivery Mode-s*: ☒ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation*

1 Introduction

Global trade expansion is putting pressure on the existing freight logistics infrastructure (Ambra et al., 2019). Modern delivery expectations, such as same-day delivery and just-in-time procurement, need smaller, more frequent shipments (Bucchiarone et al., 2021), and although innovations are increasing, they are unable to keep up with the demand (Plasch et al., 2021). Similarly, the inadequacy of traditional human mobility solutions has sparked interest in alternative transport initiatives (Bucchiarone et al., 2021). However, access to these initiatives varies significantly by location. While urban centers benefit from several passenger transport options, regional residents largely depend on personal vehicles due to limited alternatives. Yet, this dependency creates access barriers for vulnerable groups who are either not able to drive and/or own a car (Bucchiarone et al., 2021; Eckhardt et al., 2018; Hult et al., 2021; Sieber et al., 2020). Regional freight transportation also faces challenges: efficient delivery is expensive and inefficient, compounded by infrequent service and inadequate infrastructure (Bruzzone et al., 2021). Additionally, regional logistic networks suffer from organizational and spatial fragmentation, operating in silos with minimal cooperation and struggling under the weight of delivery schedules and lean inventory strategies (Sarraj et al., 2014).

At the same time, the Physical Internet (PI) concept (Montreuil, 2011) provides a novel framework to address these logistics and transportation challenges. By advocating an open system of asset sharing and consolidating flows, PI aims to enhance the integration of various transport modes, potentially improving service quality. Given the low and geographically dispersed demand in regional transport, PI's strategies of consolidation and synchronization offer promising solutions for regional transportation networks. By addressing both physical and organizational barriers, this approach aims to improve efficiency and accessibility in areas where traditional logistics and transport systems often fall short. However, the application of the PI concept has predominantly focused on urban settings and freight management, leaving regional contexts largely unexplored.

Moreover, regional transportation systems have been insufficiently analyzed, presenting several scientific challenges including a deficient understanding of detailed transport demand and difficulties in aligning supply capabilities with demand expectations. This research aims to address these challenges by providing a comprehensive understanding of both the quantitative and qualitative aspects of transport demand in regional areas. It aligns with the PI concept, treating both freight and passenger demands within a unified framework, considering them as a single customer base with common transportation needs.

The research work presented in this paper is a prerequisite for such pooling. Essential to this process is the development of methodologies capable of providing a detailed understanding of transportation dynamics, including the specifics of what is being transported, when, and how. Recognizing the unique and evolving needs of regional transport users, PI strategies must be both tailored to these specific requirements and adaptable to changing conditions. This dual need for strategies to be adapted and adaptable brings us to the following research question**: How can we accurately estimate freight and passenger transport demand in regional areas?**

To bring an answer to this question, the paper is structured as follows: Section 2 describes the theoretical background of the research. Section 3 introduces the proposed approach to characterize the regional transport demand. Section 4 describes a use case where the methodology has been applied, and finally, section 5 concludes with reflections on the findings and perspectives for future research.

2 Background and challenges of regional transportation

This section reviews the literature on current methodologies used in demand forecasting for transportation systems, focusing on models that integrate both freight and passenger flows.

Traditional demand forecasting methodologies like the Auto-Regressive Integrated Moving Average (ARIMA) have been widely used due to their capability to handle time series data. However, these models often fail to capture the complex spatial and temporal relationships among various transportation modes. More advanced techniques such as Recurrent Neural Networks (RNN), Convolutional Neural Networks (CNN), and Graph Convolutional Networks (GCN) have emerged to better address these relationships. Despite their advancements, these models predominantly focus on single-mode predictions and struggle to integrate multi-modal data effectively, highlighting the need for a unified approach that can accommodate the spatial-temporal intricacies and facilitate knowledge sharing across different prediction tasks (Ke et al., 2021).

Most existing research on transport demand modeling concentrates on urban environments, benefiting from the availability of extensive passenger and freight data. This focus leaves a notable deficiency in models suitable for regional contexts, where data is often scarce or imbalanced. Recent studies like those by (Liao et al., 2022) and (Toque et al., 2017) advocate for the integration of geographical information and the use of diverse data sources to improve prediction accuracy in these less-documented areas.

Transport demand models typically focus on either passenger or freight flows. This separation leads to inefficiencies, especially in environments where interactions between both flows are significant. The predominant models adjust demand predictions based on price or service level, risking biased estimations by ignoring the competitive effects of different transport modes (Tsekeris & Tsekeris, 2011). This highlights the need for models that are specifically designed to handle both freight and passenger data within a single framework.

There is a significant gap in the literature regarding demand forecasting within intermodal, multimodal, or synchromodal transport systems, particularly in hyperconnected environments. This gap originates from the limited detailed demand descriptions and the scarcity of studies focused on these complex networks. The current methodologies often fall short in accurately characterizing and forecasting demand in regional transport systems that require coordination between different modes.

This paper addresses these gaps by proposing a methodology designed specifically for regional contexts. It incorporates spatial and temporal elements to define more accurately the characteristics of regional transport demand, given the inadequacy of existing models to simultaneously address the demand for freight and passengers in regional transport.

3 Methodological framework for analysis

This chapter introduces a structured methodology designed to analyze the demand in regional transport systems. This methodology treats passenger and freight transport as a unified entity, thereby facilitating the application of the PI concept across both domains without distinguishing between flows. As illustrated in Figure 1, the methodology involves three sequential steps, each addressing a key question.

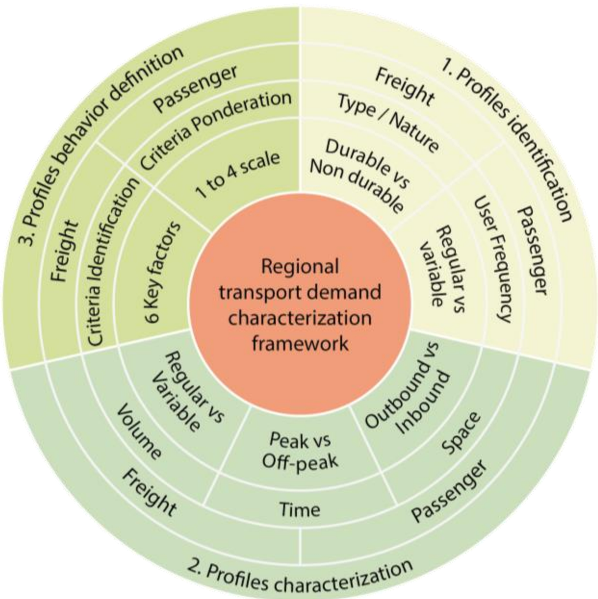


Figure 1: Regional transport demand characterization framework.

3.1. Profiles identification

In this initial phase, the focus is on identifying the potential users of the regional transport systems by establishing clear criteria for segmenting these users. This process addresses the fundamental question: *Which are the user profiles of the regional transport systems?* and is essential for accommodating their diverse transportation needs within a unified operational framework.

Passenger profiling

Users are categorized based on their transport system usage frequency (Kieu et al., 2015). The first group includes frequent commuters who make up most of the daily transportation flows. Their number (volume), travel patterns (points of origin and destination), and schedules are regular. The second group use the services less frequently than the first group, leading to a variable number of users (volume), travel patterns (points of origin and destination), and schedules.

Freight profiling

Freight is categorized based on the type of goods being transported, which affects their transport requirements. The methodology for developing freight profiles was inspired by the goods segmentation outlined by the ASCM (Pittman & Atwater, 2022), which separates goods into durable and non-durable segments. Durable goods are those expected to provide service for more than three years, such as trucks and furniture. Within durable goods, a further distinction is made between consumer goods (e.g., refrigerators) and industrial goods (e.g., forklifts). On the other hand, nondurable goods are those with a service life of less than three years, including perishable and semidurable goods.

3.2. Profiles characterization

Transport demand reflects the need for movement of both people and goods, irrespective of the extent to which these needs are met, and is quantified in terms of number of people, volume, or tons per unit of time and space (Rodrigue, 2020). This definition supports the second step of the methodology, which seeks to analyze the interactions between the different user profiles and the transport systems. The analysis involves a multidimensional characterization, examining volume, timing, and spatial factors, covering both passenger and freight transportation within a single framework. The guiding question here is: *What are the usage patterns of these profiles within the regional transport systems?*

The volume analysis distinguishes between the number of passengers, determined by user frequency, or the number of items moved, expressed in tons (Rodrigue, 2020). Then, the temporal dimension analysis begins by classifying vehicle types as heavy (freight) or light (passenger) and then gathers traffic data on each category. By examining patterns of travel, it distinguishes between peak and off-peak hours, calculating the proportion of traffic for each type during these times. Finally, the spatial analysis concentrates on identifying the most frequented points of origin and destination, considering the layout of residential, commercial, and industrial areas providing to gain insights into movements patterns, as outlined by (Rodrigue, 2020). This differentiation is crucial for understanding the dynamics of both passenger and freight movements. The analysis evaluates cities based on whether they primarily expel or attract passengers. For freight, the focus is on distinguishing between in-shop (retail) movements and domicile (consumer delivery) operations.

3.3. Behaviors definition

Building upon the identified profiles and their usage characteristics, the final step analyses the underlying factors influencing the users' choice of transport. It seeks to reveal the criteria that guide users' preferences and decisions, answering: *What motivates the usage behaviors of customers in the regional transport systems?*

Studies by (Grison et al., 2016) and (Zhu et al., 2017) underline the factors influencing public transport users' choices and satisfaction, pointing out the importance of context in transportation decisions. These studies suggest that user experiences and preferences vary significantly across different situations, suggesting the need for a flexible approach to study user preferences that recognizes these changing influences. (Beirão & Sarsfield Cabral, 2007) further contribute by focusing on the critical aspects of service quality, convenience, and the psychological basis of mode choice, underlining the need for models that adapt to situational contexts and the interplay among factors affecting transportation mode choices.

Building on these observations, this step involves two tasks: initially, identify the factors that influence travel behavior and mode choice among different users, derived from a preliminary literature review. Subsequently, evaluate how these users prioritize such criteria in their mode of transport selection. This involves cross-referencing the list of factors with real-world data to confirm if the theoretical assumptions from literature match actual transportation behaviors.

a. Factors identification

Several studies highlight the significance of transport quality from the passenger's perspective, focusing on factors such as in-vehicle time, comfort, safety, and pricing (Alkharabsheh et al., 2019), along with service quality attributes like reliability and responsiveness (Awasthi et al., 2011). They suggest using both qualitative and quantitative methods to enhance customer satisfaction. (Grison et al., 2017) suggest that comfort often prevails over the availability of transport options, especially for longer journeys, where both practical and emotional considerations influence passenger choices. (Tyrinopoulos & Antoniou, 2014) affirm that service frequency, travel conditions, and punctuality significantly impact satisfaction. Finally, trends in transport preferences are moving towards sustainability and multimodal solutions to improve efficiency and reduce environmental effects (Jonuschat et al., 2015).

From the perspective of freight carriers, the priority shifts to efficiency and logistical effectiveness. (Palšaitis & Ponomariovas, 2012) underline the need for high quality transport services, emphasizing reliability, punctuality, and cost as critical. This perspective is echoed by (Ľoch & Dolinayová, 2015), who identify price and delivery time as the primary criteria for selecting freight services.

Synthesizing the criteria influencing transportation choices, from both passenger and freight domains, as shown in Table 1, six key factors have been identified across the literature.

Table 1: Transportation choices criteria for freight and passengers.

Factor	Description for passengers	Description for freight carriers
Price	It is the negotiated monetary cost of moving a passenger or a unit of freight between a specific origin and destination (Rodrigue, 2020).	
Transport time	Concerns the real duration of transport (Rodrigue, 2020). Includes waiting time and in-vehicle time if some.	
Environmental impact	Is defined as the measure of carbon emissions from a person, organization, building, or operation (Pittman & Atwater, 2022), and is evaluated based on the carbon footprint produced during the transport of passengers and/or goods.	
Timetable compliance. (Reliability)	Signifies the adherence to published timetables, offering a measurable expectation of service reliability through the percentage probability of on-time arrival and/or departure (Pittman & Atwater, 2022).	
Comfort	Assessed through physical and emotional well-being during travel. Physically, it can be quantified by the availability of seats, comparing	Refers to the conditions under which goods are transported, including material handling and preservation of

	the time spent seated versus standing (Beirão & Sarsfield Cabral, 2007; Grison et al., 2017).	cargo's integrity (Pittman & Atwater, 2022).
Safety	Measured by the maximum speed at which the vehicle can react to emergencies, stop safely in response to obstacles or signals, and navigate through curves and other structural elements without causing danger to passengers (Wu et al., 2011).	Security concerns have been directed in two areas: worker safety and theft (Rodrigue, 2020). It refers to measures and practices to safeguard freight during transport.

b. Factors prioritization

To evaluate how each criterion influences user choices, a significance score was assigned to each criterion: 1 (indicating 'Low' importance), 2 (indicating 'Medium' importance), 3 (indicating 'High' importance), and 4 (indicating 'Very High' importance).

4 Application case

The French ECOTRAIN project, aimed at rehabilitating old railway lines and integrating them with other modes of transportation, provides an ideal environment for testing and improving the proposed regional transport demand characterization methodology. This initiative is particularly focused on introducing autonomous regional railway shuttles for both freight and passenger transportation. This section focuses on implementing the framework previously described through a case study involving six cities from the Occitanie region in France: Carcassonne, Castelnaudary, Narbonne, Castres, Béziers, and Revel. These cities were selected for their demographic diversity, population size, existing transport infrastructures, and the potential for integrating new transport services (as part of the ECOTRAIN project), which collectively provide a basis for applying and validating the proposed methodology. Such criteria ensure they mirror the complexities of regional transportation and underscore the project's goal to connect less accessible regions.

4.1. Profiles identification

Passenger profiling

The first category, which comprises regular users, is divided into students and workers who rely on public transport for their daily commutes. The second category includes variable users, notably the elderly, who consistently use the transport system, and tourists, who depend on public transportation (PT) during their visits. Further refinement within these groups took specific characteristics into account: Students were classified by age, while workers and the elderly were differentiated by their socio-professional categories. Tourists, however, are treated as a homogeneous group due to their shared characteristics and expectations of the PT system.

This analysis will primarily focus on the regular users—students and workers. By concentrating on these groups, the study intends to address the core of daily transportation demand, offering solutions for those who most frequently rely on the system.

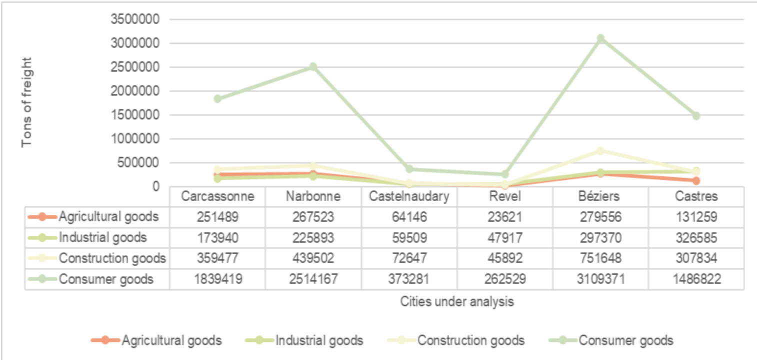
Freight profiling

Freight was further subdivided based on the categorization of economic activities related to the type of goods being transported: durable and non-durable. Durable goods were further divided into construction, industrial, and consumer goods. Meanwhile, non-durable goods comprised agricultural and livestock products.

4.2. Profiles characterization

Volume

For the passenger volume analysis, INSEE data was used to assess each city's population, which was then classified by profile. Similarly, the freight volume analysis involved estimating the volume for each freight category (in Tons) throughout the cities under study. Figure 2, shown below, illustrates these calculations.



	Carcassonne	Narbonne	Castelnaudary	Revel	Béziers	Castres
Agricultural goods	251489	267523	64146	23621	279556	131259
Industrial goods	173940	225893	59509	47917	297370	326585
Construction goods	359477	439502	72647	45892	751648	307834
Consumer goods	1839419	2514167	373281	262529	3109371	1486822

Figure 2: Profiles characterization – Volume dimension – Freight.

Time

The freight and passenger proportions of traffic are used to determine the respective contributions of freight and passenger vehicles to the overall traffic volume. Below, Figure 3 shows these traffic patterns over a 24-hour period, with freight and passenger traffic displayed separately.

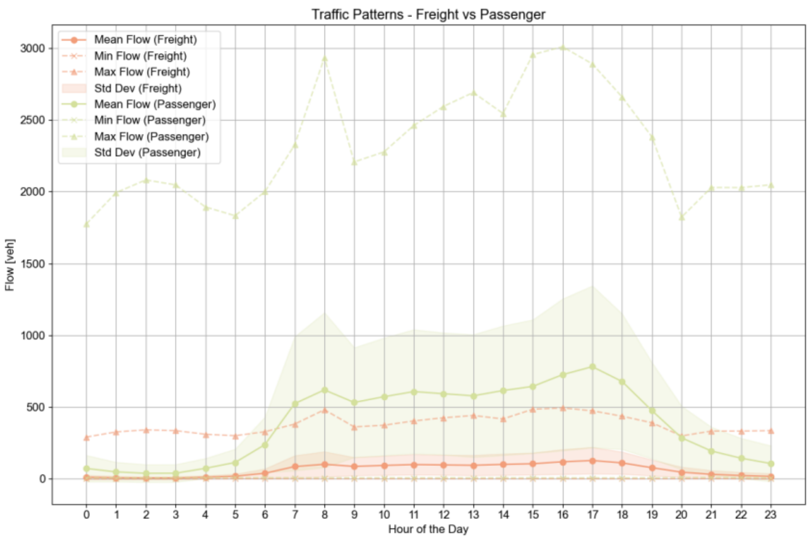


Figure 3: Profiles characterization - Time dimension - Passenger and Freight.

Space

Data from the French National Institute of Statistics and Economic Studies (INSEE) shed light on commuting patterns related to work and education between the cities being studied. Additionally, information on the locations of major employment hubs and educational institutions helps explain why certain cities attract more workers and students than others. Similarly, the freight movement analysis uses the SIRENE database (French System for the Identification of the Directory of Enterprises.), also managed by INSEE. It records legal entities and their branches throughout France and examines the principal activities of these establishments, categorizing them based on their roles in importing (bringing finished products into the city) or exporting (dispatching finished products out of the city).

Figures 4 and 5, shown below, illustrate the movement of students and workers between the cities under analysis. The origins and destinations are color-coded: green indicates cities from which more passengers depart, and red denotes cities that receive more passengers.

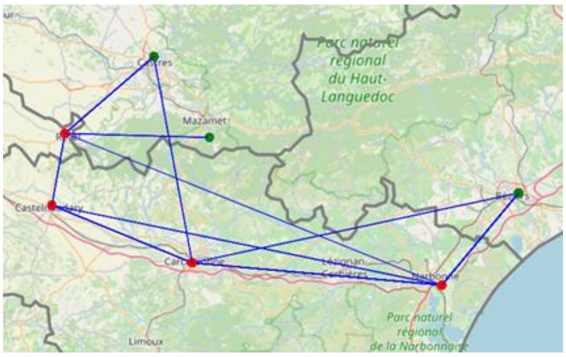


Figure 4: School mobilities of individuals (2019).

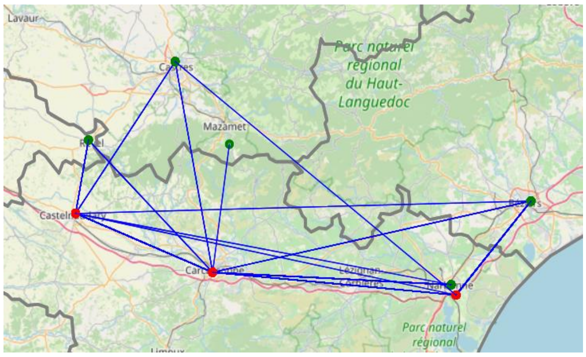


Figure 5: Professional mobility of individuals (2019).

4.3. Behaviors definition

The resulting analysis contrasts the considerations of both passengers and freight carriers, illustrating how each group prioritizes different aspects of transportation services.

Among passengers, Primary Level Students place a high value on safety above other considerations, while Secondary Level Students also prioritize environmental sustainability and timetable reliability, though less so on safety. Tertiary Level Students and Farmers show a keen sensitivity to price and time, with a special focus on trip time for the former. Individuals in Intermediate Professions and Employees/Workers express concerns over budget and time sensitivity, alongside a strong expectation for safety and reliability. Senior Intellectual Professionals, Craftsmen, Traders, and Business Leaders maintain a balanced attention across all criteria, notably valuing trip time and sustainability.

In the freight domain, the priorities shift towards operational efficiency and environmental responsibility. Construction Products and Consumer Goods profiles underscore a critical focus on all evaluated criteria, with a significant emphasis on optimal handling conditions and safety. The Industrial Products profile mirrors this critical concern but with an additional focus on sustainability and achieving carbon neutrality. Agricultural/Livestock Products, like their freight counterparts, prioritize trip time and optimal handling conditions.

Across all profiles, there is a consistent demand for reliability, comfort, and safety, with variations in priority given to price sensitivity, environmental impact, and trip time. The emphasis on sustainability and environmental concerns is more pronounced in certain passenger segments (e.g., Secondary Level Students, Senior Intellectual Professionals) and in the freight segment dealing with industrial products.

5 Conclusion and perspectives

This study develops a proposal to support the necessary demand estimation in the context of hyperconnected transportation in regional areas. Specifically, the ECOTRAIN project serves as a practical application of this analysis. This approach involves identifying user profiles and delineating their attributes in terms of volume, time, and space. It identifies price, transport time, environmental impact, schedule compliance, comfort, and safety as the main factors influencing user decisions. Additionally, the significance of these factors is quantitatively evaluated across different user profiles in selecting transportation options through a weighted matrix.

Limitations of the current methodology include potential biases in data, the impact of external factors such as economic fluctuations, and the scalability of the proposed solutions. Further discussion is needed on methodologies to address regions with sparse data availability, along with adding guidelines for scaling and adapting the methodology to different regional characteristics and technological advancements. This involves developing flexible frameworks that can be tailored to various regional contexts and integrating technologies to improve data collection and analysis. Additionally, a deeper evaluation into the roles of different stakeholders in the regional transportation ecosystem is necessary, particularly in terms of identifying their responsibilities in implementing and sustaining hyperconnected regional transport systems.

Future research will focus on practical applications to improve demand estimations for regional transportation networks. The next steps involve using the collected data alongside identified demand drivers to develop a simulation-based demand generator. This tool will incorporate scenario analysis to predict user responses to changes in transportation options. Key tasks at this stage include overcoming barriers to precise data access, selecting a demand forecasting model that accurately reflects actual demand patterns in regional contexts, and aligning supply capabilities with fluctuating demand.

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A Modular and Flexible Design of Hyperconnected Assembly Factory

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Abstract: *Modern assembly factories increasingly encounter the challenges posed by highly diversified products and fluctuating market demand. Hyperconnected mobile production, which organizes the core production equipment in standard production modules and allows them to be shared among multiple participants in the Physical Internet, is a solution in response to these challenges. In this paper, we adapt the hyperconnected mobile production concept to the assembly industry and introduce a fractal layout design. In our design, a fractal center is a standard assembly module with a predetermined throughput rate and is equipped to assemble all variants of products. All assembly tasks of an individual product, from subassembly to finishing, are performed in one fractal center. In addition, fractal centers employ mobile material handling and assembly equipment and operators that do not have to continuously occupy fixed locations. We illustrate the shareability, scalability, reconfigurability, and adaptability of the proposed hyperconnected modular design and present a design framework for fractal centers.*

Keywords: *Physical Internet, Hyperconnected Production, Flexible Assembly, Scalability, Adaptivity, Reconfigurability, Shareability.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan:* ☒ *PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories),* ☐ *Transportation Equipment,* ☐ *PI Networks,* ☐ *System of Logistics Networks,* ☐ *Vertical Supply Consolidation,* ☐ *Horizontal Supply Chain Alignment,* ☐ *Logistics/Commercial Data Platform,* ☐ *Access and Adoption,* ☐ *Governance.*

Targeted Delivery Mode-s*:* ☒ *Paper,* ☐ *Poster,* ☐ *Flash Video,* ☐ *In-Person presentation*

1 Introduction

Assembly is a type of manufacturing that combines components into final products. It is widely used for producing a variety of product types, including electronics, furniture, robots, machines, vehicles, ships, aircraft, and buildings. Typically, to improve production efficiency and ease the training of workers, the assembly work of products will be allocated to a set of workstations, and workstations are linked by specific product flows that are normally irreversible. The product and material flows among workstations are synchronized by a certain amount of time called "takt time". Takt time is defined as the time interval between two consecutive launches of production. For example, at the beginning of a takt time, workers at each station start to assemble products until the end of the takt time, then workers move the completed products to the next stations, come back to the original workstation, and repeat the same or similar assembly work in the next takt time.

Nowadays, product diversification and uncertain demand are major issues in the assembly industry, which may cause low resource utilization and excessive inventory. Furthermore, to improve customer satisfaction and gain competitiveness, assembly businesses need to shorten the product delivery time as well as maintain the production cost per product at an economic level when the throughput increases or decreases. Additionally, environmental issues, such as carbon emissions from product transportation, motivate business owners to rethink and improve their delivery system.

Modular and flexible layout design is one solution. Modular layout design refers to the design of stations and product flows in factories using standard patterns, to decrease the learning time and increase efficiency. Fractal layout organization applies the modular layout design concept and organizes equipment and workstations into “mini-factories within a factory”. In such an organization, all core production activities of one product are performed within one modular production center, or Fractal Center (FC), so that each FC functions like a “mini-factory” and operates almost all production processes independently from other FCs.

The flexible layout design indicates stations and equipment are able to be reconfigured quickly and with a low cost when products or demand changes. The emerging robotic and information technologies support progress in flexible layout design. For example, the “Plug-and-produce” concept embedded in manufacturing equipment can produce multiple variants and be reconfigured swiftly. Relying on such flexibility technologies, the concept of movable factory design has been proposed. A movable factory can be quickly uninstalled, encapsulated, transported, installed, set up, and easily reconfigured for different product variants or other factors. Extended from the movable facility concept, the mobile supply chain is proposed to relocate the facilities and optimize the performance of the overall supply chain.

Hyperconnected production, leveraging the Physical Internet (PI) principles and hyperconnectivity introduced by Montreuil et al. (2013) and Sternberg and Norrman (2017), proposes to realize on-demand production through the open certified production facilities and targets to improve the resource utilization rate as well as economic, environmental, and societal efficiency and sustainability by an order of magnitude. The material supplying and product shipping among those facilities are encapsulated in standard containers in the hyperconnected network. Extended from the hyperconnected production and movable factory concepts, hyperconnected mobile production utilizes “plug-and-play” enabled equipment to allow the dynamic relocation of production capacity.

Most of the literature regarding fractal layout organization focuses on the performance of intra-facility logistics. In fact, the use of mini-factories could also enhance the shareability among multiple facilities, because activating or deactivating one FC has less impact on others.

In this paper, we exploit the concepts of fractal layout organization and hyperconnected production for assembly factory design and propose a modular and flexible design for hyperconnected assembly factories. Such a hyperconnected assembly factory has two types of centers: (1) intra-facility network coupling centers, such as receiving centers and outbound shipping centers; and (2) fractal assembly centers, which contain all core equipment and workstations in the facility. For simplicity, in this paper, we assume that each type of equipment and workstation appears in each fractal center to ensure that each center can assemble any variant of products. Furthermore, we utilize movable equipment and operators for material handling with no fixed material handling equipment to enhance flexibility.

Equipped with the concepts of PI and hyperconnectivity, our research further allows for sharing equipment and workstations in the open certified facility network, and such sharing could be enabled by adding, removing, or reassigning FCs from one user to another. It could allow assembly factories to efficiently scale their production capacity up or down by activating or deactivating fractal centers as necessary. The drawbacks of such a distributed production design may be higher cost and lower equipment utilization when the demand is rarely changed and the product variants are minorly altered.

Figure 1 illustrates an example of how fractal centers are shared among hyperconnected production factories. When customer demand changes in certain regions in period T+1, a hyperconnected assembly factory allows its FCs to be shared with other PI-certified facilities instead of fixing FCs in factories and sending final assembly products over a long distance. Such FC sharing could occur within the same company, or between competitors for horizontal collaboration (e.g., company 1 and 2), or between a company and its supplier for vertical collaboration (e.g., company 1 and its supplier).

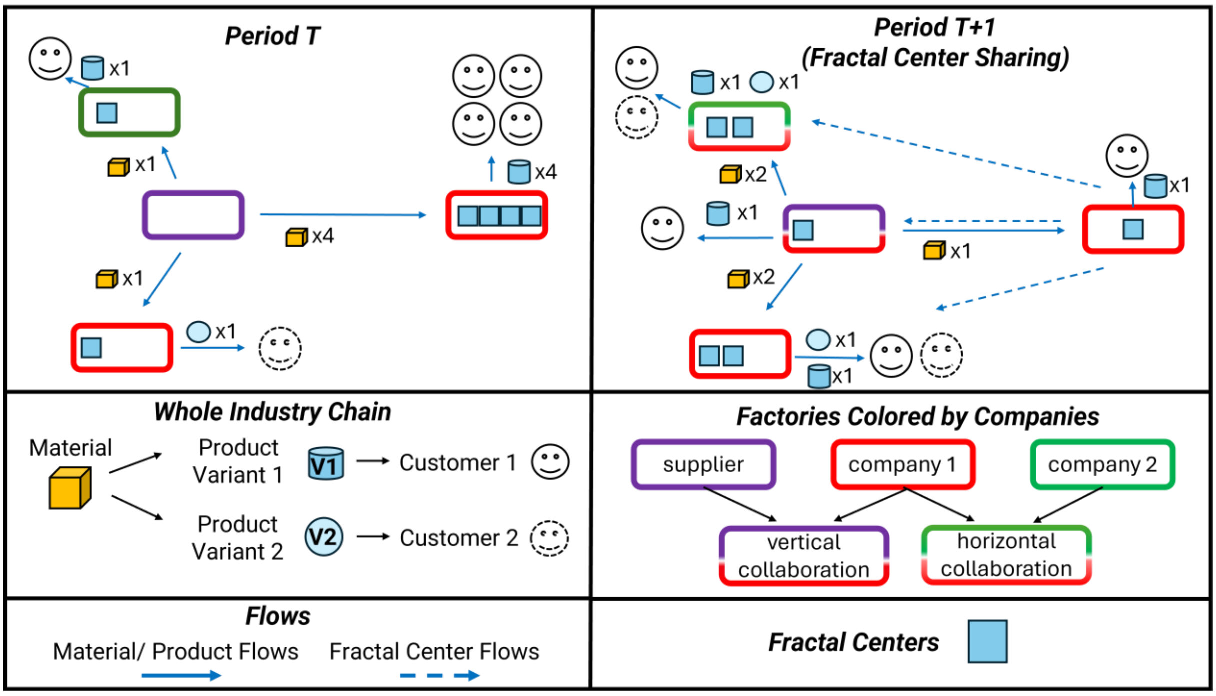

Figure 1 Illustrating the Shareability of Hyperconnected Production Factories with Fractal Centers

This paper is organized as follows: in Section Two, we present a review of related literature; in Section Three, we provide a use case that the proposed hyperconnected assembly factory design can be applied; in Section Four, we provide the details of the design assumptions and framework for assembly fractal centers; and in Section Five, we summarize the key aspects of the hyperconnected assembly factory design with fractal layout organization and outline avenues for future research.

2 Literature Review

This section provides a detailed literature review on flexible production, fractal layout organization, and hyperconnected production.

Flexible Production

Flexibility refers to the ability of the production system to adapt to product variants or demand changes. One key aspect is to organize the layout of machines and workstations in a way that material and product flows are easier to adjust, such as cellular production (Rajagopalan & Batra, 1975) and matrix production (Schmidtke et al., 2021). Another important aspect is to use equipment and tools that can be efficiently reconfigured, such as agile production robots (Jin et al., 2023; Nilsson et al., 2023), flexible conveyors (Bulgakov et al., 2022) or auto-guided vehicles (Vlachos et al., 2022).

The development of flexible production technologies promotes the concept of movable factories. Kazemi et al. (2023) reviewed the related literature. They summarized some advantages of the movable factories and listed numerous applications in industries, such as reducing the transportation effort for heavy and fragile final products (for example, wind turbine tower sections assembly), improving responsiveness to customers for shorter delivery time, decreasing the carbon footprint, and minimizing the storage space for Just-In-Time assembly and delivery (for example, prefabricated construction). Alarcon-Gerbier and Buscher (2022) presented a systematic review of the facility routing and locating methodologies for modular and movable facilities, and enumerated some potential areas and requirements for implementing a mobile supply chain.

Fractal Layout Design

Venkatadri et al. (1997) developed a design methodology jointly assigning products to fractal centers and the layout of fractal centers for the job shop environment. Montreuil (1999) introduced a new concept of fractal layout organization where the total number of major workstations is allocated equally across several fractal centers. Saad and Lassila (2004) investigated various fractal center configuration techniques with different objectives and constraints. Shih and Gonçalves Filho (2014) discussed a fractal center layout principle and implemented it in a Tabu search heuristic.

Hyperconnected Production

Hyperconnected production (Marcotte & Montreuil, 2016; Montreuil, 2016) not only focuses on equipment re-deployment among facilities of one company, but also enables equipment sharing among either competitors at the same stage in the supply chain horizontally, or businesses at up- and down-stream stages vertically. In such a way, on the one side products can be further realized through a hyperconnected supply chain with fewer business-dedication restrictions, on the other side businesses could efficiently and agilely scale up or down their facilities as needed.

Such design relies on open and readily available facilities in the PI network with standard production principles, to guarantee both technical and economic feasibility. Additionally, hyperconnected production requires core equipment leveraging the start-of-the-art flexible manufacturing technology to reduce the effort on installment and removal, thus bringing higher agility.

3 Use Case

We consider a use case in which the products are large and heavy items with variants having similar production requirements. Here, the similarity of variants is measured by their process types required (bolting, screwing, welding, etc.), precedence diagrams, and task durations. Second, transportation and storage of materials require much less time and cost than in-process or finished products. In this way, relocating factories would become more beneficial than fixing factories and delivering products. Third, customers are geographically dispersed, and demand fluctuates over time. Fourth, core equipment is “plug and produce” enabled. In our context, the core equipment is measured by its necessity in the given assembly process and its cost. For instance, if certain pre-processing equipment is not costly and can be replaced by other alternatives, then it could be classified outside of the fractal center and each local facility could select the equipment by their own decision. Fifth, all business participants are PI-certified. This allows equipment sharing to be as seamless and efficient as possible.

4 Proposed Hyperconnected Assembly Factory Design

This section aims to illustrate how the proposed hyperconnected assembly factory design can be applied to the use case.

Assumptions for Fractal Center Design

A hyperconnected assembly factory is composed of network coupling centers and fractal assembly centers. After arrival at the factory, materials are unloaded and temporarily stored in the inventory area, which serves all FCs. According to the assembly schedule, materials are sent to assigned fractal centers for further processing. When products are completed, they will be transported to the global outbound staging area and ready to depart. Some assembly methods may require utilities, for example, electricity, waste removal, or cooling water for heat dissipation. Flexible pipes or tubes that are easy to reconfigure and set up may be needed in such cases.

All FCs are designed to have the same workstations, product flows among workstations, and the same pre-determined takt time. The "same takt time" assumption simplifies the FC allocation and transportation modeling. When the overall throughput of the factory needs to be adjusted, we could adjust the number of FCs instead of redesigning them to achieve the desired throughput rate.

Figure 2 exemplifies a hyperconnected assembly factory with fractal layout organization where the receiving and inventory area is global to the overall factory. Note that material workers can globally serve multiple fractal centers, and different fractal centers may have different starting times, for example, to avoid surges in logistics traffic. Fractal centers have a constant throughput of x units per day, and the factory throughput is a multiple of x.

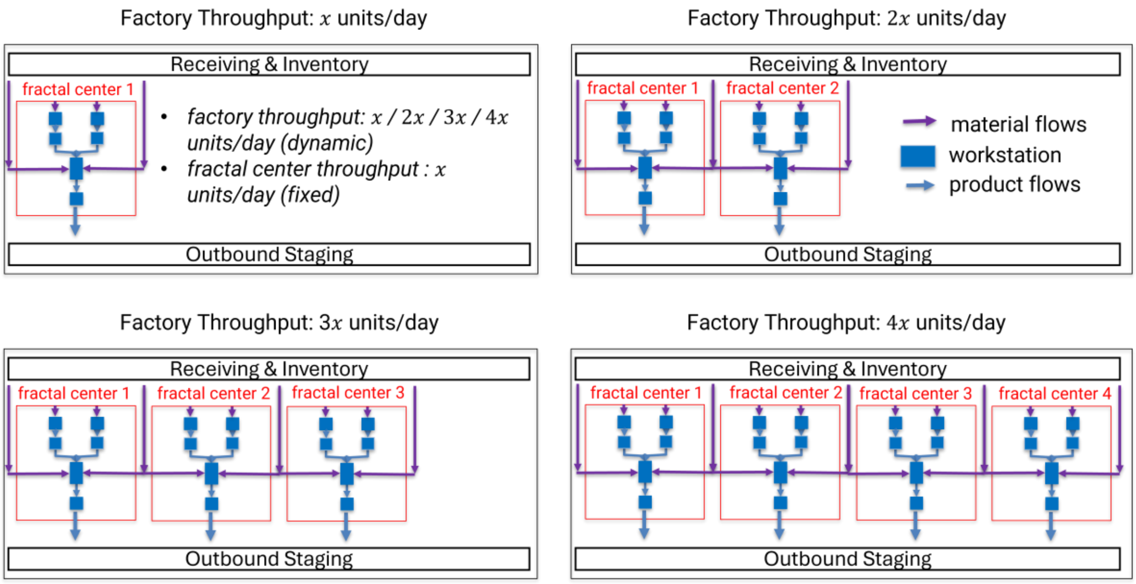

Figure 2 Example of Product and Material Flows in A Hyperconnected Assembly Factory with Changing Throughput

Fractal centers are adjustable to all variants of products cost-efficiently within a short time. This poses a high requirement on the machines and equipment and relies on the similarity of the product variants. Jin et al. (2023) studied a control method for flexible robots in a fully automation manner with pre-defined task execution information and implemented a test production for three types of Tetris-like puzzles. Nilsson et al. (2023) built a "plug-and-produce" and configurable multi-agent system for flexible manufacturing robots and conducted the production for structural components of wooden houses with modification on part design. More feasibility and viability tests of this assumption need to be conducted for other products.

Note that although fractal centers share the same fraction of each type of equipment, workers could be different. Some fractal centers could be staffed to assemble more labor-intensive product variants, while others may be less staffed to improve the utilization. Furthermore, because of the mobility, workers may be allowed to travel across fractal centers and work in multiple centers. For example, highly skilled workers could travel to work on rare and difficult tasks in different centers.

Design Framework

The proposed design framework incorporates nine interactive models. The structure of models for fractal center design is detailed in figure 3. The design process starts from the demand model to the performance analysis model, with feedback loops to the previous model and the beginning demand and project model.

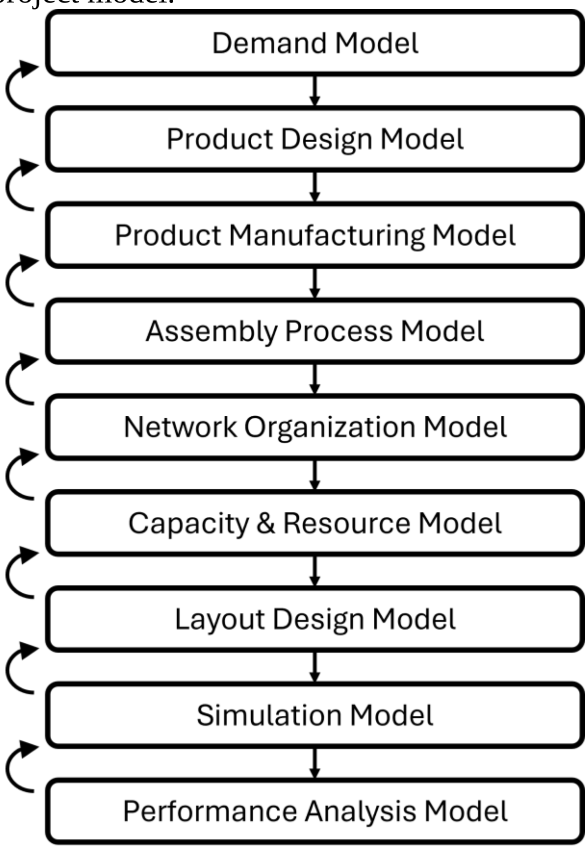

Figure 3 Design Models for Fractal Center

The demand model decides the throughput rate of fractal centers, considering the market demand, inventory, production and logistic efficiency, and disruption risks. The product design model outputs the multi-tiered structure of products that need to be assembled in fractal centers, which includes the details from components to the final products. Given the inputs about product design and the manufacturing technology alternatives, the product manufacturing model determines what manufacturing processes and manufacturing equipment are required in fractal centers, and generates the manufacturing bill of material. For instance, computer-aided product manufacturing information (PMI) can be leveraged to promote automation of assembly and inspection requirements, material specifications, and other definitive digital data. The assembly process model defines precedence diagrams for all product variants and executable assembly instructions given the inputs from the previous models. The network organization model outputs product flows in fractal centers according to the results from previous models. Common example organizations are integrated serial lines, job shops, product-oriented lines. The capacity and resources model comprehensively decides the number of workers (can be human workers or robots), the type and quantity of equipment, machines, and tools, as well as the assignment on how to use them. Assembly balancing, material handling, and worker scheduling are common decision processes involved in this model. The Layout design model executes the detailed facility layout via predefined modularized resources. The model in a hyperconnected assembly factory impacts the need for rapid and cost-saving design processes and increases the tendency to apply the fractal concept of mobile production in the manufacturing environment. The simulation model is used to aid in the production process design, process planning, operations validation, and performance assessment. In the design phase, while building the model and running the experiment, improvement opportunities were identified in the production process, which led to changes in the manufacturing process. The performance analysis model examines the performances of previous models, assesses the assumptions of models, and identifies improvements for the next round of design.

The proposed fractal layout design for hyperconnected assembly factories is based on the following assumptions:

1. The design process starts from the demand analysis and assumes the fractal center takt time is fixed. The capacity and resource model employs takt time driven processes for assembly balancing and material handling processes. Simulation model and performance analysis model need to track and analyze the intra- and inter-facility operations.
2. Product and process are designed specifically to support modular and flexible production. For instance, "plug-and-produce" production and material handling equipment could be considered in the product manufacturing model. Products should be designed for easier and more secure material handling, for example, having some handles, grips or knobs that are easier for mobile gantries or AGVs to lift, transport, drop, and store.
3. Kitting is selected as the main part feeding mode for most parts to alleviate the logistic workload of the assembly for multiple product variants. The kit storage is dedicated to fractal centers for management simplicity.
4. Logistics and layout interaction should be considered among fractal centers. Although all production processes in one FC are independent of other FCs, the logistics and layout of FCs may interact with each other. For example, logistics workers can feed kits and consumable parts to stations in multiple FCs in one travel.

Figure 4 shows the high-level core foundation of the model used to create the layout. It identifies how different pieces come together to become a layout, and all the decision-making is done using standard tasks and rules. The layout design model simplifies the complicated process and reduces redesigning effort by standardizing the underlying rules. In fact, it is used to integrate design and engineering concepts more efficiently by employing reusable solutions. Such a model can also translate human interpretation into computer language to be reusable for modular facility design with dynamically changing products.

This model applies a substantial foundation for automated dynamic layout design, which needs a deep understanding of the production process, resource flows, and physical arrangement of the resources.

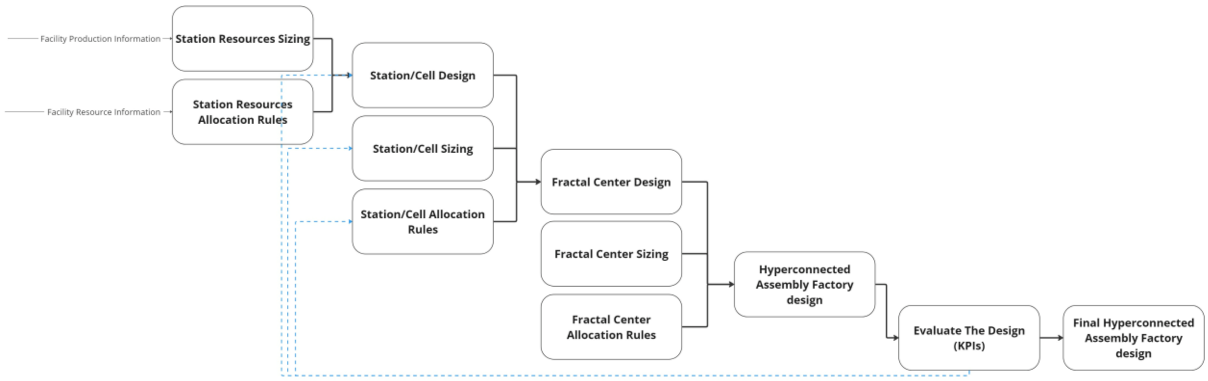

Figure 4 Fractal Center Layout Design Steps

Characteristics

Dynamic activation and deactivation of fractal centers enhances scalability. Mimicking the digital network, the standard fractal centers in the PI facility network act in the "plug-and-produce" mode with standard protocols. In a whole industry chain, companies at the same stage could share or combine their standard production modules at an economic scale, business at different stages could also share the equipment, like outsourcing or subcontracting, to realize an efficient mobile production with necessary governance and certification according to the PI regulations.

Reconfigurability is achieved by mobile equipment and operators. Reconfigurability refers to the ability to re-deploy equipment within FCs quickly and inexpensively. Mobile equipment and operators do not have to continuously occupy a fixed floor space enabling the movement of equipment during reconfiguring.

Adaptability measures the ability to change the equipment and adjust the configuration to adapt to product changes, including the change of the mix of product variants and the change of product design. Sharing the same proportion of equipment enables every fractal center to produce any product variant, saving the effort of adapting to changing product mix. Furthermore, for innovative projects, the validation test can be conducted on one fractal center. If the test succeeds, other fractal centers can be adjusted accordingly thanks to the similarity of product flows. This saves the testing time and enhances the agility of the factory.

Still, the proposed hyperconnected assembly factory design may incur duplicated equipment and bring more risks during FC sharing. Thus, more management effort on dynamic coordination and collaboration is required to operate the hyperconnected assembly factory network.

5 Conclusion and Future Design

In this paper we develop a modular and flexible design for hyperconnected assembly factories and provide a design methodology for the fractal centers, the standard production modules that are shareable to participants in the PI network. The design relies on the PI principles, modular layout with independent product flows, plug-and-produce mode enabled equipment, and the pioneering flexible assembly system technology. It aims to promote global collaboration and optimization among PI facilities in the whole industry chain, improve the shareability, scalability, reconfigurability, and adaptability of assembly facilities, and ultimately magnify efficiency and sustainability from economic, environmental, and social perspectives. The shareability is improved by the PI-enabled hyperconnected assembly factory network. The scalability of factories is achieved by activating and deactivating fractal centers with independent product flows. The adaptability and reconfigurability are improved by plug-and-produce mode enabled flexible assembly system technology. The environmental sustainability could be enhanced by reducing product delivery distance and thus decreasing carbon footprint due to the relocation of FCs.

There are several opportunities for further research. We hereafter summarize four key threads. First, research on multi-standard fractal centers is needed. In a multi-standard fractal center design, FCs may have different workstations or the same number of workstations but different product flows. Note that in the multi-standard fractal center cases, every FC could still produce any variant of product, but is more efficient for a subset of products. For example, for automotive assembly factories, some types of FCs can be more suitable for sedans, whereas vans and trucks can be preferred in other types of FCs. What takt time and what equipment should be used in each type of FCs may depend on specific product and process attributes in such cases.

Second, rigorous comparison with other assembly factory designs is also essential. On the one side, the comparison should encompass a detailed assessment of fixed factories with dedicated equipment, fixed factories with shareable equipment, movable factories with dedicated equipment, and movable factories with shareable equipment. On the other side, other layout organizations should be investigated, such as serial line design, product-oriented design, and typical modular design allowing product flows across multiple production modules.

Third, powerful optimization and decision-making models are in need for coordinating and scheduling FC sharing in the hyperconnected assembly factory network. Some representative research problems include how many FCs should be active in each factory, when and how FCs should be transported to other facilities, and if workers should be allowed to work in different FCs.

Fourth, pilot tests are crucial to validate the technical and economic feasibility of the proposed hyperconnected assembly factory design, especially when FCs are shared among different businesses.

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Exploring IoT's Potential for Risk Management in Prefabricated Construction: A Preliminary Study Towards the Physical Internet

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Keywords: Internet of Things, Risk Management, Prefabricated Construction, Physical Internet, Efficiency

Conference Domain Fitness:

Our study humbly contributes to the themes of IPIC 2024, aiming to modestly enhance how physical objects, specifically in prefabricated construction, are managed for societal, economic, and environmental benefits. By integrating Internet of Things (IoT) technologies, we seek to offer a small step towards the broader vision of the Physical Internet, focusing on the potential for improved risk management within construction projects. This effort aligns with the conference's call for leveraging technological advancements to foster more connected and sustainable supply chains, hoping to add to the collective knowledge and practices in this evolving domain.

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☒ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☐ PI Networks, ☐ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☒ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

Targeted Delivery Mode-s*: ☐ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation*

Research Contribution Abstract

Addressing the critical challenge of progress management in prefabricated construction, this paper introduces a novel IoT-enabled schedule risk alert approach within a prefabricated housing construction (PHC) management framework. Built upon the A* algorithm and incorporating the worst-fit resource allocation strategy, our approach provides early warnings of schedule risks by analyzing dynamic changes in prefab states and resource allocations. Moreover, we propose a method for abstracting workflow into a unified data structure, enhancing the algorithm's adaptability across different project types. Our methodology not only demonstrates a substantial improvement in schedule risk management — evidenced by the proactive detection of the first significant project delay — but also exemplifies a scalable, real-time responsive risk management solution, embodying the Physical Internet's goals. Specifically, our research contributes to developing PI Nodes and Logistics/Commercial Data Platforms by ensuring seamless, transparent,

and efficient information flow throughout the construction process, thereby facilitating a robust framework for risk-sensitive progress management. This integration heralds a significant step forward in applying PI principles within the construction sector, offering enhanced efficiency, security, and transparency in logistics and supply chain networks.

Network Deployment of Battery Swapping and Charging Stations within Hyperconnected Logistic Hub Networks

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Abstract: *The rapid proliferation of electric vehicles emphasizes the importance for logistics companies to strategically integrate electric vehicles into their freight transportation systems to optimize the environmental impact and efficiency of freight operations. Battery swapping stations (BSS) have been gaining attention and interest for the swift replacement of depleted battery with a charged battery, handling the obstacles regarding to the traditional charging methods. The discharged batteries will be charged at Battery charging stations (BCS), either at the service location or through central collections. Lateral transshipments between stations involve the redistribution of batteries and offering a solution to optimize resource utilization and enhance the overall efficiency of the charging network. To consider the integration of battery swapping and charging stations with hyperconnected hub networks, this paper jointly determines station localization and sizing, freight consolidation and routing, and battery inventory and transshipment. We formulate the problem with a mixed integer programming model to optimize the total system cost, including site fixed cost, freight transportation cost, battery leasing, charging and transshipment cost over multiple time intervals. Two charging strategies are discussed with the deployment of battery swapping and charging stations, including 'Swap-Locally, Charge-Locally' and 'Swap-Locally, Charge-Centrally' strategies. Through comprehensive mathematical modeling and analysis, we investigate the effects of 'Swap-Locally, Charge-Centrally' strategy with centrally managed battery inventory on less facility depreciation cost, higher battery utilization rate and stable safety stock of charged batteries, thereby enhancing efficiency and resilience against potential risks.*

Keywords: *Electric Trucks; Hyperconnected Transportation; Battery Swapping Stations; Battery Charging Stations; Hyperconnected Networks; Logistic Hubs; Resource Lateral Transshipments.*

Conference Domain Fitness: *Physical Internet; Clean Energy; Network Deployment; Hyperconnected Logistic Hub Networks; Net Zero Freight System; Battery Swapping and Charging Stations; Resource Allocation.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☒ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☒ PI Networks, ☐ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

Targeted Delivery Mode-s*: ☒ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation*

1 Introduction

The Electric Vehicles Initiative, formed by 15 countries such as Canada, China, Germany, and the United Kingdom, aims to achieve a 30% market share for Electric Vehicles by the year 2030. The United States declared their goal of achieving 50% of all new passenger cars and light trucks sold in 2030 to be zero-emission vehicles [1]. Despite global initiatives and efforts, significant barriers to adoption persist, particularly in relation to charging infrastructure. Driven by advancements in battery and charging technology and the growing demand for zero emission transportation solutions, the heavy-duty Electric Trucks industry is growing rapidly. Long-haul freight distribution with Electric Trucks is planned by companies like Tesla, Daimler AG, and Volvo for mass production within this decade [2,3].

Since heavy-duty trucks account for near half of global road freight emissions, it is important for logistics companies to integrate Electric Trucks into their freight transportation systems to optimize the environmental impact and efficiency of freight operations. Since significant energy is required for long-haul freight transportation with heavy-duty trucks, Megawatt Battery Charging Stations (BCSs) are introduced recently for their high charging capabilities and improving communication, especially for logistics hubs where fleets of electric vehicle are large. However, limitations for those stations including high infrastructure cost and potential grid strain make it infeasible and economically demanding to deploy charging stations in some logistic hubs within the networks.

Battery Swapping Stations (BSSs) offer a solution by swiftly replacing depleted batteries with charged batteries, and effectively overcoming obstacles regarding to the traditional charging methods [4,5]. The swapped discharged batteries can be charged at Battery Charging Stations (BCS), either at the service location or through central collections [6]. Compared with other charging strategies like overnight charging or charging on-the-move, battery swapping not only eliminates additional downtime and potential grid constraints at logistic hubs, but also offers scalability for large fleets or high-demand operations due to its modular nature and potential for incremental expansion. Therefore, we propose the deployment of both Megawatt Battery Charging Stations and Battery Swapping Stations in the logistic hub networks to leverage the advantages of both charging infrastructures.

The Physical Internet initiative, introduced in [24], aims to enhance global logistics efficiency and sustainability. Due to high cost of charging infrastructures and limited availability of public stations, open-access hubs in the hyperconnected logistic networks offer an opportunity for deploying charging infrastructures to provide shared charging services and enhance the utilization of charging stations. With the settings of hyperconnected transportation system where long-haul shipments are transported via multiple short-haul route segments and logistic hubs in a relay manner, the high connectivity of network infrastructure facilitates efficient battery charging and swapping operations, in line with the transport distance constraints and charging needs of electric heavy-duty trucks. Furthermore, this hyperconnected network configuration has been extensively studied, demonstrating its potential to increase consolidation opportunities, improve delivery efficiency, and enhance the working conditions of truck drivers.

Heavy-duty truck battery swapping has also been launched as a solution provided by companies recently in the real world. As illustrated in Figure 1, CATL released a heavy-duty truck chassis battery swap solution - QIJI Energy, offering a fast and low-cost refueling solution for electric heavy-duty trucks, including includes battery blocks, battery swap station, and cloud platform

[31]. In this paper, we propose an innovative network deployment strategy for battery swapping and charging stations within hyperconnected logistic hub networks. This approach also involves centrally managing the battery inventory levels at these stations, considering the inbound and outbound trucks of the hubs. Lateral transshipments between stations refer to the redistribution of batteries to optimize resource utilization and enhance the overall efficiency of the charging network [2]. By assuming shared capacity of transportation for both freight and battery flow, we jointly consider the station localization and sizing with freight consolidation and routing, and battery inventory and transshipment within the framework. We formulate the problem with a mixed integer programming model to optimize the total system cost, including site fixed cost, freight transportation cost, battery leasing, charging and transshipment cost over multiple time intervals. Two charging strategies are discussed with the battery swapping and charging stations, including 'Swap-Locally, Charge-Locally' (SLCL) and 'Swap-Locally, Charge-Centrally' (SLCC) strategies. Our findings suggest that centrally managed battery inventory results in less facility depreciation cost, higher battery utilization rate and smoother safety stock of charged batteries, thereby enhancing efficiency and resilience against potential risks.

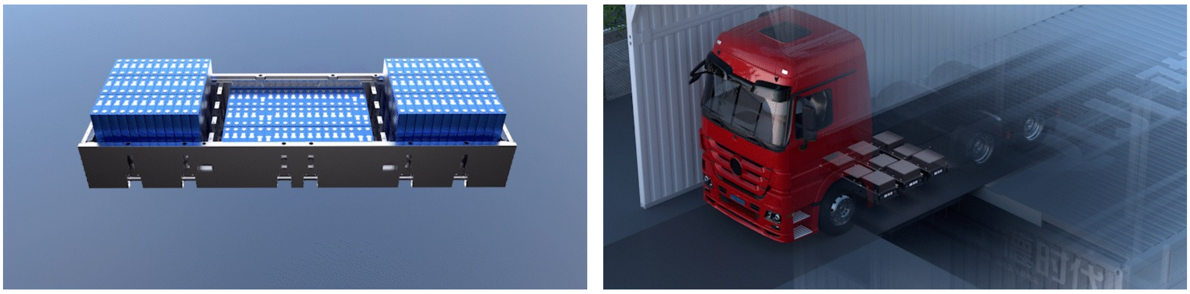


Figure 1: QIJI Energy heavy-duty truck battery swapping solution: battery blocks (left) and battery swap stations (right; source: CATL [31])

2 Literature Review

During the past few years, a significant surge in scholarly papers has been dedicated to exploring various aspects of electric trucks. For example, [8] explores perceived social, technological, and economic barriers to heavy-duty truck electrification, focusing on commercial and public fleets operating heavy-duty trucks in California. [9, 10] investigate the viability of long-haul electric truck adoption as a competitive alternative to diesel trucks, also from the perspective of truck fleet managers. [11] assesses the public charging, energy, and power requirements for electric trucks in long-haul operations in Europe in 2030. Numerous studies focus on the transition of vehicle fleets from diesel to electric vehicles. [12] present a general research framework to analyze electric vehicles adoption decisions based on a collaborative effort between a taxicab company and an infrastructure service provider. [13] consider the case in which a firm that owns and operates a fleet of diesel trucks and decides to invest in the charging infrastructure required to support this transition, either because the public charging infrastructure is currently inadequate or for strategic reasons.

The design, planning and operation of an electric vehicle charging network has received attention in the research literature. Different kinds of charging infrastructure are discussed in the design of electric vehicle charging networks [14,16]. For example, [14] designs an electric vehicle charging network where battery swap and supercharging are jointly coordinated. Deployment of charging infrastructure for electric vehicles has been discussed in [15], considering investment and operation costs, and the building of storage systems. Additionally, many papers work on the planning and operation for electric fleets, including planning for electric commercial vehicle fleets within the retail mid-haul logistics networks [17], electric vehicle routing with public charging stations[18], and joint scheduling of electric truck routing and charging [19, 20].

Battery swapping has garnered significant attention in discussions recently surrounding the accelerated electrification of heavy-duty trucks. [21] have identified that battery swapping is the most cost-effective energy supply mode for electric heavy trucks when the station utilization rate is high, and will be further expanded with the battery technology improvement and traffic density increase in the future. A battery swapping station system that exclusively serves an electric truck fleet has been studied in [22], where a battery charging management strategy to enhance cost efficiency is proposed considering battery degradation effects. The allocation of battery swapping stations has been frequently addressed as a location-inventory problem in various studies [23, 24], with [24] proposing the adoption of "swap-locally, charge-centrally" network, citing that faster charging accessible at centralized charging stations can significantly reduce the system-wide battery stock level.

Shared charging is proposed as a solution to enhance utilization and mitigate the high cost of charging infrastructures and limited availability of public stations, particularly within the logistics industry. Union battery swapping stations for multiple logistics companies has been established by some investors [23]. Hyperconnected city logistics leverages massively open multi-party multi-modal asset sharing and flow consolidation through seamless interconnectivity within and between urban environments for increased economic, environmental, societal efficiency and sustainability [25, 26, 27]. It is materialized through a multi-tier urban logistics web [28], whose nodes are hyperconnected logistic hubs facilitating freight consolidation and resource sharing among them [29, 30]. These open-access hubs offer an opportunity for deploying charging infrastructures to provide shared charging services to multiple stakeholders participating in the hyperconnected logistic hub networks.

3 Problem Description and Formulation

Sets		**Parameters**	
R	set of routes	C_h^{BSS}	depreciation cost of BSS at hub location h
K	set of commodities	C_h^{BCS}	depreciation cost of BCS at hub location h
R_k	set of available routes for commodity k	C_h^{CAP}	unit capacity cost at hub location h
L	set of connected lanes	${G_h}^{Cap}$	capacity of charging capability at hub location h
T	set of time units in the planning horizon	D_l	transportation cost on lane l
H	set of hubs, including a dummy location for truck flow balance	α / β	capacity of shipments/ battery transshipments per truck.
$In(h)$	inbound lanes of hub $h \in H$, $\{(i,h)\|(i,h)\in L\}$	B_h	battery charging cost at hub location h
$Out(h)$	outbound lanes of hub $h \in H$, $\{(h,i)\|(h,i)\in L\}$	$V_{k,t}$	volume demand of commodity k on day t
		A	depreciation cost of battery
Decision variables			
$x_{r,t}$	binary, whether a route $r \in R$ is selected on day t	$y_{h,t}^c$	number of fully charged batteries left at hub h and day t
f_h^{BSS}	binary, whether a hub h is selected as a BSS	$y_{h,t}^d$	number of depleted batteries at left hub h and day t
f_h^{BCS}	binary, whether a hub h is selected as a BCS	$m_{l,t}^c$	number of fully charged batteries transshipped on lane l on day t
$g_{h,t}$	integer, the number of batteries charged at hub h and day t	$m_{l,t}^d$	number of depleted batteries transshipped on lane l on day t
$n_{l,t}$	integer, the number of trucks dispatched on lane l and day t	z_h	the capacity required in hub h
$v_{l,t}$	total shipment volume on lane l and day t		

Table 1: Descriptions of sets, parameters, and decision variables

In this section, we present the problem we aim to address and outline our proposed a mixed integer programming model to tackle it. We consider a hyperconnected network composed of a finite set H of hubs and L of connected lanes. For each hub $h \in$ H, $In(h)$ and $Out(h)$ denote the inbound and outbound lanes, respectively. A commodity entails freight deliveries share the same origin and destination pair. Each commodity has a defined set of available freight transportation routes, and one route among them needs to be assigned for each commodify in a finite set K. To achieve a NetZero freight system, we propose the deployment of network infrastructure, including battery swapping and charging stations, within hyperconnected logistic hub networks. We assume that upon electric trucks' arrival at a hub, battery swapping services are provided. Depleted batteries are swiftly exchanged with fully charged ones, so that trucks' dwell time in hubs could be minimized.

Battery inventories are managed centrally within the proposed charging network considering the inbound and outbound freight flow with battery swapping requests. In this paper, we compare two charging strategies, named as 'Swap-Locally, Charge-Locally' and 'Swap-Locally, Charge-Centrally' strategy. In the 'Swap-Locally, Charge-Locally' scenario, swapped batteries are charged locally within the same hub with the swapping station. Meanwhile, in the 'Swap-Locally, Charge-Centrally' strategy, depleted batteries can be transported to a central charging station via lateral transshipments between hubs. In addition, we assume shared capacity of shipment trucks for freight transportation and battery transshipments, taking into account their respective size and weight.

We propose a mixed integer programming model to deploy stations and batteries in the hyperconnected networks considering infrastructure and battery depreciation costs, battery charging cost, capacity cost and transportation cost. With detailed notation, including the sets, parameters and decision variables listed in Table 1, the proposed model for the network deployment problem is formulated as follows:

$$Min \sum_{h\in H}(C_h^{BSS} f_h^{BSS} + C_h^{BCS} f_h^{BCS} + C_h^{CAP} z_h) + \sum_{l\in L}\sum_{t\in T} D_l n_{l,t} + \sum_{h\in H} A(y_{h,0}^c + y_{h,0}^d) + \sum_{h\in H}\sum_{t\in T} B_h g_{h,t} \quad (1)$$

subject to:

$$\sum_{r\in R_k} x_{r,t} = 1 \qquad \forall k \in K, \forall t \in T \quad (2)$$

$$v_{l,t} = \sum_{k\in K}\sum_{\{r\in R_k | l\in r\}} V_{k,t}\, x_{r,t} \qquad \forall l \in L, \forall t \in T \quad (3)$$

$$\frac{v_{l,t}}{\alpha} + \frac{m_{l,t}^c + m_{l,t}^d}{\beta} \le n_{l,t} \qquad \forall l \in L, \forall t \in T \quad (4)$$

$$y_{h,t}^d = y_{h,t-1}^d + \sum_{l\in In(h)} n_{l,t-1} + \sum_{l\in In(h)} m_{l,t-1}^d - \sum_{l\in out(h)} m_{l,t-1}^d - g_{h,t-1} \qquad \forall h \in H, \forall t \in T\backslash\{0\} \quad (5)$$

$$y_{h,t}^c = y_{h,t-1}^c - \sum_{l\in Out(h)} n_{l,t-1} + \sum_{l\in In(h)} m_{l,t-1}^c - \sum_{l\in out(h)} m_{l,t-1}^c + g_{h,t-1} \qquad \forall h \in H, \forall t \in T\backslash\{0\} \quad (6)$$

$$\sum_{l\in In(h)} n_{l,t} = \sum_{l\in Out(h)} n_{l,t} \qquad \forall h \in H, \forall t \in T \quad (7)$$

$$y_{h,t}^c + y_{h,t}^d \le z_h \qquad \forall h \in H, \forall t \in T \quad (8)$$

$$g_{h,t} \le G_h{}^{Cap} f_h^{BCS} \qquad \forall h \in H, \forall t \in T \quad (9)$$

$$y_{h,t}^d + \sum_{l\in In(h)} n_l t + \sum_{l\in In(h)} m_{l,t}^d - \sum_{l\in out(h)} m_{l,t}^d \ge 0 \qquad \forall h \in H, \forall t \in T \quad (10)$$

$$y_{h,t}^c - \sum_{l\in Out(h)} n_{l,t} + \sum_{l\in In(h)} m_{l,t}^c - \sum_{l\in out(h)} m_{l,t}^c \ge 0 \qquad \forall h \in H, \forall t \in T \quad (11)$$

$$\sum_{l\in In(h)} (m_{l,t}^c + m_{l,t}^d) + \sum_{l\in out(h)} (m_{l,t}^c + m_{l,t}^d) \le M(f_h^{BCS} + f_h^{BSS}) \qquad \forall h \in H, \forall t \in T \quad (12)$$

$$\sum_{l \in In(h)} v_{l,t} + \sum_{l \in Out(h)} v_{l,t} \leq M f_h^{BSS} \qquad \forall h \in H, \forall t \in T \qquad (13)$$

The objective function (1) minimizes the total cost including depreciation and capacity cost of battery swapping and charging stations, battery depreciation and charging cost, and transportation cost. Constraints set (2) and (3) ensure that for each commodity with an origin and destination, a route is assigned and freight volume for each arc is calculated via hyperconnected transportation. Constraints set (4) makes sure that the number of trucks is calculated based on the volume of freight and the battery transshipments. Constraints set (5) and (6) indicates the flow of depleted and charged batteries respectively. To make it clear, the sum of $\boldsymbol{y}_{h,t}^{d}$ and $\boldsymbol{y}_{h,t}^{c}$ is a constant, which indicates the total number of batteries required in the system. Constraints set (7) ensures that the number of trucks arrive at a hub equal to the number of trucks depart. Constraints set (8) controls the battery inventory capacity while Constraints set (9) makes sure batteries are charged at a hub only if it is selected as a charging station and the number of batteries charged should smaller than its charging capacity. Constraints set (10) and (11) make sure the number of battery available is larger than required at each hub and time unit. Lastly, constraints set (12) and (13) ensure that battery tranship only between battery stations and battery swapping is required once a truck arrives at a hub.

4 Case Study

In this section, we utilize a case study to illustrate the effectiveness of our proposed model with a real-world instance. We consider an open-access hub network consisting of hubs and regional centers, given the daily demand of each origin destination pair generated based on estimated US freight flows from Freight Analysis Framework (FAF) database from Bureau of Transportation Statistics [7]. A designed hyperconnected logistic hub networks for freight transportation of southeast United States are assumed to be given to our proposed model. In the experiments, we assume 5% of the flow utilizes the network. Also, we utilize designed hyperconnected logistic hub networks for freight transportation in 7 states of southeast United States, consisting of 111 hubs and 2996 edges, as shown in Figure 3. The planning horizon is set to be one year, divided into 13 durations, each lasting 28 days. The depreciation cost of battery swapping stations and battery charging stations is set to be \$100,000 and \$300,000 respectively, while the depreciation cost of a battery is set to be \$7800 during the planning horizon. We currently ignore the capacity cost and the battery charging cost is set to be \$50 per battery. We assume that at most 27 batteries can be carried on a truck and the transportation cost is \$50 per hour of driving. The cost structure for hubs may be tailored to reflect their unique characteristics in future research.

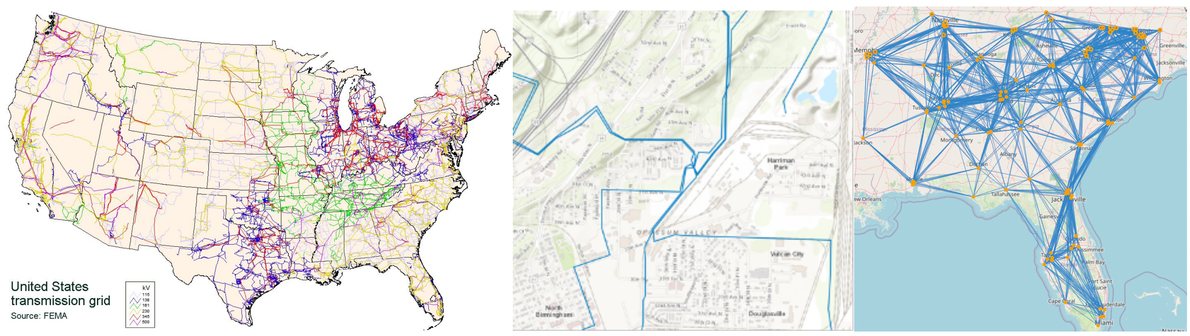
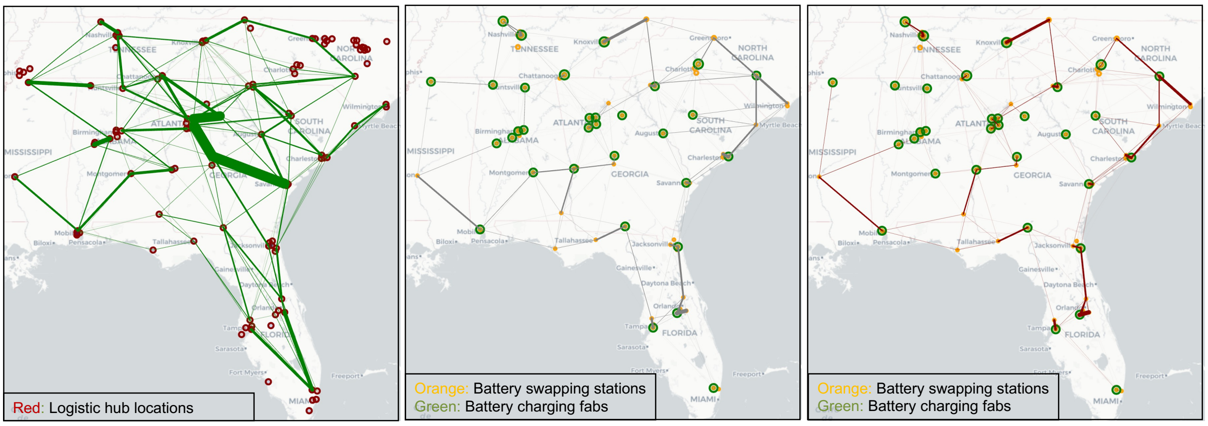


Figure 2: United States transmission grid (left; source FEMA), electric power lines (middle; [32]) and proposed hyperconnected transportation networks

In addition, we utilize the transmission grid of the United States to provide us the charging availability and capacity for the potential station locations in the selected area. Given the electric power lines [32], we find out the maximum power voltage $\boldsymbol{\gamma_h}$ of station candidates, as shown in Figure 2. We then assume the capacity of the potential station location $\boldsymbol{G_h} = \frac{6000\gamma_h^2}{115^2}$.

Given our proposed model, some routes are selected from the top shortest paths for each OD commodity, and the average freight flow on each leg is illustrated in Figure 3(a). Also, some of the hub locations are selected to be battery swapping stations, as indicated by the orange circles, and some of the hubs are selected to be battery charging stations, as indicated by the green circles. Across the stations selected, we also plot the average charged and depleted battery flow in the network, as shown in Figure 3(b) and (c), while the width of the lines indicates the number of batteries transported on each leg. We can clearly see that a few locations are selected as charging stations, and the hyperconnected freight transportation networks are utilized for battery transshipments between charging stations and the swapping stations.



(a) Average truck flow (b) Average charged battery flow (c) Average depleted battery flow

Figure 3: Illustration of locations of logistic hubs, battery swapping stations and charging fabs, along with freight and battery flow between them

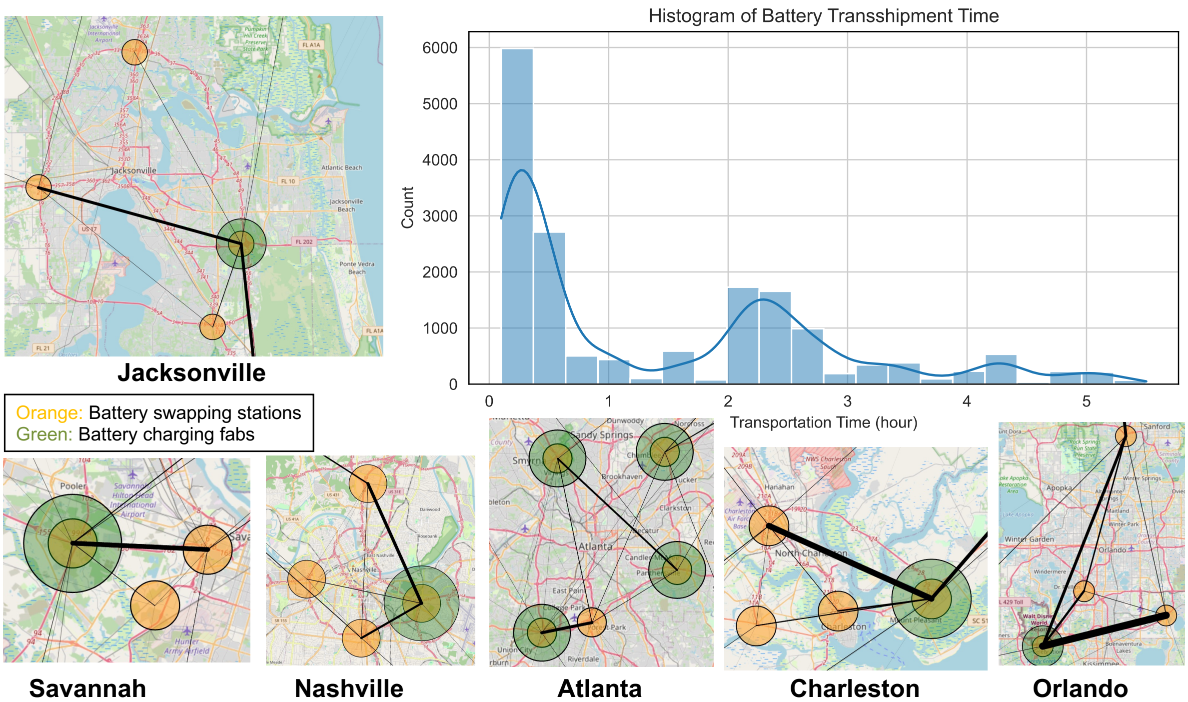


Figure 4: Battery swapping stations, charging fabs and transshipments within large cities; distribution of battery transshipment times

We also plot the locations of battery swapping stations and charging fabs within large cities in Southeast of the United States, along with battery transshipments among them, as shown in Figure 4. Based on the freight demand and the capacity of the charging facilities in each city, one or multiple charging hubs are strategically located. Batteries are transshipped between central charging hubs and swapping stations to enhance the utilization of charging resources. As shown in the histogram of battery transshipment times in Figure 4, many batteries are transshipped within cities in less than one hour. However, the transshipment durations of some batteries exceed two hours. This delay is due to the current limitations of charging capacity in certain areas based on our assumption, which could be mitigated with the development of electricity grids and charging technologies.

Additionally, we present a comparison of two charging strategies: 'Swap-Locally, Charge-Locally' (SLCL) and 'Swap-Locally, Charge-Centrally' (SLCC). In the SLCC scenario, battery charging fabs are deployed in all hubs except the locations has no charging availability based on current transmission grids. Some key performance indicators can be found in the Table 2. With the SLCL strategy, additional 37 charging stations are required, resulting in higher infrastructure depreciation costs. Conversely, the SLCC approach necessitates a slightly larger transportation costs due to battery transshipments. Overall, the SLCC approach saves about 4% of the total cost. Also, employing the SLCC strategy results in a reduction of charging fabs in the network without causing increase in the total number of batteries needed, which would further decrease if we took high charging efficiency of central charging stations into consideration.

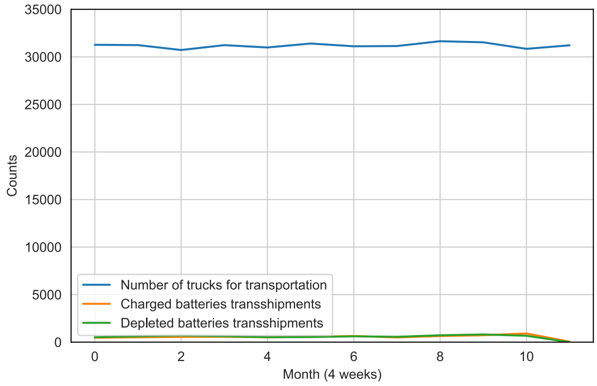
	Swap-Locally, Charge-Locally	Swap-Locally, Charge-Centrally
Number of swapping stations	73	72
Number of charging fabs	69	32
Number of batteries	32732	32132
Total cost	3.66E+08	3.51E+08
Infrastructure depreciation cost	2.80E+07	1.68E+07
Battery depreciation cost	2.55E+08	2.51E+08
Battery charging cost	1.87E+07	1.91E+07
Transportation cost	6.44E+07	6.49E+07

Table 2: Key performance indicator of the two proposed strategies

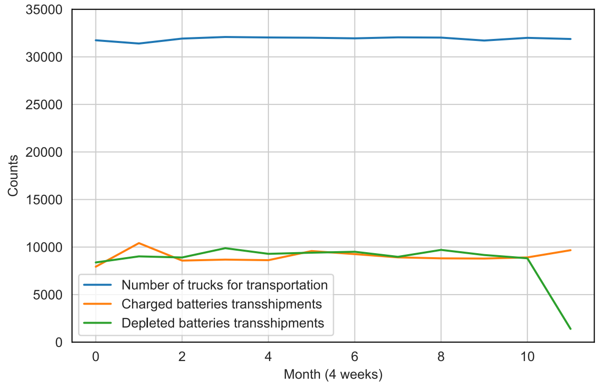
We also plot the number of transporting trucks and battery transshipments over the entire planning horizon to observe their temporal dynamics. Firstly, the blue line indicates the number of trucks, including those for battery transshipments, as depicted in Figure 5. Figure 5(b) illustrates a slightly increase in the required number of trucks in the SLCC scenario. Also, the orange and green lines depict the charged and depleted battery transshipments, about 5000 batteries are transshipped monthly between hubs with no charging capability (Figure 5 (a)) and above 10000 batterie are transshipped monthly to be charged centrally (Figure 5 (b)).

5 Conclusion and future research

Overall, we conclude that there are several benefits of implementing battery swapping in hub logistic networks. Firstly, the downtime of trucks at hubs would be minimized, and we can reduce the number of charging stations utilizing the hyperconnected freight transportation system. Benefits of 'Swap-Locally, Charge-Centrally' (SLCC) strategy are also discussed in this paper. For example, we can centrally manage battery inventory in the system, allowing shared batteries with transshipments. Also, collaborative transportation helps us integrate freight transportation and battery transshipments so that resource utilization can be increased, and the overall efficiency can be enhanced. Moreover, the utilization of electrical resources can be optimized while overcoming limitations within the power grid, considering the potential for faster charging accessible at centralized charging stations.



(a) Swap-Locally, Charge-Locally



(b) Swap-Locally, Charge-Centrally

Figure 5: Comparison of the number of transporting trucks and battery transshipments

Regarding future research, exploring a mixed policy that includes both trucks on-site charging and battery swapping is worthwhile, and detailed comparison between our proposed and other alternatives is necessary, such as transportation using combustion engines or hydrogen fuel cells. Also, exploring the integration of battery inventory policies, like (r, Q) policy, at each swapping stations could offer valuable insights into realistic battery utilization. Additionally, the impact of different charging infrastructure types, including mega-charging, fast-charging and slow-charging in the network presents an avenue for further exploration. Moreover, strategic-tactical models that combining long-term planning with short-term leasing opportunities could be investigated to enhance the agility and responsiveness of the system. Furthermore, exploring the scalability of the proposed framework to accommodate larger-scale transportation networks could provide valuable insights into its applicability in broader contexts. Finally, shared charging options with existed public charging locations, and the potential environmental and sustainability implications of the proposed strategies could contribute to the development of more environmentally friendly and socially responsible freight transportation solutions.

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https://resilience.climate.gov/datasets/fedmaps::u-s-electric-power-transmission-lines/explore

Predictive Demand Disruption Signals for Supply Chain Networks

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Abstract: *Supply chain networks today are complex networks with various actors spread across the globe. They operate in a volatile, uncertain, and disruption-prone environment which requires them to perceive, react, and respond proactively to effectively manage their operations and maintain customer satisfaction. In this paper, we introduce a signaling methodology to generate early warning signals for a time series upon deviation from the normal pattern, serving as complementary information to demand forecasts. The methodology can be used to detect deviations in the demand curves, which will be propagated through the network to enable the decision makers in taking prompt actions to minimize the effect of the deviation, and better position the supply chain in the wake of disruptions. Relying just on demand forecasts for decision-making can be detrimental as occasionally demand forecasts are unable to capture sudden discrete changes (step up or down) or a turning point (e.g., change from a decreasing time trend to an increasing trend) accurately and rapidly. In such situations, demand disruption signals with characteristics that complement the behavior of demand forecasts play an essential role in proactively assessing and preparing to navigate the disruptions. The developed demand disruption signals leverage bias-identification tracking signals on demand forecasts to proactively detect demand disruption potentiality. Through real-world industrial experiments, our model significantly outperforms typical disruption detection models and are able to capture changes in demand patterns.*

Keywords: *Physical Internet, Supply Chain Networks, Early Warning Signals, Demand Disruption Signals, Tracking Signals*

1 Introduction

There are numerous disturbances in the highly sophisticated supply chain networks of today that call us to perceive, recognize, react, and respond proactively. Demand disruption signals are early warning indicators that detect deviations in demand patterns from the expected norm, enabling proactive measures to mitigate potential disruptions. These signals serve as complementary information to traditional demand forecasts, providing an additional layer of insight that helps in anticipating and managing unexpected changes in demand. Demand forecasting may occasionally fall short of fully capturing all these demand disturbances, particularly in the volatile, uncertain, complex, and ambiguous (VUCA) world of supply chain networks. Therefore, developing predictive disruption signaling methodologies becomes necessary. Demand disruption signals are very useful tools to make up for the insufficient performance of demand forecasts, avoiding out-of-stock situations, aligning multiple suppliers to ensure timely inventory availability, and making supply chain networks more resilient.

At the end of 2019, COVID-19 broke out worldwide, affecting people's lives and even claiming many of them. In addition to having a high fatality rate, COVID-19 severely disrupted global supply chain networks (Choudhury et al., 2022). It simultaneously interrupts the supply or demand for certainty, stability, availability, visibility, and persistence in the supply chain (Sodhi & Tang, 2021). Along with many instabilities due to the outbreak of COVID-19, forecasts are limited in their ability to capture all these disruptions. If there are early warning signals to inform humans of some disturbances in advance, people can prepare for the disruptions in their early phases and minimize the damage caused by the epidemic. These signals play crucial roles in sensing and predicting unexpected shifts in demand, thereby alerting decision-makers to potential upcoming disruptions.

Enabling to identify rising variability between past and present patterns becomes a crucial technique in our fast-growing supply environment. The capability to respond to supply chain disruptions is enhanced with the use of state-of-the-art supply chain risk tools, such as control tower systems (Lund et al., 2020), which enable end-to-end monitoring, tracking, and transparency. The introduction of the Physical Internet (Montreuil et al., 2013) concept, with its focus on creating an interconnected and resilient global logistics system, further underscores the importance of agility and adaptability in today's supply chain networks. In order to make supply chain networks more resilient, sensitive, agile, and intelligent, most of the current research focuses on the improvement of the demand side (Malmstedt & Bäckstrand, 2022), i.e., how to enhance demand forecasting. However, professional and practical contributions to the enhancement of the supply side are not enough. Therefore, the purpose of this paper is to perceive disruptions in early stages and enable decision-making agents to take prompt actions in advance to reduce the impact of turbulence.

This paper is structured as follows: Section 2 provides the review of existing literature on demand forecasting and signaling methodologies; Section 3 outlines our proposed methodology for generating, filtering, and validating demand disruption signals; Section 4 highlights the performance of our signaling methodology for a real-world e-commerce-based manufacturing firm operating in a highly uncertain and volatile environment; and Section 5 provides concluding remarks and avenues for future research.

2 Related Work

In the current volatile and uncertain world we live in, reliable and fast-evolving prediction has become the main theme in supply chain networks. It is crucial to have predictive capability in manufacturing processes, quality, management, inefficiencies, and even inside manufacturing systems (Choudhary et al., 2009). There are lots of statistical methods and machine learning approaches implemented for predictive analytics (demand forecasting), such as the neural network and Fourier transform (Saito & Kakemoto, 2004), SARIMA (Liu et al., 2001), and Holt-Winters Exponential Smoothing (Hasin et al., 2011), which are widely used in industry.

Most of these methodologies are solely dependent on historical data, which is not well correlated with exogenous events, including economic downturns and upturns, advertising and competing activities, the development of consumer social media use, and interruptions brought on by natural catastrophes (Byrne, 2012). These exogenous events affect the demand realization, leading to the emergence of a bias in the demand forecasts, which should be identified and signaled to the decision-makers of the supply chain network for proactive preparation and mitigation.

Demand disruption signals, broadly speaking, are data streams that the participants in the supply chain may regularly access (Evrard-Samuel, 2008). Demand disruption signals have sensing capabilities, which could enable a firm to identify a disruption in its early phases (Pattanayak et al., 2023). In addition to previous demand insights that connect with present and future demand, they also offer advanced information on demand, such as future planning and scheduling on demand (Hillman & Hochman, 2007). Researchers have utilized anomaly detection and change point methods for identifying such signals. Ensemble anomaly detection helps prevent supply chain input errors from disrupting the quality of realistic sales and projected supply plans (Glaser et al., 2022). Change point detection algorithms use a binary classifier, which are used to identify pattern changes and release early warning signals in the demand process (Aminikhanghahi & Cook, 2017).

The evolution of tracking signals from Page's (1955) initial concept to their enhancement with Brown's (1959) cumulative sum technique highlights their crucial role in identifying changes in pattern. By comparing the cumulative sum of forecast errors against the Mean Absolute Deviation (MAD), tracking signals serve as a powerful mechanism to promptly detect and alert us to disruptions. Tracking signals are widely used in industry to supervise inventory and sales demand (Gorr & McKay, 2005). These signals are able to automatically and rapidly identify pattern changes, such as step jumps and turning points in product demand. Moreover, tracking signals have also been utilized for automatic update of forecasts when an unexpected structural change is observed in the process (Snyder & Koehler, 2009); validation of the proposed forecasting methods (Saroha et al., 2021); and monitoring of forecast results (Rizki et al., 2021). Overall, the use of tracking signals can lead to more efficient inventory management, better allocation of resources, and improved decision-making in response to changes in product demand. Despite their widespread use, tracking signals for demand disruption signals in supply chains have notable limitations. One significant limitation is that they typically use only one-day ahead forecasts, rather than incorporating multi-day ahead forecasts. In this paper, we employ the tracking signal method to identify demand disruption signals, ensuring that companies can efficiently adjust to market dynamics and maintain a proactive stance in the face of potential disruptions.

Our contributions of this paper are as follows:

- We propose an adaptive tracking signal method to identify demand disruption signals.
- We combine tracking signals estimated from multi-day ahead forecasts rather than utilizing just single previously generated forecast.
- We leverage a real-world supply chain network as a testbed for validation of our method, demonstrating superior performance over traditional disruption identification methods.

3 Proposed Method

In this paper, we propose an Adaptive Tracking Signal method to identify demand disruption signals. The method begins by using tracking signal statistics based on multi-day ahead forecasts to generate modified tracking signals. These modified tracking signals quantify deviations from the interquartile range (IQR) of tracking signal statistics and are used as features in the Adaptive Tracking Signal model. The formula of tracking signal could be seen from equation (1), which is the ratio of cumulative sum of error to mean absolute deviation. Our Adaptive Tracking Signal method is constructed in three pivotal sections. We begin by estimating these tracking signal statistics. Then, we modify them to measure their deviation from the control limits using interquartile range (IQR) method (*Section 3.1*). Afterwards, we use filtering method to select highly deviated data to train the model (*Section 3.2*). Finally, we employ a binary classification model to predict demand disruption signals that reveal structural deviations from expected demand patterns (*Section 3.3*). Definitions of the notations used in this paper are listed in Table 1.

$$Tracking\ Signal = \frac{\sum(Actual - Forecast)_t}{Mean\ Absolute\ Deviation} \quad (1)$$

Table 1: Notations and definitions of sets, parameters, and variables

Notation	Definition
$\mathcal{T} = \{1, \dots, T\}$	set of days considered
$\mathcal{H} = \{1,2,3, \dots\}$	set of days ahead forecast considered
d_t	observed demand on day t
a_t	exponentially smoothed demand on day t
$f_{t,\hat{t}}$	demand forecast generated on day $\hat{t}$ for day t
n	length of rolling horizon
$e_{t,h}$	rolling-horizon Mean Absolute Deviation of h-day ahead forecast errors
$s_{t,h}$	tracking signal on day t, based on h-day ahead forecast
$m_{t,h}$	modified tracking signal on day t, based on h-day ahead forecast
b_t	forecast bias using forecast generated on day t

3.1 Estimation of Modified Tracking Signal Based on Multi-Day Ahead Forecasts

We propose modified tracking signal statistics for estimation of demand disruption signals, which quantifies the deviation of the tracking signal statistic from the IQR control limits. These modified tracking signals are used as features in the subsequent classification model. The procedure is described in Algorithm 1. We first compute the tracking signal $s_{t,h}$ based on exponentially smoothed demand data a_t, and then consider a rolling horizon of n periods for estimating the IQR range. The modified tracking signal $m_{t,h}$ is then estimated as the ratio of deviation from IQR to the length of IQR. We estimate $m_{t,h}$ based on multi-day ahead $h \in \mathcal{H}$ forecast generated for a given day $t \in \mathcal{T}$.

In an environment with highly uncertain and volatile demand, demand forecasts are unable to capture the demand accurately. This effect is seen in our experiments from the value of modified tracking signals, but can be used to identify structural changes in demand pattern. When the value of the modified tracking signal is greater than 0, it indicates that the demand data is greater than the demand forecast, implying forecast is underestimating demand. When the value of the modified tracking signal is less than 0, it indicates that the demand data is less than the demand forecast, implying forecast is overestimating demand. A critical observation from our analysis is the gradual transition between overestimating and underestimating demand, marking these periods as pivotal indicators of changes in demand patterns. These modified tracking signals reflect the straight relationship between estimated demand and demand forecast, and will be used as features in the following classification model.

3.2 Implementation of Filtering Method Based on P-Values

We get modified tracking signals, namely features from Section 3.1. In this section, we select data which is highly deviated using filtering method. The reason for the filtering method is that we want to predict significant demand disruption signals. Thus, if demand forecast is good enough, we will not take it into consideration in the model. There are two rules for the filtering method: (1) select increasing signal and decreasing signal (which will be introduced in Section 3.3); (2) select data with p-value smaller than specific threshold. From the perspective of labels, increasing signal and decreasing signal indicate that the forecast falls outside the normal range. On the other hand, p-value assists in data selection by indicating the strength of the relationship between demand and demand forecast, with the selection of threshold adjustable on a case-by-case basis. We choose 0.3 as the threshold in the current case. The combination of two rules makes us select highly deviated data, which will help us train the model. The calculation method of p-value is to compute the percentile of the test residual in the empirical distribution of training residuals. We illustrate the function of the p-value using demand data from 2020, along with a confidence interval based on a 1-day ahead forecast, as shown in Figure 1. In Figure 1, demand data is colored according to the p-value. Data significantly diverging from the prediction, indicating a potential demand disruption signal, yields a very small p-value and is marked in red. An intermediate p-value results in yellow coloring, suggesting a moderate deviation from the forecast. Green indicates that the demand forecast falls within the normal range, associated with a large p-value.

Algorithm 1 Procedure for estimation of modified tracking signal

Input observed demand on day t: d_t, demand forecast generated on day $\hat{t}$ for day t: $f_{t,\hat{t}}$, $\forall t, \hat{t} \in \mathcal{T}$
Output modified tracking signal on day t based on demand forecast generated h-days prior: $m_{t,h}$, $\forall t \in \mathcal{T}$, $\forall h \in \mathcal{H}$

$t \leftarrow 0$ ▷ initialization
$a_0 \leftarrow d_0$
for $t \in \mathcal{T}$ **do**
  $a_t \leftarrow \alpha * d_t + (1-\alpha) * a_{t-1}$ ▷ demand smoothing parameter (α)
  for $h \in \mathcal{H}$ **do**
    $e_{t,h} \leftarrow \frac{1}{n} \sum_{\tau=t-n}^{t} |a_\tau - f_{\tau,\tau-h}|$ ▷ rolling-horizon Mean Absolute Deviation
    $s_{t,h} \leftarrow \frac{\sum_{\tau=t-n}^{t}(a_\tau - f_{\tau,\tau-h})}{e_{t,h}}$ ▷ tracking signal
    $Q_{1,t}, Q_{3,t} \leftarrow IQR(s_{\tau,h}, \forall \tau \in \{t-m, \ldots, t\})$ ▷ interquartile range
    if $s_{t,h} \geq Q_{3,t}$ **then** $m_{t,h} \leftarrow \frac{s_{t,h} - Q_{3,t}}{Q_{3,t} - Q_{1,t}}$ ▷ modified tracking signal
    else if $s_{t,h} \leq Q_{1,t}$ **then** $m_{t,h} \leftarrow \frac{s_{t,h} - Q_{1,t}}{Q_{3,t} - Q_{1,t}}$
    else $m_{t,h} \leftarrow 0$
    end if
  end for
end for

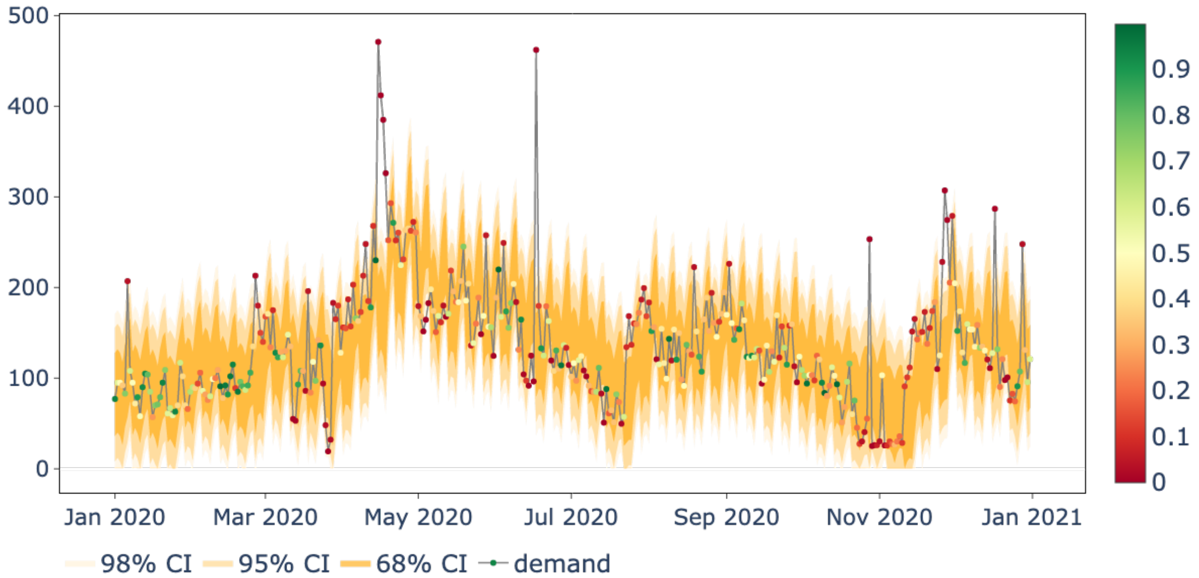

Figure 1: Demand in 2020 with confidence interval using 1-day ahead forecast

3.3 Estimation and Validation of Demand Disruption Signal

In Section 3.1, we focus on deriving features for our model by utilizing modified tracking signals $m_{t,h}$ on day t with h-day ahead forecasts. In Section 3.2, we introduce filtering method to help us select significant data to train the model. In Section 3.3, we aim to estimate the demand disruption signal, implying a structural change in demand pattern, based on the past and present modified tracking signals, as well as multiple days ahead forecasts. For this purpose, we utilize a classification model, Logistic Regression, with demand disruption signal as the dependent variable. Logistic regression is a binary classification algorithm, predicting probabilities using a logistic function. As shown in Equation (2), forecast bias b_t for forecast generated on day t, is defined as the cumulative forecast error in the short term, 14 days for instance. Forecast bias is used to evaluate forecast on day t. We then classify forecast bias using the interquartile range (IQR) method into three categories: negative bias, no bias, and positive bias. A forecast bias above the third quartile is labeled as positive bias, indicating an underestimation of demand; below the first quartile, it is labeled as negative bias, reflecting an overestimation of demand. If the forecast bias falls between these quartiles, it is classified as normal pattern, suggesting that the forecast aligns accurately with actual demand. In our model, forecast biases are directly linked to demand disruption signals. A positive bias combined with demand consistently being greater than demand forecast over the following 14 days signifies an increasing signal, which prompts the need to escalate the forecast. Conversely, a negative bias combined with demand consistently being smaller than demand forecast indicates a decreasing signal, calling for a decrease in the forecast.

$$b_t = \sum_{i=1}^{14}(d_{t+i} - f_{t+i,t}) \tag{2}$$

Figure 2 presents a systematic approach to generating demand disruption signals. The process begins with data collection, comprising six years of demand history from an e-commerce manufacturer, with the initial four years designated for training. The training phase employs a filtering method to select highly disrupted data, preparing for the Logistic Regression model - our chosen tool for its understanding in signaling occurrence confidence. This model is then tested against the subsequent two years of data, which serve as our test dataset. It's important to note that filtering label is excluded during testing to simulate real-world unpredictability. We specifically target data with a p-value less than 0.3, aligning with patterns of significant disruption. The model's effectiveness is gauged through accuracy, precision, and recall metrics. To bring the model online for industrial use, it undergoes daily updates informed by current predictions, parameter adjustments, and label revisions, encapsulated within the red dashed box of Figure 2. This iterative refinement cycle ensures our model continuously adapts to sense and signal demand disruptions effectively.

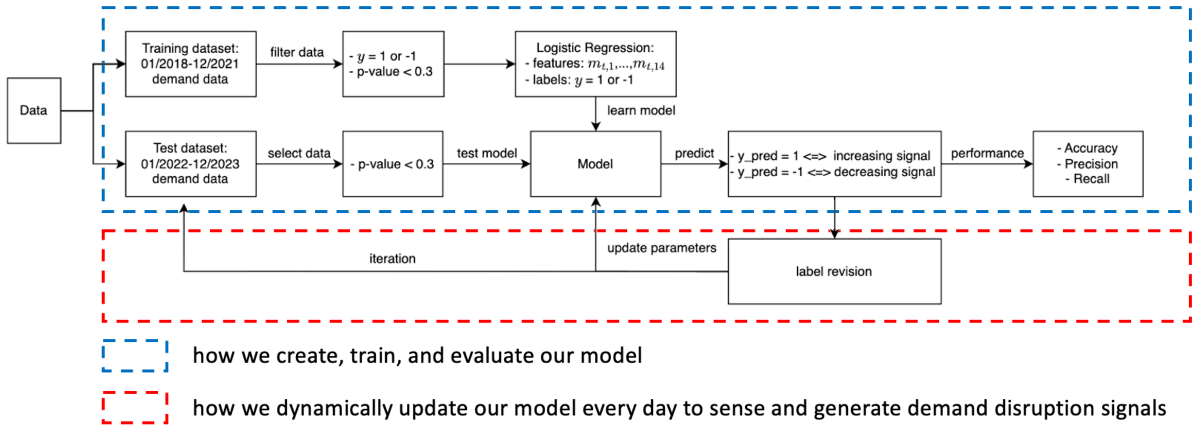

Figure 2: Process of generating demand disruption signals

4 Results

In this section, we show the performance of Adaptive Tracking Signal method in detecting demand disruption signals. In Section 4.1, we evaluate the effectiveness of different signal generation methods. Then, Section 4.2 delves into the sensitivity of our model, analyzing how adjusting the confidence threshold influences the number of detected signals and overall accuracy. Finally, in Section 4.3, we provide practical examples showcasing the detection of increasing demand.

4.1 Results on Validity of Signal Quality

Our study conducts a comprehensive comparison of different signal generation methods applied to master-bedroom bed category from e-commerce-based manufacturing company, focusing on signals with confidence level greater than 75%. We select the rolling horizon of training dataset as 2 weeks, ensuring the model continuously integrates the most recent data and enhancing its responsiveness to changing conditions and trends. The quality of the signals is evaluated against three primary metrics: Accuracy, Precision, and Recall. Accuracy represents the proportion of all signals correctly captured by model; Precision measures the proportion of predicted signals correctly captured by model; and Recall denotes the proportion of true signals correctly captured by model. We validate our model's efficacy using a dataset that encompasses a training phase from January 2018 to December 2021 and a subsequent testing phase from January 2022 to December 2023. Table 2 displays the superior performance of the Adaptive Tracking Signal method, which achieves 77% in Accuracy, 84% in Precision, and 78% in Recall, outperforming the Tracking Signal and Change Point methods in detecting demand disruptions. Adaptive Tracking Signal method outperforms the Tracking Signal and Change Point methods by dynamically adapting to demand patterns, which enhances its ability to accurately capture demand shifts. We use Signal Count to describe the total number of demand disruption signals detected by each method. Missing Value, on the other hand, represents count of signals that the method failed to detect. The similar numbers of missing values across the methods suggest that, while the Adaptive Tracking Signal method detects disruptions more accurately, all methods have comparable sensitivity to when a signal does not appear.

Table 2: Performance of different signal generation methods

Method \ Metric	Accuracy	Precision	Recall	Signal Count	Missing Value
Adaptive Tracking Signal	**77%**	**84%**	**78%**	31	14
Tracking Signal	41%	42%	45%	34	11
Change Point	40%	20%	50%	30	15

4.2 Sensitivity Analysis of Signal Confidence Threshold

This subsection examines the impact of the Signal Confidence Threshold on the accuracy and detection count of demand disruption signals. Figure 3 illustrates that as the threshold increases from 50% to 93%, there is a general trend of increasing accuracy, indicating a more selective and precise signal detection. The count of signals declines as the Signal Confidence Threshold rises, indicating more signals are missed. This balance between accuracy and signal count highlights the importance of setting an optimal confidence threshold to maximize the model's effectiveness in identifying true demand disruptions while minimizing missing values.

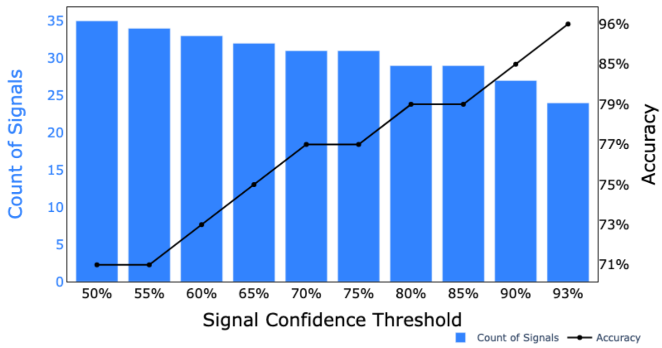

Figure 3: Signal detection and accuracy across different confidence thresholds

4.3 Example of Increasing Demand Disruption Signals

In this section, we use an example of an increasing demand disruption signals to indicate the structural change in demand pattern, where demand forecast is unable to accurately capture the upcoming demand pattern. Figure 4 presents a table of Modified Tracking Signals over a span of days, highlighting a transition in forecasting from overestimating to underestimating, beginning on March 24, 2020, with an 84% confidence level. This shift signifies the model's detection of increasing signals, which grow more accurate over time. Figure 5 visualizes a truly predict increasing demand disruption signal on April 2nd, 2020, highlighting a forecast underestimation for the subsequent, indicating the preparation of out-of-stocks and minimizing lost sales.

	Modified Tracking Signal (based on x-days-ahead forecast)																
Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	p-value	Signal	Confidence
2020-03-20	-0.29	-0.26	-0.17	-0.08	-0.03	-0.13	-0.19	-0.25	-0.09	0.00	0.00	0.00	0.00	0.00	0.51		
2020-03-21	-0.29	-0.19	-0.10	-0.05	-0.14	-0.20	-0.27	-0.13	0.00	0.00	0.00	0.00	0.00	0.13	0.76		
2020-03-22	-0.21	-0.10	-0.05	-0.15	-0.25	-0.32	-0.14	0.00	0.00	0.00	0.00	0.20	0.32	0.39	0.30		
2020-03-23	-0.11	-0.06	-0.20	-0.30	-0.44	-0.22	0.00	0.00	0.00	0.05	0.47	0.66	0.59	0.60	0.92		
2020-03-24	-0.08	-0.26	-0.37	-0.52	-0.28	0.00	0.00	0.00	0.24	0.78	1.03	1.01	0.82	0.81	0.02	Increasing	84%
2020-03-25	-0.29	-0.43	-0.61	-0.28	0.00	0.00	0.00	0.58	1.09	1.50	1.46	1.33	0.78	0.66	0.03	Increasing	92%
2020-03-26	-0.44	-0.65	-0.21	0.00	0.00	0.39	1.04	1.67	1.94	2.04	1.42	0.88	0.63	0.53	0.00	Increasing	98%
2020-03-27	-0.67	-0.16	0.00	0.14	1.14	1.33	2.14	2.57	2.51	1.44	0.86	0.67	0.51	0.52	0.02	Increasing	100%
2020-03-28	-0.13	0.00	0.39	1.29	1.93	2.25	2.95	2.51	1.37	0.76	0.61	0.50	0.50	0.49	0.03	Increasing	100%
2020-03-29	0.00	0.22	1.12	1.66	2.56	2.47	1.94	1.14	0.68	0.48	0.41	0.45	0.45	0.34	0.09	Increasing	100%
2020-03-30	0.04	0.84	1.36	2.10	1.71	1.28	0.84	0.56	0.43	0.32	0.35	0.38	0.31	0.21	0.12	Increasing	100%
2020-03-31	0.69	1.00	1.45	1.04	0.79	0.63	0.41	0.35	0.28	0.29	0.32	0.28	0.21	0.07	0.46		
2020-04-01	0.84	1.27	0.78	0.56	0.50	0.34	0.27	0.25	0.27	0.28	0.25	0.20	0.08	0.00	0.10	Increasing	98%
2020-04-02	1.53	0.90	0.58	0.47	0.39	0.32	0.24	0.31	0.32	0.22	0.19	0.08	0.04	0.00	0.15	Increasing	97%
2020-04-03	1.31	0.73	0.52	0.37	0.37	0.28	0.30	0.37	0.27	0.17	0.08	0.03	0.04	0.00	0.07	Increasing	96%
2020-04-04	1.08	0.65	0.42	0.36	0.33	0.38	0.41	0.34	0.23	0.07	0.03	0.03	0.04	0.00	0.12	Increasing	95%
2020-04-05	0.84	0.47	0.35	0.32	0.44	0.51	0.38	0.27	0.10	0.04	0.04	0.03	0.03	0.00	0.09	Increasing	94%

Modified Tracking signals

±0 | ±1 | ±2 | ±3

A tracking statistic denoting ***deviation*** *of today's realized demand from forecast generated x-days ago*

p-value

0.00 | 0.25 | 0.50 | 0.75 | 1.00

A tracking statistic denoting ***position*** *of today's realized demand with respect to forecast confidence interval*

0: demand is far outside confidence intervals
1: demand is well within confidence intervals

Figure 4: Illustrative example of structural change in demand pattern

5 Conclusion

In this paper, we introduce a novel method for generating demand disruption signals within supply chain networks, designed to detect deviations in the demand curve. Our Adaptive Tracking Signal approach demonstrates significant improvements over traditional models by effectively capturing and responding to sudden shifts in demand patterns. The real-world application to an e-commerce-based manufacturing firm highlights our method's ability to

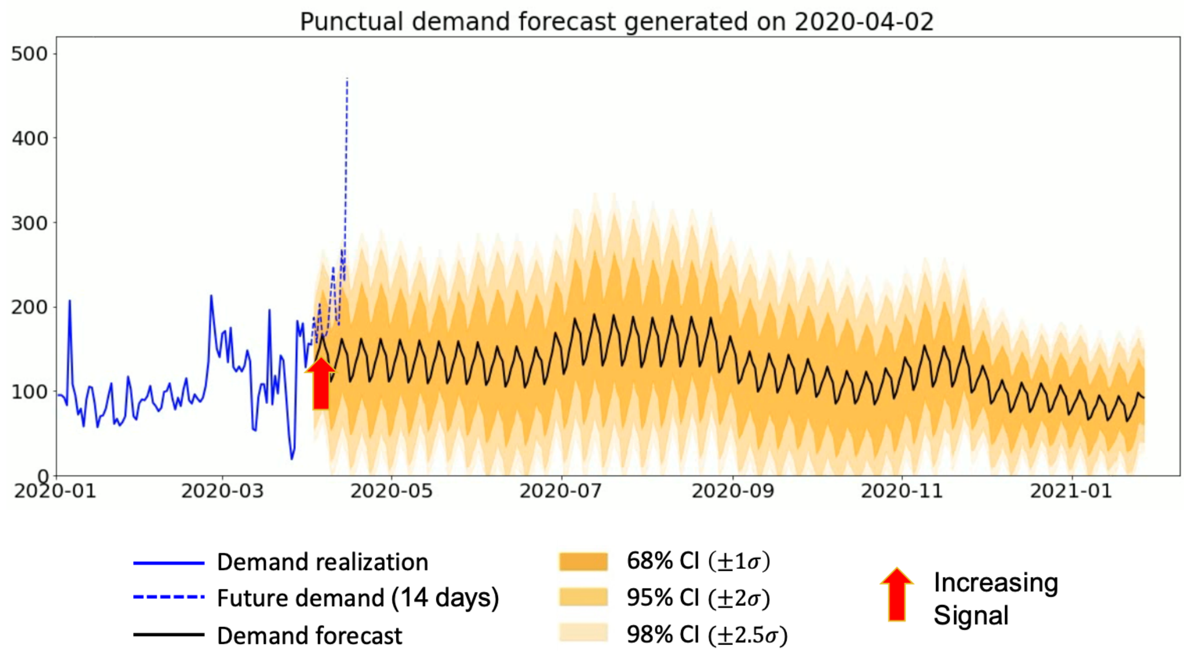

Figure 5: Visualization of an increasing demand disruption signal

proactively identify disruptions, thereby enhancing the resilience and agility of supply chains. By enabling more accurate predictions of demand disruptions, companies can better manage inventory levels, optimize resource allocation, and minimize the impact of supply chain disturbances. This capability is particularly crucial in today's volatile market environments, where conventional forecasting techniques often fall short. Future research could explore the integration of more complex machine learning models, such as neural networks, to develop a more coherent model. Additionally, expanding the scope of our study to include a broader range of industries would further validate the adaptability and effectiveness of our approach across various market dynamics, including supply, transportation, and other critical aspects of supply chains beyond demand.

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Hyperconnected Transportation Planning: Advancing a Multimodal Relay Ecosystem

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***Abstract**: This paper introduces the concept of hyperconnected transportation, drawing inspiration from the Physical Internet, as a sustainable approach to addressing economic, environmental, and social challenges in regional overland transport. It is characterized by three types of connectivities (i.e., shipper-to-network, intra-network, and network-to-carrier connectivity), and incorporates five logistics strategies (i.e., demand aggregation, freight containerization, an interconnected hub network, multimodal transportation, and relay-based transportation). Our study investigated a scenario where a hyperconnected transportation planning platform (HTPP) interfaces with a network of relay hubs to manage bulky goods shipping demands from shippers over time. Unlike conventional systems, the HTPP collaborates with multimodal relay carriers that offer both rail and truck services, optimizing the movement of goods from origins, through hubs, to destinations. We developed a novel Rolling-Horizon Hyperconnected Transportation Planning Framework and a Multimodal Relay Service Network Design optimization model for the HTPP to tactically plan deliveries, with goals to minimize lateness, reduce costs, and decrease emissions. A case study in the Southeastern US automotive delivery sector was conducted to validate the effectiveness of our methodology, considering varying shippers' preferences for delivery velocity, timeliness, and sustainability. We also examined the potential benefits of integrating rail services and clean-powered truck technologies to further improve efficiency, lower costs, and strive towards a zero-emission logistics network. Overall, this research promotes the advancement of a multimodal relay ecosystem by establishing foundational concepts, offering a relevant business model, and proposing a scalable decision-making model to enhance the sustainability and efficiency of regional overland transportation.*

***Keywords**: Hyperconnected Transportation; Transportation Planning Platform; Rolling-Horizon Framework; Multimodal Relay Service Network Design; Bulky Goods; Interconnected Hub Network; Multimodality; Electric and Hydrogen Trucks; Driver Daily Returning Home; Sustainability; Physical Internet*

Main Paper

1 Introduction

The current way of transporting physical objects is unsustainable economically, environmentally, and socially. This problem is particularly acute in regional overland transportation, which predominantly relies on a fragmented connection of rail and truck services. Rail systems, while cost-effective and environmentally friendly for bulk and long-distance hauls, suffer from inflexibility due to fixed routes and schedules. Trucks, on the other hand, provide essential flexibility and can access remote areas not served by rail, but they come with substantial operational costs, significant environmental impacts, and issues like a severe driver shortage and poor long-haul working conditions. Furthermore, emerging technologies such as electric and hydrogen trucks offer greener alternatives, though they face challenges with elevated costs and limited range.

To tackle these prevalent challenges, we introduce the concept of Hyperconnected Transportation, inspired by the digital internet's data transmission, as depicted in Figure 1. Like the digital internet, where data packets travel through interconnected routers, this concept envisions a similar approach for goods—starting with demand aggregation from multiple shippers, followed by freight containerization. The containerized goods then move through an interconnected hub network using multimodal transportation and relay truck drivers, culminating in last-mile deliveries. The notion of hyperconnectivity originates from Physical Internet to enable massively open asset sharing and flow consolidation, thereby improving efficiency and sustainability in transportation, distribution, and production. Achieving hyperconnectivity necessitates comprehensive integration across physical, data, digital, operational, transactional, legal, and personal dimensions. In this paper, we focus on defining hyperconnectivity in the context of transportation through three types of connectivities: Shipper-to-Network Connectivity, involving demand aggregation from various shippers and freight containerization for building loads; Intra-Network Connectivity, leveraging an interconnected hub network moving beyond traditional hub-and-spoke structures by allowing each hub for secure load transfers and storage; and Network-to-Carrier Connectivity, integrating multimodal transportation options and relay truck drivers from different carriers to move freight between hubs. Collectively, these connectivities forge a more efficient and sustainable framework for regional overland transportation, enhancing flexibility and robustness, and enabling relay truckers returning home daily.

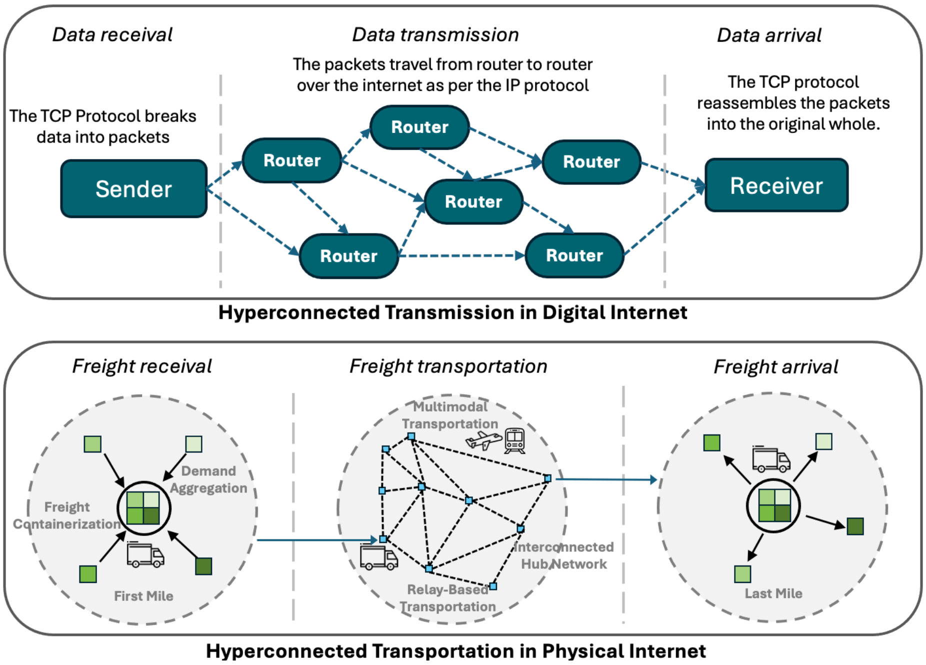

Figure 1: An Analogy from Hyperconnected Transmission in Digital Internet to Hyperconnected Transportation in Physical Internet

As an applicable scenario of Hyperconnected Transportation, this paper considers a Hyperconnected Transportation Planning Platform (HTPP), which interfaces with a network of relay hubs. Shippers transmit their logistic requests to the HTPP, which are then coordinated with multimodal relay carriers to optimize the distribution of goods via efficient hub transfers. To enhance the tactical decision making of the HTPP, we propose a novel Rolling-Horizon Hyperconnected Transportation Planning Framework (RHHTPF) coupled with a Multimodal Relay Service Network Design (MRSND) optimization model. RHHTPF enables HTPP to dynamically plan deliveries based on the status of shipping demands and in-transit services. MRSND aids HTPP in optimizing multimodal relay service selection during the delivery process, aimed at minimizing lateness, reducing costs, and cutting emissions. Specifically, our freight focus is on bulky goods, such as machinery, vehicles, and containers. Unlike parcel or packages, these items are often in heavy weights or uniquely shaped and require crating. They are typically transported together, arriving at destinations simultaneously.

We validate our concept and methodology through a case study in the automotive delivery sector within the Southeastern United States. We first assess the efficacy of our HTPP model in optimizing hyperconnected transportation planning using a single modality as diesel trucks. Specifically, we compare the model performances given various shipping preferences, including delivery velocity, timeliness, and sustainability. Furthermore, we explore the potential of integrating rail services and transitioning to electric and hydrogen-powered trucks as steps toward establishing a multimodal relay ecosystem. This ecosystem aims to achieve enhanced efficiency, cost savings, punctuality, and zero-emission targets.

The structure of the paper is outlined as follows: Section 1 introduces the study's background and focus. Section 2 reviews relevant literature and highlights the unique aspects of our research. Section 3 details our proposed rolling-horizon hyperconnected transportation planning framework and coupled optimization model. Section 4 discusses results from a case study in automotive delivery sector across the Southeastern USA. Finally, section 5 concludes the paper by summarizing key contributions and identifying promising avenues for future research.

2 Literature Review

The traditional logistics sector primarily relies on point-to-point and hub-and-spoke transport models, operating over the networks that are often fragmented and dedicated to specific companies or markets. This contrasts sharply with the highly interconnected nature of the Digital Internet. To address the inefficiencies and unsustainability that plague global logistics, a groundbreaking paradigm known as the Physical Internet has been proposed [1]. This innovative paradigm aims to globally interconnect logistics services, mirroring the connectivity of digital networks. The Physical Internet is structured by thirteen interlaced characteristics designed to address thirteen critical symptoms in existing logistics systems, potentially meeting the Logistics Sustainability Grand Challenge [1, 3]. Additionally, a seven-layer Open Logistics Interconnection model has been introduced to seamlessly integrate logistics services within the Physical Internet, ensuring its adaptability across diverse economic, technological, and regional landscapes. [2]

Within the framework of the Physical Internet, the transportation sector is envisaged to transition towards a distributed, multi-segment intermodal transport system through a meshed hub network [1]. This evolution embraces the notion of hyperconnectivity, akin to data transmission in the Digital Internet. This paper elaborates on the concept of hyperconnectivity in transportation by embodying essential strategies such as demand aggregation, freight containerization, an interconnected hub network, and the utilization of multimodal transportation services, along with relay truck drivers. Such strategies have been proven effective in numerous practical scenarios. [4, 5] Our review seeks to reframe these strategies within a unified framework, aiming to spearhead the next generation of transportation solutions.

Extensive research has delved into various decision-making aspects supporting hyperconnected transportation. Studies have explored hub network design [6, 7], hub capacity allocation [8], and the planning and operations of transportation systems [9, 10, 11, 12]. Additionally, similar studies have been conducted focusing on synchro-modal transportation [13, 14], which further emphasizes the importance of synchronized decision-making across different transportation modes to optimize efficiency and responsiveness in logistics networks. Moreover, simulation assessments [15, 16, 17] have been performed to compare the performances of hyperconnected transportation over traditional models like end-to-end and hub-and-spoke systems, thus highlighting the potential improvements in efficiency and sustainability that hyperconnected transportation offers.

Our paper focuses on a practical scenario wherein a hyperconnected transportation platform manages demands from various shippers, accesses an interconnected hub network, and contracts with multiple carriers providing multimodal transportation services, including relay truck drivers. Unlike prior studies that compare hyperconnected and traditional transportation models, our research emphasizes planning and operational strategies within a hyperconnected framework. This includes transitioning from diesel-powered trucks to more sustainable multimodal options like rail, electric, or hydrogen trucks. Our goals align with diverse delivery speeds, cost-efficiency, timeliness, improved working conditions for drivers (enabling daily home returns) and advancing towards a zero-emission target.

3 Methodology

In this section, we discuss the methodology of the Hyperconnected Transportation Planning Platform (HTPP) to plan and manage deliveries within the realm of hyperconnected transportation.

The HTPP interfaces with a strategically placed network of relay hubs near critical logistics points like factories, railheads, ports, and major highway intersections. This setup enhances connectivity and reduces detours. Some inter-hub arcs are exclusively for trucks, while others accommodate both trucks and rail. The design of the hub network ensures that the arc durations with truck mode, including traveling, processing, and mandatory resting periods, do not exceed half of the maximum daily on-duty time for truckers. This strategic design allows truck drivers to complete their daily arcs and then return home within the same day, ensuring compliance with government regulations.

Shipping demands from shippers are processed by the HTPP over time. Each demand originates from an entry hub and must be delivered to an destination hub by a specified deadline. While delivery delays beyond these deadlines are permitted within predefined limits, they incur a penalty calculated in dollars based on the volume of the shipment and the number of hours late.

The HTPP utilizes multimodal relay services between hubs, provided by contracted carriers. Rail services operate with arc-based schedules and transportation costs are charged per railcar mile, with a uniform railcar size assumed. Truck services are provided with path-based schedules and costs are assessed per truck mile for standard-sized trucks. The trucks are powered by diesel, electric, or hydrogen engines, each with specific cost rates per mile and CO_2 emissions per ton-mile of freight. HTPP categorizes all truck drivers as short-haul relay drivers, ensuring they can return home daily.

3.1 Rolling-Horizon Hyperconnected Transportation Planning Framework

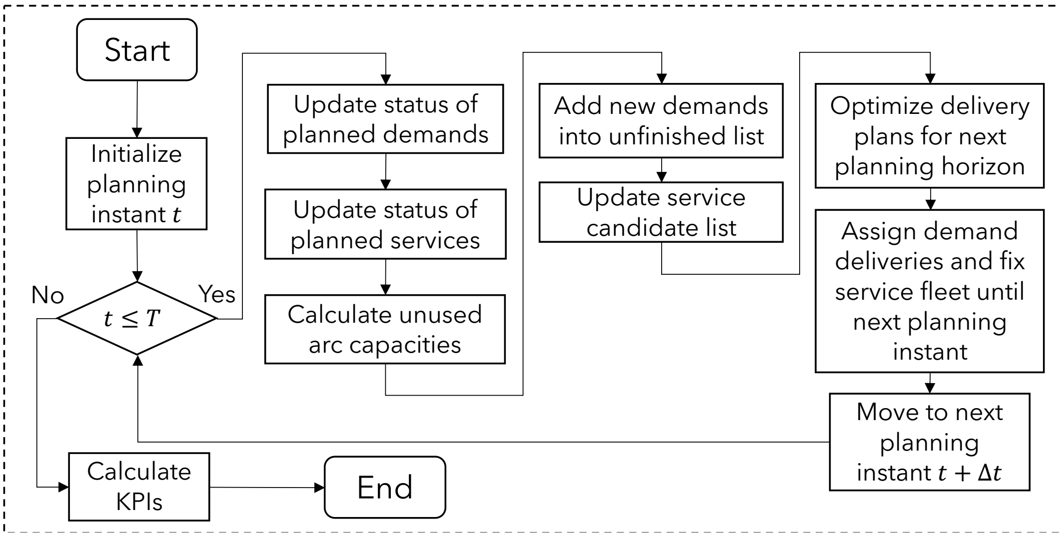

Figure 2: The decision flow chart of RHHTPF

We proposed a Rolling-Horizon Hyperconnected Transportation Planning Framework (RHHTPF) as the cornerstone of tactical decision support for the HTPP. Figure 2 depicts the decision flowchart of the RHHTPF. The HTPP operates over a testing horizon of length T, divided into uniformly distributed time instants. At the start of each planning instant, the delivery status of planned demands and the transit status of planned services are updated. Concurrently, the unused capacities across all inter-hub arcs are recalculated. Subsequently, new demands are received by the HTPP and added to the list of unfinished demands. Based on the current time, we refresh the candidate service list for the upcoming planning horizon, which is offered by multimodal carriers between hubs. At this point, the Multimodal Relay Service Network Design (MRSND) optimization model is employed to optimize delivery plans for the next planning horizon, utilizing the latest demand, service, and unused arc volume information. However, only the delivery plans up to the next planning instant are finalized, and the required service fleet is updated accordingly. The process then advances to the next planning instant, repeating this cycle in a rolling manner until the testing horizon concludes.

3.2 Multimodal Relay Service Network Design

To present the MRSND optimization model, we first define the sets, parameters, and decision variables pertinent to the model formulation.

<u>Sets:</u>

- Set of time instants: $\mathcal{T}$
- Set of shipping demands: $\mathcal{K}$
- Set of hubs: $\mathcal{H}$
- Set of time-expanded nodes (short for nodes): $\mathcal{N} \subseteq \mathcal{H} \times \mathcal{T}$
- Set of time-expanded arcs (short for arcs): $\mathcal{A} \subseteq \mathcal{N} \times \mathcal{N}$, where $\mathcal{A} = \mathcal{A}^m \cup \mathcal{A}^{\mathscr{h}}$ with moving arc set $\mathcal{A}^m$ and holding arc set $\mathcal{A}^{\mathscr{h}}$
- Set of holding arcs at hub h: $\mathcal{A}_h^{\mathscr{h}}, \forall h \in \mathcal{H}$
- Set of modes (including rail and truck-related modes): $\mathcal{M} = \{rail\} \cup \mathcal{M}^{truck}$
- Set of truck-related modes (including diesel, electrical and hybrid trucks): $\mathcal{M}^{truck}$
- Set of moving arcs with mode m: $\mathcal{A}_m^m \subseteq \mathcal{A}^m$, $\forall m \in \mathcal{M}$
- Set of multimodal services: $\mathcal{S}$
- Set of moving arcs of service s: $\mathcal{A}_s^m$, $\forall s \in \mathcal{S}$
- Set of services with mode m: $\mathcal{S}_m \subseteq \mathcal{S}$, $\forall m \in \mathcal{M}$

<u>Decisions</u>

- $X_{kma}^m \in \{0,1\}$: whether shipping demand k is moved over arc a via mode m, $\forall k \in \mathcal{K}, m \in \mathcal{M}, a \in \mathcal{A}_m^m$
- $X_{ka}^{\mathscr{h}} \in \{0,1\}$,: whether shipping demand k is held over arc a, $\forall k \in \mathcal{K}, a \in \mathcal{A}^{\mathscr{h}}$
- $Y_s \in \mathbb{N}^{\geq 0}$: fleet size of relay service s, $\forall s \in \mathcal{S}$
- $L_k \in \mathbb{R}^{\geq 0}$: delivery lateness of shipping demand k, $\forall k \in \mathcal{K}$

<u>Parameters</u>

- h_k^e, h_k^d: entry and destination hubs of demand $k, \forall k \in \mathcal{K}$
- t_k^e, t_k^d, t_k^ℓ: entry, due and latest due time instants of demand $k, \forall k \in \mathcal{K}$
- h_a^+, h_a^-: starting and ending hubs of arc $a, \forall a \in \mathcal{A}$
- t_a^+, t_a^-: starting and ending time instants of arc $a, \forall a \in \mathcal{A}$
- u_{ma}: unused volume capacity of mode m over arc a, $\forall m \in \mathcal{M}, a \in \mathcal{A}_m^m$
- p_k^t: timeliness penalty per unit of lateness of shipping demand k, $\forall k \in \mathcal{K}$
- c_{kma}^m: transportation cost of shipping demand k traversing arc a via mode m, $\forall k \in \mathcal{K}, m \in \mathcal{M}, a \in \mathcal{A}_m^m$
- e_{kma}^m: greenhouse gas emission of shipping demand k traversing arc a via mode m, $\forall k \in \mathcal{K}$, $m \in \mathcal{M}, a \in \mathcal{A}_m^m$
- u_s^{max}: volume capacity of service s, $\forall s \in \mathcal{S}$
- $c_s^{\mathscr{s}}$: transportation cost of service s per unit of fleet size, $\forall s \in \mathcal{S}$
- $e_s^{\mathscr{s}}$: greenhouse gas emission of service s per unit of fleet size, $\forall s \in \mathcal{S}$
- p^e: sustainability penalty per greenhouse gas emission

Give the above notions, we then formulate a mixed-integer programming model for the MRSND problem.

$$\min \sum_{k\in\mathcal{K}} p_k^t L_k + \left(\sum_{k\in\mathcal{K}}\sum_{m\in\mathcal{M}}\sum_{a\in\mathcal{A}_m^m} c_{kma}^m X_{kma}^m + \sum_{s\in\mathcal{S}} c_s^{\mathscr{s}} Y_s\right) + p^e\Big(\sum_{k\in\mathcal{K}}\sum_{m\in\mathcal{M}}\sum_{a\in\mathcal{A}_m^m} e_{kma}^m X_{kma}^m + \sum_{s\in\mathcal{S}} e_s^{\mathscr{s}} Y_s\Big)$$

$s.t.$

$$\sum_{m\in\mathcal{M}}\sum_{a\in\sigma^+(n)\cap\mathcal{A}_m^m} X_{kma}^m + \sum_{a\in\sigma^+(n)\cap\mathcal{A}^{\mathscr{h}}} X_{ka}^{\mathscr{h}} - \sum_{m\in\mathcal{M}}\sum_{a\in\sigma^-(n)\cap\mathcal{A}_m^m} X_{kma}^m - \sum_{a\in\sigma^-(n)\cap\mathcal{A}^{\mathscr{h}}} X_{ka}^{\mathscr{h}} = \begin{cases} 1, & if\ n = (h_k^e, t_k^e) \\ -1, & if\ n = \left(h_k^d, t_k^\ell\right) \\ 0, & o.w. \end{cases}, \forall k \in \mathcal{K}, n \in \mathcal{N} \tag{1}$$

$$\sum_{k\in\mathcal{K}} v_k X_{kma}^m \leq \sum_{s\in\mathcal{S}_m : a\in\mathcal{A}_s^m} u_s^{max} Y_s + u_{ma}, \forall m \in \mathcal{M}, a \in \mathcal{A}_m^m \tag{2}$$

	$$L_k \geq t_k^{\ell} - t_k^{d} - \sum_{a \in \mathcal{A}^{\hbar}_{h_a^+}: t_k^d \leq t_a^+ < t_k^{\ell}} (t_a^- - t_a^+) X_{ka}^{\hbar}, \forall k \in \mathcal{K}$$	(3)

The objective function consists of timeliness penalties of late deliveries, total transportation cost, and sustainability penalties of overall greenhouse gas emission. There are three constraints: Constraint 1 is the flow balance constraints of shipping demands. It also requires the delivery times of all shipping demands not exceeding the latest due times; Constraint 2 ensures the arc volume induced by all shipping demands not exceeding the arc capacity provided by all services in both current and previous planning; Constraint 3 calculates the delivery lateness of shipping demands.

3.3 Results and Discussion

In this section, we perform a case study with setup described in subsection 3.3.1 and then discuss the results in subsection 3.3.2.

3.3.1 Case study Setup

We consider a Hyperconnected Transportation Planning Platform (HTPP) having access to a hyperconnected hub network across the Southeastern United States, encompassing the seven states (i.e., Tennessee, North Carolina, South Carolina, Georgia, Alabama, Mississippi, and Florida). This network consists of 24 hub nodes shown in Figure 3, strategically positioned near key infrastructure such as highway intersections, rail terminals, and port locations to optimize connectivity and minimize detours. Of these hub nodes, 8 are multimodal, accommodating both rail and truck services, while the remaining 16 are exclusively for truck use. A fundamental design criterion for this network is ensuring that the travel time between any two adjacent hubs does not exceed 5.5 hours, which is half the daily driving limit set by traffic regulations. This design criterion allows drivers to visit any adjacent hub from their domicile hubs and return home within the same day.

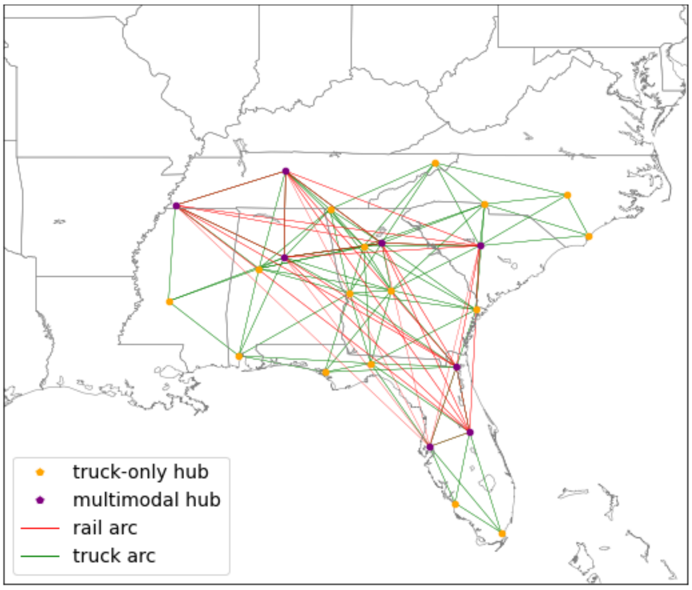

Figure 3: Hyperconnected Hub Network in the Southeastern United States

To model shipping demands for the HTPP, we use data from the Freight Analysis Framework (FAF). Developed jointly by the Bureau of Transportation Statistics (BTS) and the Federal Highway Administration (FHWA), the FAF combines data from various sources to provide a detailed view of freight movements across states and major metropolitan areas via all transport modes. Our specific focus is on the transportation of automotive goods by truck in 2021, which encompasses imports, exports, and domestic movements. The demand generation process is structured into three main steps: Firstly, we convert the weight of freight flows reported by the FAF from tons to an equivalent number of vehicles, using an average weight of 2.165 tons per vehicle. Secondly, we refine the freight flows, originally organized by FAF regions, by estimating the origins and destinations of flows using regional centroids. These flows are then aggregated to designated entry and destination hubs based on their directions and geographical locations. From this analysis, we identified 242 inter-hub pairs with an average daily demand of 23,144 vehicles, as depicted in Figure 4. Lastly, we assume that the HTPP captures a consistent market share of the total daily inter-hub freight demands. Given this market share, we then randomly generate daily demand samples, which become known to the HTPP at the start of each day. By setting this share at 5%, the HTPP manages the shipping demands of approximately 1,157 vehicles daily and 32,396 vehicles in total for a testing horizon of 28 days.

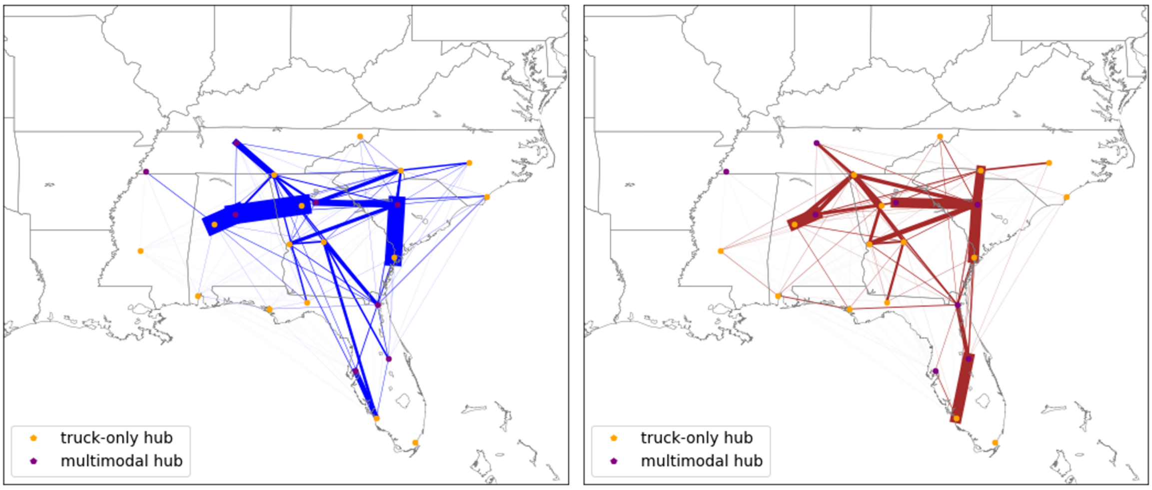

Figure 4: FAF-Data-Based Inter-Hub Shipping Demands Towards the East (Left) vs. West (Right)

To facilitate freight movement across the network, we utilize both rail and truck transportation options to link the hubs. Figure 3 illustrates these connections with 49 rail arcs and 168 truck arcs between the hubs. Rail services operate according to arc-based schedules provided by CSX Corporation. For truck transportation, we arrange for services between two hubs, ensuring that drivers can return to their home hub daily. This involves each driver starting from their domicile hub, traveling to an adjacent hub, and then returning. Potential departures are scheduled for 12 AM, 8 AM, and 4 PM. The maximum allowable waiting time at non-domicile hubs is 2 hours to minimize delays. Additionally, we include a buffer of 1.5 hours per arc to cover both transshipment activities at hubs and any potential traffic congestion. This precaution also ensures that the duration of all truck services does not exceed the 14-hour daily on-duty limit mandated by traffic regulations. Further details of both rail and truck transportation services are outlined in Table 1.

Table 1: Key Parameters in Rail and Truck Transportation Services

Service Mode	Rail Services	Truck Services		
Average Speed (MPH)	50	60		
Fleet Type	Tri-level auto-rack railcars (Capacity: 15 vehicles)	8-car hauler trucks (Capacity: 8 vehicles)		
Fuel Type	Diesel	Diesel	Electricity	Hydrogen
Cost Rate (Per Fleet Unit Per Mile)	\$0.67	\$2.00	\$2.25	\$2.42
CO_2 Emission Rate (Per Ton Mile)	0.021	0.12	0.07	0.06

3.3.2 Experimental results

In this subsection, we share the results of our experiments. All the experiments are based on a testing horizon of 28 days and the optimality gap of the MRSND model is set as 5%.

We begin by evaluating scenarios where only diesel trucks were used, considering different shippers' preferences for delivery velocity (either short or long distances), timeliness, and sustainability across 12 scenarios, as shown in Table 2. Table 3 summarizes statistics of four key performance indicators (KPIs) across these scenarios. On average, each truck driver works for 6.85 hours, which allows them to return home daily while minimizing trips without cargo. Our findings also show that, on average, trucks travel without cargo 9.27% of the time, emit 0.26 kg of CO2, and incur a cost of $2.37 per mile per demand unit. We use these numbers as baseline references for further experiments. Additionally, the small variation in these values (less than 6%) suggests that our results are consistent in this diesel-truck-only setup. Figure 5 displays the average late percentage and delay time per demand unit across different scenarios. We observe that tighter delivery schedules slightly increased delays. Nevertheless, all scenarios had an average lateness less than 0.7% and less than 3 minutes per demand unit, demonstrating the reliability of our proposed method in managing deliveries on time.

Table 2: Scenario designs for diesel-truck-only hyperconnected transportation

Scenario ID	1	2	3	4	5	6	7	8	9	10	11	12
Delivery velocity for short haul demands	1-Day Delivery w/ 1-Day Penalty Period				1-Day Delivery w/ 1-Day Penalty Period				2-Day Delivery w/ 1-Day Penalty Period			
Delivery velocity for long haul demands	1-Day Delivery w/ 1-Day Penalty Period				2-Day Delivery w/ 1-Day Penalty Period				3-Day Delivery w/ 1-Day Penalty Period			
Lateness penalty ($ per demand unit per late hour)	10		40		10		40		10		40	
Emission penalty ($ per demand unit per CO_2 tons)	20	80	20	80	20	80	20	80	20	80	20	80

Table 3: KPI Statistics for Diesel-Truck-Only Hyperconnected Transportation

KPI	***Mean***	***SD***	***SD/Mean***
Average Travel Hours per Truck Driver (hrs)	6.85	0.02	0.3%
Average Empty Travel Percentage per Truck Driver (%)	9.27	0.51	5.5%
Average CO2 Emission per Demand Unit per Mile (kg)	0.26	0.00	0.0%
Average Overall Cost per Demand Unit per Mile ($)	2.37	0.01	0.4%

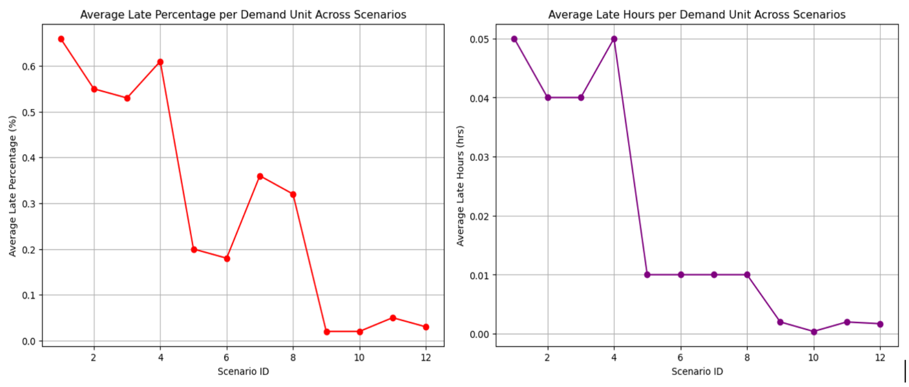

Figure 5: Average Late Percentage (Left) and Late Hours (Right) per Demand Unit across Scenarios

Starting with a diesel-truck-only setting, we then add rail transportation to our study. We compare the diesel-only with the rail and diesel truck combination across key performance indicators (KPIs) such as timeliness, efficiency, sustainability, and cost (summarized in Table 4). We can observe that under the same delivery velocity requirements, switching from diesel-only to a combined rail and diesel truck transportation, lateness percentages rise from 0.36% and 0.05% to 7.11% and 1.73%, respectively. Meanwhile, CO2 emissions decrease from 0.26 kg per mile to 0.19 kg per mile, and overall costs drop from $2.36 and $2.37 to $1.87 and $1.90 per demand unit per mile for long haul and short haul demands, respectively. This shift reflects the advantages of rail in reducing costs and emissions, although the fixed schedules and limited locations of rail transport can lead to increased delays and detours.

Lastly, to achieve a zero-emission logistics ecosystem, we further explore replacing diesel trucks with cleaner truck technologies, such as electric-vehicle (EV) and hydrogen trucks, given the combination with rail transportation. According to Table 5, using rail combined with EV or hydrogen trucks result in an increase in lateness percentages from 7.11% to 10.75% and 14.02% respectively, while CO2 emissions decrease from 0.19 kg to 0.11 kg and 0.09 kg per demand unit per mile. Costs per mile also rise from $1.87 to $2.02 and $2.05 per demand unit. This shift is due to the lower emissions of electric and hydrogen trucks compared to diesel trucks, though they incur higher costs per mile. Our proposed methods allow for some delays in consolidating shipments to reduce CO2 emissions, albeit at a slightly increased cost.

Table 4: Assessing the Impact of Rail Mode

	Mode	Diesel Trucks		Rail + Diesel Trucks	
	Delivery velocity for short haul demands	1-Day Delivery w/ 1-Day Penalty Period	2-Day Delivery w/ 1-Day Penalty Period	1-Day Delivery w/ 1-Day Penalty Period	2-Day Delivery w/ 1-Day Penalty Period
	Delivery velocity for long haul demands	2-Day Delivery w/ 1-Day Penalty Period	3-Day Delivery w/ 1-Day Penalty Period	2-Day Delivery w/ 1-Day Penalty Period	3-Day Delivery w/ 1-Day Penalty Period
Timeliness	Avg late percentage per demand unit (%)	0.36	0.05	7.11	1.73
	Avg Late hours per demand unit	0.01	.002	0.37	0.26
	Avg lateness penalty per demand unit ($)	0.42	0.08	14.6	10.44
Efficiency	Avg rail transportation hours per short haul demand unit	-	-	1.08	1.07
	Avg truck transportation hours per short haul demand unit	3.71	3.73	2.99	2.98
	Avg rail transportation hours per long haul demand unit	-	-	5.48	5.39
	Avg truck transportation hours per long haul demand unit	9.05	9.54	5.36	6.02
	Avg travel hours per truck driver	6.85	6.87	6.27	6.26
	Avg empty travel percentage per truck driver (%)	9.19	9.49	9.85	10.32
Sustainability	Average CO_2 emission per demand unit per mile (kg)	0.26	0.26	0.19	0.19
	Average emission penalty per demand unit per mile ($)	0.010	0.010	0.008	0.008
Cost	Average transportation cost per demand unit per mile ($)	2.34	2.35	1.81	1.86
	Average overall cost per demand unit per mile ($)	2.36	2.37	1.87	1.90

4 Conclusion

The contributions of this paper are multifaceted. First, it conceptualizes hyperconnectivity in transportation through three types of connectivities and five logistics strategies. Second, it explores a novel business model where a HTPP coordinates with multimodal relay transportation services to meet over-time shipping requirements and multi-dimensional targets. Third, it develops a tactical decision support prototype for the HTPP, with the core as a combination of the RHHTPF and the MRSND optimization model. Lastly, it performs a detailed case study to validate the proposed decision support prototype, as well as demonstrate the potentials of enhancing efficiency and sustainability of regional deliveries through hyperconnected transportation planning, thus advancing a multimodal relay ecosystem. In conclusion, our research calls for a paradigm shift towards hyperconnected transportation for regional overland deliveries. By fostering a sustainable multi-modal relay ecosystem, this transition has the potential to improve delivery timeliness, cost savings, and environmental friendliness, as well as create a more favorable environment for drivers.

Future research directions offer several promising paths. Firstly, developing more efficient algorithms for accelerating the MRSND optimization model, such as a dynamic discretization discovery algorithm, is essential for shifting to larger test cases or higher market shares. Additionally, the current model underestimates CO2 emissions by only considering emissions from freight trucks but omitting those from empty travels. Thus, addressing the underestimation of CO_2 emissions by including those from empty truck travels will refine environmental impact assessments. Additionally, correcting the simplified linear CO2 emissions formula to better match the nonlinear real-life emissions and evaluating the resulting errors is vital. Lastly, testing the robustness of the combined RHHTPF and MRSND model in scenarios with traffic uncertainty, specifically for rail schedules, will help confirm its effectiveness in real-world conditions.

Table 5: Assessing the Impact of Electrification and Hydrogen Transition

	Mode	Rail + Diesel Trucks	Rail + EV Trucks	Rail + Hydrogen Trucks
Timeliness	Average late percentage per demand unit (%)	7.11	10.75	14.02
	Average Late hours per demand unit	0.37	0.60	0.81
	Average lateness penalty per demand unit ($)	14.6	23.9	32.23
Efficiency	Average rail transportation hours per short haul demand unit	1.08	1.22	1.73
	Average truck transportation hours per short haul demand unit	2.99	2.91	2.67
	Average rail transportation hours per long haul demand unit	5.48	6.47	6.77
	Average truck transportation hours per long haul demand unit	5.36	5.06	4.83
	Average travel time per truck driver	6.27	6.22	5.88
	Average empty travel percentage per truck driver (%)	9.85	11.32	11.98
Sustainability	Average CO_2 emission per demand unit per mile (kg)	0.19	0.11	0.09
	Average emission penalty per demand unit per mile ($)	0.008	0.005	0.004
Cost	Average transportation cost per demand unit per mile ($)	1.81	1.94	1.95
	Average overall cost per demand unit per mile ($)	1.87	2.02	2.05

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A Physical Internet-Enabled Container Loading Solution Leveraging Virtual Reality and Building Information Modeling

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Abstract: *The process of bundling items that need to be together in a container is known as kitting. In the context of Modular Construction (MC), kitting has the potential to streamline productivity since all the necessary parts to complete an assembly will be closed to each other. However, the kit generation process has associated challenges such as dealing with irregularly shaped objects and complex constraints. This paper explores the integration of Virtual Reality (VR) and Building Information Modeling (BIM) to overcome these challenges and develop optimal kitting strategies. Our value proposition involves a Human-VR-driven approach for efficient kit generation. Results indicate that our method not only has the potential to improve volume utilization rates compared to traditional optimization methods but also is capable to produce feasible solutions with less computational expense under specific scenarios. Lastly, this case opens new research opportunities to extend our findings to larger-scale applications.*

Keywords: *Physical Internet, Immersive Technologies, Modular Construction, Virtual Reality, Resilient Supply Chains, Sustainability.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan:☒ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories),☒ Transportation Equipment, ☐ PI Networks, ☒ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

Targeted Delivery Mode-s*: ☒ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation*

1 Introduction

Modularity is a key principle in the concept of the Physical Internet (PI). Just as digital information can be partitioned into smaller and standardized units, physical goods can be broken down and then packaged into standardized containers, which can then be effectively routed (Montreuil, et al., 2014). By integrating this principle into Modular Construction (MC), a construction method that parallelizes work between offsite and onsite locations, it is possible to boost MC's strengths in executing parallel operations. Our proposal to enhance MC's value proposition involves two key components: the Kitting Center (KC) and the Assembly Center (AC). Within the KC, elemental construction components are consolidated into kits, essentially containers carefully designed to bundle only the parts required for specific assemblies at designated workstations and times. This method facilitates their later use in the AC, where workers will only need to focus on performing assemblies with the kits received.

The process of kit generation can be conceptualized as a 3D bin packing problem; therefore, optimization techniques can be employed to obtain solutions. However, existing solutions are often based on numerous assumptions and constraints relaxations to make problems solvable. The aforementioned points are particularly pertinent when dealing with irregularly shaped items of varying weights and materials.

In this paper, we propose moving away from heuristic approaches that produce suboptimal solutions. Instead, we recommend leveraging Virtual Reality (VR) and Building Information Modeling (BIM), an approach commonly used in construction, where all elements necessary for the final product are modeled in a virtual environment using 3D modeling software such as Revit. These virtual assets can then be integrated into VR engines, allowing human agents to interact with them and propose containerization solutions. The human capacity to recognize patterns and employ spatial intelligence makes our feedback valuable for the kitting creation processes, especially when dealing with irregularly shaped objects that are challenging to model accurately with mathematical optimization.

2 Industry Context

To properly introduce the case study and our proposed VR driven containerization framework, it is crucial to understand the operations model to study. For realizing a modular construction project, the architectural team creates the designs, followed by the engineering team developing 3D representations of these proposals. These representations are constructed starting from their most elemental parts, such practice is known as Building Information Modeling (BIM). The information generated in this setting is fundamental because it is a precise representation of every single item that will be used in the construction process and provides details regarding the shape and geometry of the items.

The system to study in this paper consists of a modular construction manufacturing network which includes two main facilities: the KC and the AC. In the KC, one encounters the foundational 3D components utilized in assemblies, hereinafter designated as items. These items are classified into four different categories: i) Containerized, objects of relatively small size suitable for placement in containers like totes or boxes; ii) Sheeting, comprising drywall sheets used for subproduct cladding; iii) Bundle, predominantly consisting of plumbing pipes; and iv) Big, denoting objects with large dimensions like appliances. Our research focus revolves around elements within the 'Containerized' category, as they are the most abundant items and improving their containerization process is vital to improve the flows from the KC to the AC. Moreover, subsequent findings will show the robustness of the proposed framework and demonstrate how to extends these discoveries to the other categories.

Items are consolidated in the KC into containers, referred to as kits, before being shipped to the AC. This consolidation process cannot be arbitrary. To maximize efficiency at the AC, a smart kitting decision strategy must be employed, ensuring that items are logically grouped. One such logical approach is to include components in a kit that are part of a given subproduct (e.g., a wall) within a specified period, and to be assembled by the same team. This criterion, known as Kitting Containerization, is pivotal as it minimizes material handling costs at the AC, and enables transferring workload from the AC to the KC, easing the work of assembly workers which are subject to complex tasks. This strategy intends to improve the productivity in the AC.

Upon their arrival at the AC, the kits are received and processed at designated workstations, where they are transformed into subproducts. These subproducts form the building blocks for the subsequent stage, where they are volumetrically assembled into PODs. Finally, the PODs are combined to form the final modules. Figure 1 illustrates this multi-tiered structure.

Figure 1. Multi-tiered product structure. (a) Example of items designated for consolidation into kits (Source: BREAKA brackets) (b) Representation of Kits prepared for dispatch to AC (Source: Pengoodet shop) (c) An assembled subproduct utilizing its associated kits (Source: coloradosun) (d) Representation of a volumetric

assembly comprising multiple subproducts (Source: coloradosun) (e) Example of final module (Source: https://upsideinnovations.com/prefab-versus-modular-construction/)

3 Problem Description

The operational and logistical dynamics presented in MC propose two major challenges. Firstly, they require synchronizing operations between KC shipments and AC processing, to correctly parallelize manufacturing activities across onsite and offsite locations, propelling for time reduction and efficient space utilization. Secondly, they require the kit containerization plan to be strategically designed to balance the trade-off between maximizing volume utilization in a container and ensuring that only the appropriate items are dispatched within it. This trade-off will be the fundamental problem addressed in this paper.

Traditionally, a common strategy for managing this trade-off is through the application of optimization techniques. This challenge falls under the domain of the *Cutting and Packing Problems (CPP)*, whose three-dimensional variants are well-known for being NP-hard. Further complications in the construction sector include that the items inside a kit may have irregular shapes, such as interconnected tubes, valves, hoses, and connectors. Additionally, the elements required in each workstation can have dramatic changes in sizes, making each kit unique. These additional layers of complexity make conventional optimization techniques hard to solve and might require the adoption of heuristic approaches to obtain good quality solutions in a reasonable time.

These heuristics typically begin by relaxing certain assumptions. In the literature, practitioners who have similar problems often approximate the shapes of irregular items as rectangular prisms. If the resulting assortment is weakly heterogeneous, the problem can be addressed as a *Cutting Stock Problem (C&SP)*; on the other hand, a strongly heterogeneous assortment can be treated as a *3D Bin Packing Problem (3DBPP)*. However, this relaxation comes with a significant drawback: every feasible solution will be suboptimal. Usually, when the process is reversed from prisms to the original shapes, it is found that there is still more space that can be utilized inside the kits. Furthermore, object shapes can be leveraged to overlap pieces together, which is intuitive for humans but challenging to model in a mathematical optimization framework.

Given the NP-hard nature of the problems, it is possible that the previous relaxation is not enough to obtain solutions in polynomial time, and there is a need to further simplify some constraints. Common relaxations for the constraints in the literature include reducing the number of possible rotation orientations of the bins, suppose that all bins are strong enough and it is always possible to stack them vertically, keeping uniform priority among all bins, or assuming that all of them are unloaded at a single destination and that the order of unloading does not pose a problem (Poncelet, 2022).

Finally, one final challenge that arises when a kit containerization plan is obtained through an optimization-heuristic approach is that it becomes difficult to gain visual insights of the 'optimal solution'. Moreover, as we will show later, given that solutions to these approaches are suboptimal, incorporating the human factor is an easy but powerful way to enhance the solution. Under this setting, immersive technologies like Virtual Reality (VR) or Augmented Reality (AR) can play an important role in this regard, as enablers of the creation of virtual environments for testing and refining solutions without incurring additional expenses associated with acquiring and deploying a physical setup.

4 Literature Review

Cutting and packing problems (CPP) have been extensively studied in literature for various reasons, but primarily due to their wide-ranging real-world applications across numerous industries. Additionally, these problems present a high degree of versatility, as even minor variations introduce new and intriguing challenges. Any variant of the CPP will be termed from now on as a subproblem. Identifying the specific subproblem is key since any approach to solve this problem will heavily rely on the proper description of the subproblems. For this reason, it is important to introduce a systematic way to characterize any subproblem, and relevant literature accomplishes this by defining its typology and associated constraints.

4.1 Typology of Cutting and Packing problems

In any CPP problem is possible to identify two sets (Wäscher, et al., 2007):

- A set of large objects (for our case, the kits) that will contain the next set.
- A set of small items (for our case, the pieces used in a workstation).

Using this notion, the authors proposed five criteria to classify a CPP:

- Type of assignment: The primary objectives of any optimization problem are maximization or minimization. In a CPP, a maximization problem arises when researchers aim to allocate a set of small items into a limited (fixed) number of large objects. Conversely, a minimization problem occurs when practitioners seek to allocate the small items using the fewest (dynamical) possible large objects.
- Characterization of small items: According to this typology, small items can be categorized as identical, weakly heterogeneous, or strongly heterogeneous.
- Characterization of large objects: The typology for large items mirrors the one of small items: identical, weakly heterogeneous, or strongly heterogeneous.
- Dimensionality: The problem can be considered in one, two, or three dimensions. The case studied for this paper pertains to a 3D scenario.
- Shape of the small items: It is possible to identify an item with a geometric shape (rectangles, circles, etc.), or the object may have an irregular shape.

The combination of these five criteria generates the basic combinations that exist on a CPP. However, to fully characterize the problem, it is important to also consider the set of constraints.

4.2 Constraints in Cutting and Packing problems

In a literature analysis of the CPP's constraints (Bortfeldt & Wäscher, 2013), it was noted that the primarily focus was on small item's orientation and stability of the large objects, while other constraints such as weight distribution were often overlooked. Extending upon these findings, Ramos et al. (2018) proposed two key points: i) Most attempts to address the CPP have failed because the constraints considered, tend to oversimplify the real case scenarios; ii) the early literature lacked a comprehensive structure to categorize formally the constraints of a CPP. To address this last issue, the authors proposed the constraints classification described below.

4.2.1 Safety constraints

As the name suggests, this type of restrictions is related to conditions that guarantee the well-being of the workers and other actors while loading, handling, and unloading the cargo. At the same time, these limitations are designed to maintain cargo integrity. In this group the following constraints are considered:

- Weight limit constraints: Indicate the maximum weight capacity of a large object.
- Weight distribution constraints: Detail how weight should be spread within the large object. Typically, the weight is evenly distributed across the floor, but this may vary based on the object that works as a container.
- Orientation constraints: Specify permissible orientation variations for small items. This could range from allowing six different orientations (any rotation in 3D) to disallowing any single orientation change (preloaded pallets for example).

- Stacking constraints: Limit the number of small items that can be placed on top of each other.
- Physical positioning constraints: Restrict the placement of specific small items within the large object, for example placing the largest small item at the bottom of a bin.
- Stability constraints: Designed to ensure the safety of cargo operators during loading/unloading operations by ensuring that small items are fully supported by the bottom side of the large object when stacked.

4.2.2 Logistic constraints

These restrictions pertain to operational decisions rather than the physical properties of the objects. Within this set, the following are considered:

- Loading priorities constraints: In this setting, the number of large objects is fixed and limited, but there is a degree of priority among the small items. The overall solution assigns various levels of importance when creating the loading plan.
- Complete shipment constraints: Assume that either all items will be loaded in the same shipment or none at all. This is useful to ensure that all items for a company are placed together.
- Allocation constraints: Prevent small items from being placed in the same large container because of their nature.
- Customer positioning constraints: Facilitate bundling a set of small items together or within a predefined distance to expedite the unloading process, assuming all these objects belong to a specific company.
- Complexity constraints: Related to the level of difficulty that represents for a robot or a worker to learn the loading pattern.

As shown, the universe of subproblems that may exist is extensive and is given by the combination of typology and the two sets of constraints. However, the subset of problems studied in literature has primarily focused on safety constraints and variations of the first three criteria of the typology (Bortfeldt & Wäscher, 2013). For the fourth criterion, most studies only analyze the 1-dimensional and 2-dimensional problems. Regarding the fifth criterion, typically, the objects involved are considered with a well-defined geometric shape. It is precisely in these last two points where the literature presents a significant gap since the study of irregular and 3-dimensional objects remains underexplored.

To tackle the problem of 3-dimensional and irregular objects, practitioners typically begin by studying the 2D case and then attempt to extend these heuristics. In this line, one of the earliest proposals to address this problem was the no-fit Polygon (Art, 1966). This method performs effectively with convex objects, and several updates of this method were introduced to address the non-convex case, although they come with significant computationally costs (See Bennell, et al., 2001 and Dean, et al., 2006). Another common method is the Raster Method (Oliveira & Ferreira, 1993), where objects are represented by a grid and leverage binary variables to indicate if a cell is part of the piece or not. This method can address non-convex cases more effectively, but the trade-off is the inability to accurately represent an object, being memory-intensive, and remaining computationally expensive.

Since the previous alternatives require approximating the object, other methods have been developed aimed to preserve their true geometry. One such method is the D-function (Konopasek, 1981) which computes distances using the relative position of a point P, that corresponds to one object, with respect to an edge AB from another object. Based on the resulting distance, several cases are considered along with an algorithm indicating how to proceed while placing both items. Another widely used method in literature is the Phi-function method, leveraging the concept of ‘phi-objects’ in topology. Under this premise, phi objects can be primary or composed (where the composed can be described as the union of primary objects). Objects are then described using linear, non-linear, and piecewise inequalities. The proper placement is defined trying to minimize the Euclidean distance (Leao, et al., 2020).

All these approaches can be extended to the 3D case, but the results often tend to be suboptimal (Huwei, et al., 2023). Addressing the non-polyhedral case then implies the need to explore new alternatives that, instead of relying on restrictive rules based on geometry—which is challenging to represent—adopt a more self-optimizing strategy. It is within this line of thought that the most recent publications are emerging. Harrath (2022) proposed a three-stage heuristic algorithm for packing ‘n’ different items into the least number of boxes, considering the rotation of objects in any direction and balance constraints. Shuai et al. (2023) introduced a novel algorithm allowing for the self-correction of packed items using various sensors. Zhao et al. (2021) approached the 3D bin packing problem as a MDP and employed deep reinforcement learning techniques to obtain a solution. It is evident from these recent studies that technology plays a crucial role in seeking innovative solutions, and the subsequent literature section will be related to the approach proposed in this study: Virtual Reality for the 3-dimensional and irregular objects case.

4.3 Virtual Reality for irregular shaped objects containerization

Traditionally, VR literature has focused on the potential of VR for training, especially in cases where real-life scenarios are expensive, difficult to replicate, or pose significant risks. However, researchers have recently expanded their analysis of VR to other settings. Among these, the logistics processes have emerged as promising candidates due to its potential in the traditional lines of VR research - such as training for warehouses and design of assembly lines (Lucas & Thabet, 2008) - but also it offers opportunities in non-traditional lines of VR research - such as exploring the potential in item containerization and performance analysis.

Among the non-traditional applications of VR in logistics, this paper focuses on analyzing the implications of employing this technology in the containerization of irregularly shaped 3D objects. Since this idea is relatively new, the existing literature on this topic is scarce. Moreover, literature predominantly explores the use of another immersive technology, Augmented Reality (AR). For instance, Poncelet (2022) developed a method utilizing AR to visualize the proper placement of items within a container, ensuring compliance with stability, weight, and orientation constraints. Jaoua et al. (2023) generated a more comprehensive approach, first developing an optimization module that identifies the ideal location for each item while respecting constraints related to stability, weight, and dimensions. Leveraging this optimization module, a visualization module in AR was created to verify the placement. It is worth noting that both solutions are specifically designed for items with regular shapes.

To the best of our knowledge, the only paper addressing the 3D irregular shape problem using VR is found in Zhao et al. (2021), the authors proposed a comparison of packing efficiency when training individuals to pack both regular and irregular objects using VR. It is important to note that their primary concern was not to optimize containerization, but rather to understand the nuances while training for packing different shapes. Lastly, it is important to highlight that the 3D bin packing problem in the context of construction has remain understudied.

5 Methodology

In this paper, the formulation introduced in (Grover & Montreuil, 2021) serves as the starting point. This formulation proposes a two-stage optimization approach. In the first stage incoming parcels are assigned to a departing vehicle. Once this initial step is completed, the second stage focuses on loading parcels in containers which then are loaded into the assigned vehicle. Is important to highlight two considerations of this formulation: i) It assumes regular-shaped 3D items, and ii) The overall objective of this model aims to minimize empty volume and does not consider other aspects such as the placement of items that need to be together.

From the outset, our objective has been to address the issue of containerizing irregularly shaped 3D items while considering a kitting strategy, neither of which have been considered in the previous formulation. However, it is important to note that solving the second stage of the problem offers a solution for our case when relaxing the constraints of irregular shapes items and permitting items that need to be together (in a kit) to be spatially separated. The rationale behind initially allowing this relaxation stems from our literature review findings, which suggest that methods attempting to replicate the specific geometry of items often result in overly constrained models or situations that are nearly impossible to model. Doing this relaxation does not imply that we will overlook these challenges; rather, it means that we will approach them from a distinct perspective.

Since the studied company leverages on BIM technology, all components associated with a modular unit have been meticulously modeled in a CAD software named Revit, this ensures exact virtual replicas of every item. Furthermore, it is possible to perform a virtual decomposition of each modular unit into subproducts and generate a list of items associated with each one, this capability enables to define which items need to be placed together in a kit. Another advantage is that these virtual items can be easily exported to any VR engine compatible software such as Unity or Gravity, this allows to represent and interact with any kitting solution in an immersive environment. The final advantage is that all these items can be converted into 3D regular shape objects without difficulty, allowing us to use the initial formulation and obtain an initial solution. Once we have this solution, we can further refine it with the original items in a safe virtual environment generated in VR. Figure 2 provide a schematic representation of this loop.

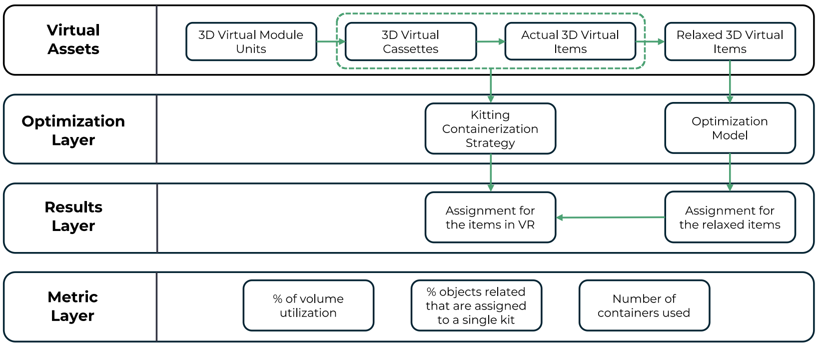

Figure 2. Proposed framework for the improved assignment using VR.

6 Experimental setup and results

6.1 3D Objects (Items)

Items are fundamental for the study; they determine the optimization model's performance and play a crucial role when interacting in VR. Information from an industry partner regarding all the constituent elements of a modular unit was used for this study exported from Revit. The next step involved decomposing this unit until we reached the level of items. From this disassembly, artificial labels were generated to help us track which elements should be grouped together, as they are part of the same subproduct and are used in a certain time (See Figure 3).

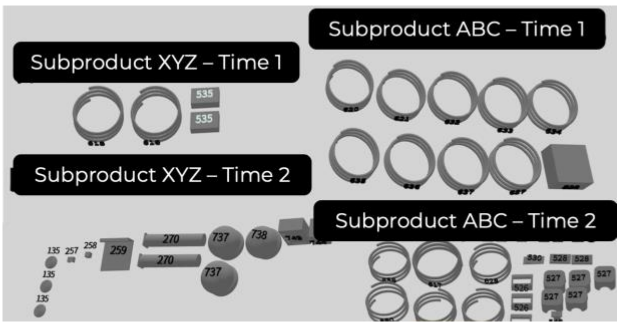

Figure 3. Illustration of containerized items associated with different subproducts and used at various times

Additionally, during this decomposition, we encountered several types of items. For the purposes of this study, we excluded ‘Sheeting,’ ‘Bundle,’ and ‘Big’ items, focusing exclusively on items in the ‘Containerized’ category.

Another important aspect to highlight is that, as previously explained, a simplified representation of each item was used, while maintaining the geometry of the object. To achieve this, we considered the farthest points on each side of the object and constructed a face from them. The resulting prism is the union of these six faces.

6.2 Virtual Reality Setting

Given that all the 3D models of the items were accessible in Revit, the following stage was to make them available on a VR appropriate platform. We opted for Gravity Sketch (GS), an immersive environment tool recognized for its versatility, user-friendly interface, and compatibility with Revit. The next step involves exporting the items in. fbx format and importing them into GS.

In the VR environment, a 30-year-old male participant, with prior experience in using immersive tools, begins by manually grasping objects whose labels indicate they belong together in a kit. These objects are then placed into a container chosen by the participant based on their understanding of what constitutes the correct container size. A kit is considered complete when there are no more objects to add that share the same label. If there are additional objects but the kit is full, the participant decides if the kit will be split in multiple containers or to use a bigger container. If the container picked was the largest available, then the participant will select an additional container to accommodate the remaining items. The experiment concludes when there are no more remaining items to add to any kit.

6.3 Results

Our findings demonstrate that it is possible to generate a reasonable kitting containerization strategy exclusively using VR. The subject only knows the label and must make decisions about which container to use from a set of available containers by visually matching items to containers based on his experience. The instance used consisted of 747 items to be organized into 96 kits for which the required time to containerize did not exceed 4 hours for the first iteration, resulting in 108 containers being used for the containerization, including Bundle, Big, Containerized, and Sheeting kits. This suggests that with more training, practice, and knowledge, this time could be further reduced.

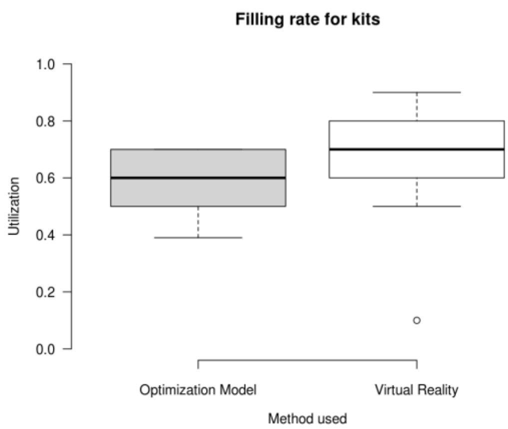

Figure 4: Comparison between the two containerization methods

In various scenarios, using the optimization model described in section 5, the model exceeded by far the time used by the human, only to package 457 ‘Containerized’ items into 38 containers. To reduce the time required by the optimization model, an optimization-based heuristic was implemented. This heuristic involves manually splitting kits containing more than 14 items into multiple kits before running the optimization model based on the shapes of the items. It was identified that for this number of components, splitting the container load didn’t significantly impact the container utilization. Additionally, the model still took a considerable amount of time to find suitable containers, but there was a reduction in the model's runtime from hours to minutes. However, it is important to remember that the model uses a simplification of all items and assumes that all objects are prisms, which compound the impacts of the low utilization of the kits.

Regarding this last point, when comparing both methods, our approach using VR significantly outperforms the optimization approach. This superiority is evident not only in terms of average utilization but also in the kits with the highest utilization, reaching up to 93% utilization in some cases, whereas the results of the optimization model never exceeded 70% utilization. Even when comparing the weakest performers (first quartile), better results are observed.

It is worth mentioning that there are cases where VR shows kits with low utilization. A deeper analysis identified that the set of available containers was not efficient for elongated objects, such as pipes (Refer to Figure 5 Kit Subproduct AB-Time 5). Additionally, the Kit Subproduct AB-Time 10 which was containerized in two of the red boxes with the optimization model could be packed in a single container given the opportunity to overlap items due to their shape. These types of insights were also an advantage of using the VR methodology, which are way harder to achieve from the results of the optimization model or even nor reachable at all.

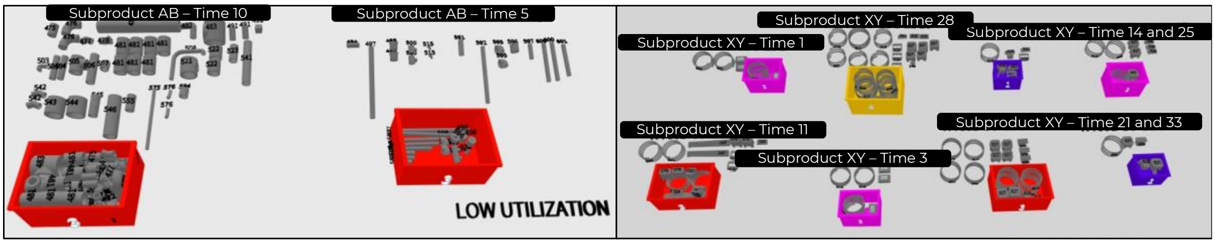

Figure 5: Results of VR containerization kits

7 Conclusions

In this paper, the primary contributions are as follows: Firstly, it introduces a novel perspective for addressing the 3D irregular variants of CPP problems by integrating VR and BIM (which strongly leverage modular principles of PI) into the containerization process. Furthermore, it demonstrates that incorporating available technology notably improves cargo consolidation, which serves as a strong incentive for companies to decide to invest in new practices.

Secondly, the method presented distinguishes itself for its flexibility and precision. It is deemed flexible because it can be applied to a broad spectrum of object assortments, encompassing both regular and irregular shapes, as well as identical, weakly heterogeneous, or strongly heterogeneous types of objects. Its precision is asserted by its independence from constraint relaxations or the need to discard important assumptions. The utilization metric obtained through our VR method will be reliable, as it closely mirrors real-world settings.

Another noteworthy aspect is the research avenues proposed by this paper. An immediate extension is the application of this framework to analyze other types of items not included in the study. One interesting case is the ‘Bundle’ category, where arranging tubes within other tubes is possible - a task challenging for optimization approaches but straightforward for humans.

However, our approach also has limitations. It heavily relies on human decision-making, and while the decisions have proven to be correct in our case study and have improved utilization, this may not hold true for another individual. In other words, the human element introduces variability that complicates extrapolating results. Additionally, even with exceptional human performance, it is challenging to envision a person creating hundreds or thousands of kits—a common scenario in other industries that are part of hyperconnected networks serving multiple clients. Nonetheless, this limitation offers a promising avenue for research, which involves integrating reinforcement learning techniques. Specifically, an agent could be trained to learn from human decisions. Once trained, this agent could autonomously make containerization decisions, likely resulting in more efficient outcomes on larger scales.

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Unleashing the Potential of Digital Twin-Enhanced Cellular Hyper Hubs

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Abstract

Parcel logistics hubs play a crucial role in aggregating and distributing packages, requiring significant capital and labor investments, primarily determined by conveyor infrastructure. Recently, the HyperHub concept has emerged, employing PI-Boxes and racks for parcel consolidation and transport. HyperHub functions as a cross-dock, transferring PI-Boxes between inbound and outbound trucks. However, challenges persist in developing a practical, cost-effective, and risk-free implementation methodology for HyperHub, despite advancements in its conceptualization, design, and execution system. To address this challenge, the authors present a comprehensive methodology for designing and developing a HyperHub based on the concept of digital twin (DT) in the early stages of the design process. A digital replica of the system is used in the early stages of design to create a physical layout and test the control system in a risk- and cost-effective environment. This is accomplished by integrating a model-based system into the digital copy of the real system. Firstly, we propose a concept of a generic digital twin cellular logistic hub (DT-CLH) methodology for the HyperHub, inspired by the cellular manufacturing (CM) and cellular warehousing (CW) concepts. Secondly, we formulate and define a cellular logistic hub (CLH), considering the objective of minimizing total movement.

Keywords: *Physical Internet, Hyper Hub, Logistic hub, Parcel logistics, Digital twin and Cellular manufacturing*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☒ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☐ PI Networks, ☐ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

Targeted Delivery Mode-s*: ☐ Paper, ☐ Poster, ☐ Flash Video, ☐ In-Person presentation*

1 Introduction

In recent years parcel logistics has been strongly impacted by globalization and the pandemic, which has resulted in increased global competition. This logistics competition has acted as a driving force for utilizing modern technologies, systems, and paradigms that have better capabilities to help enterprises increase their agility and responsiveness to meet end-user expectations regarding service levels and costs [1]. In this respect, the Physical Internet (PI) has been formulated as a new paradigm for improving economic, social, and environmental [2]. The PI is defined as an open global logistics system founded on physical, digital, and operational interconnectivity, through encapsulation, interfaces, and protocols. PI is not something on the cloud or just on the server, but rather a structure made of physical objects: parcels, containers, hubs, routes, trucks, and robots are just some of the elements that make PI concept-based parcel logistics possible.

Most recently for parcel logistics purposes, a multi-hub parcel logistic web underprint of PI concept is proposed with interconnecting meshed transportation networks along four different hubs[3, 4]. Zero-point hub; linking original destination customer locations and pickup-and-delivery points. e.g., household, office, factory, and parking. First-point hub is the access point hub. It facilitates the direct transfer of parcels between sources and destinations in nearby zones. The second-point hub is an inter-area network that consolidates parcels to the PI containers or tote. Third-point hub or gateway hub is the main interface between areas of a megacity. In this paper, our main aim is to design and develop the HyperHub that could support the gateway hub responsibility. HyperHub uses modular containers or totes to consolidate parcels and racks to consolidate containers for transport.

The idea of HyperHub is expressed in most recent publications, including [5, 6] underprint of PI concepts that motivate this work. The consolidation of parcels into modular containers is discussed in [7, 8]. An originating hub will consolidate all parcels with the same destination into one or more modular totes then totes are consolidated into racks for transport in standard trucks or semi-trailers to HyperHub. Besides a network of logistics hubs, as suggested in [3, 9, 10]. The trucks from the originating hub connect to a HyperHub that is part of this network. At each HyperHub, an arriving rack gives up totes that are not going to the same next destination as the rack and acquires totes that are until the rack is fully consolidated and ready for transport to the next hub. A tote in a rack from a particular originating hub may visit several logistics hubs and be transferred to other racks before it finally arrives at its destination hub. At each HyperHub, some totes may be removed from a rack, because their next destination is different from the rack's next destination, and some totes may be added. It is possible that a rack in a HyperHub is stripped of totes and stored temporarily because it is not needed at the moment to transport totes, and all the totes it contains can be accommodated by other racks. The last essential concept robotic transport of both racks and totes within the HyperHub, thus dramatically reducing the service time and number of humans involved in the HyperHub operations, in line with robotic mobile fulfillment systems. Further, the resources for moving totes between hubs and for temporarily storing racks between these processes are organized according to a standard footprint, resulting in easily replicated cells.

Despite the contributions of existing works in terms of conceptualization, design, and the execution system of HyperHub, there remains a challenge in achieving a practical, cost-effective, and risk-free design and implementation methodology for HyperHub. It is obvious that design and implementation of HyperHub for the real industrial applications require risky, careful decisions to ensure that the system and technology will successfully satisfy the demands of an ever-changing market. The behavior of a HyperHub is not deterministic. Yet the direct experimental testing of it with the physical system/control environment being involved is not only extremely expensive, but non-realistic as well. Hence, the companies need methods and tools for modeling and emulation of such complicated systems in a quick, cost-effective, error and risk-free way with complete physical configuration and human in loop perspective [17].

An important question that follows from research in this area is, given that HyperHub system is dynamic, robotized and human friendly in nature, how to define and validate the most appropriate physical layout and execution architecture for any given HyperHub without really implementing it into the operations? This decision corresponds to defining ways of implementation and the level of integration within the system through digital twin tool. Researchers evolved several specific simulation methods in the literature for modelling and simulation of complex systems for industrial applications. However, conventional simulations approaches and tools support users in understanding the process characteristic but often suffer from limitations in the detailed analysis necessary for accurate system adoption and in capturing visual details of implementation []. In addition, most existing tools after evaluation cannot be used for implementation of real system for example the code with used to simulate control robotic system cannot adapted to real system which are considered for simulation respect [18, 19]. The digital twin can be considered as a solution for such problems, as the user and the information support elements are put in direct relation with the operation of the system in a virtual physical environment to provide a sense of reality and an impression of 'being there', which is considerably effective in representing the activities. Using a digital twin of the physical system to perform real-time execution, scheduling, and optimization. The breakthrough is achieved from three aspects: 1) Calculation time has gone from hours to minutes, which has made it possible to explore the solution space searching for the global optimum; 2) Increased use of sensors and on-line measuring equipment [11] are making it possible to reuse simulation models during both pre-production and production phases, now with real context data rather than estimated or historical data as input [12]. This will allow for adjustment of machine settings for the work-in-process in line based on simulations in the virtual world before the physical changeover, reducing machine setup times and increasing quality.3)Testing and implementing different types of configuration as well as automation in order to full feel the factory layout problems such as the confusion of logistics, overlong distance and accumulation of WIP and the low utilization rate of tooling due to the unreasonable material distribution route and the low accuracy of material distribution.

In this paper, a methodology that uses a digital twin-based cellular logistic hub (DT-CLH) for modeling and implementing a HyperHub in the early stage of design has been proposed to test and evaluate the proposed execution architecture and physical systems in the natural practical industry environment. This work is motivated by the need for HyperHub that are able to adapt to internal and external disturbances. In this system, new robotic human friendly systems can easily be added or removed, and different demands can be met by re-configuring the system.

2 Overall methodology

The conceptual methodology of DT-CLH is shown in Figure 1. It consists of three main subsystems: system design, real world and cellular logistic hub. Each subsystem is described as follow:

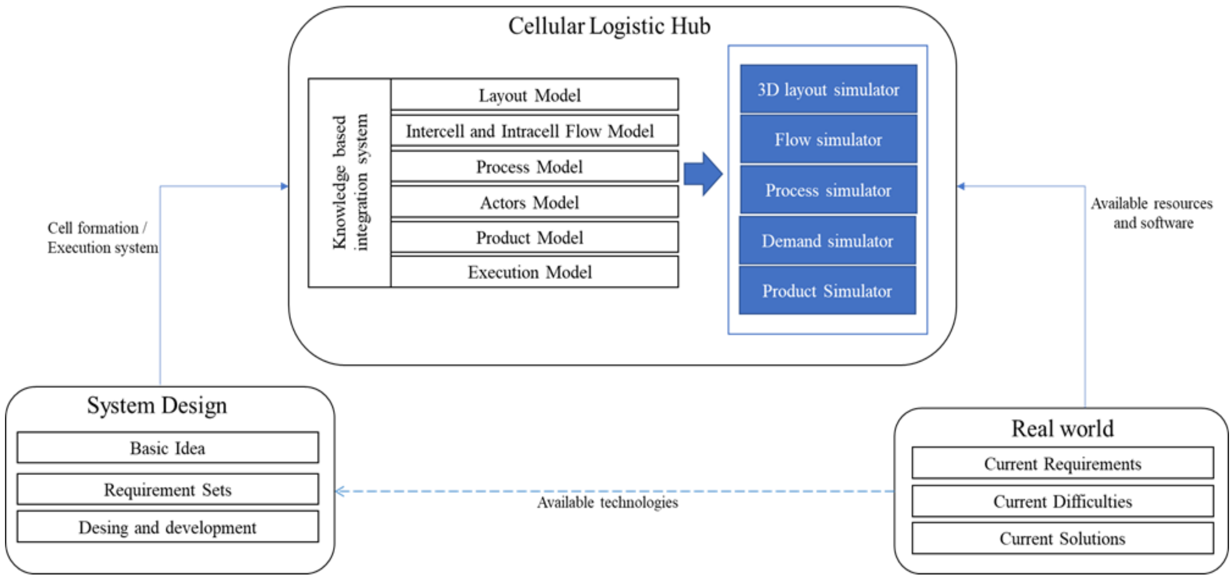


Figure 1 Conceptual architecture of DT- CLW

2.1 Real world

The real world (RW) encompasses three primary dimensions: firstly, the existing technological landscape and solutions; secondly, the prevailing challenges, difficulties, and issues that act as motivating factors prompting individuals to seek resolutions; and thirdly, a broad overview of current solutions or strategies employed to address these problems. In terms of parcel logistics hubs, where packages come in from many origins and are sorted to their many destinations, are both capital and labor intensive, with capacity that is largely determined by investments in conveyors of fixed automation which are not reconfigurable and agile, therefore currently most of the hub suffering from low utilization through the day. This happened because the whole hub could be active as a full system for a couple of hours to fulfill the high demand in the system. Therefore, most of the days and time they are not active. HyperHub would be able to answer this problem by employing CM and CW approaches. The RM responsible to provide existing resources and physical requirements of the HyperHub by examining current technologies, for example which types of robotics manipulator could be best solution to handle the shuffling process or what are the best cell definition as well as intracell and intercell operations. Therefore, RM contains two main sections;(1) primary physical cell definition section, this section is responsible for defining types of cells, intercell and intracell paths as well as layout perspective of cells, in order to provide reconfigurability and agility between cells and system. (2) Resource definition section, it is responsible to provide physical requirement and capabilities of resources which would be possible to use in the cells. The main components of the resource definition section are divided into two parts: hardware/worker specifications and software specifications. Hardware specifications comprise machines, robots, and the material handling system. Software specifications consist of computational models, low-level control software, data gathering software, etc. Figure 2 illustrates the main concept behind the RW subsystem in the DT-CLH. The output of the resource definition is divided into two categories based on the level of automation: first, the pool of available resources and technologies for fully robotized and automated cells, and second, the pool of available resources and technologies considering human in the loop for cell operation which is highly align with industry5.0 concept [13].

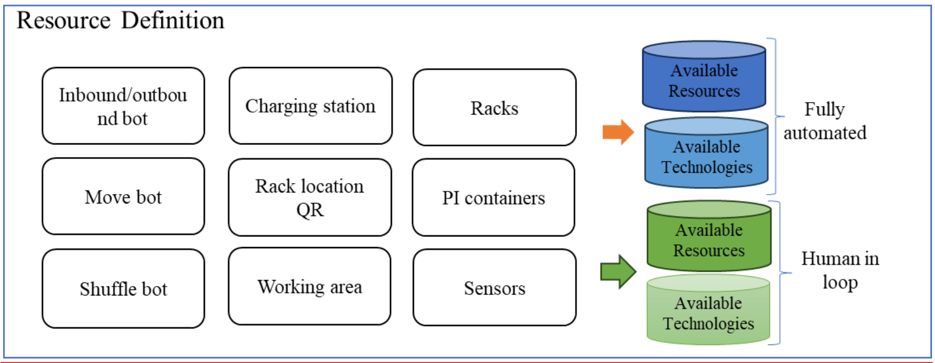


Figure 2 Real world of Hyper Hub modeling

Consequently, RW yields a reservoir of available resources, software, system capabilities, and requirements. These resources are subsequently disseminated to other subsystems, thereby contributing essential elements to the system design, and cellular logistic hub.

2.2 System design

System design mainly deals with design and development of whole system. The systematic process of system design encompasses three key phases: Basic Idea, Requirement sets, Design and development phase. In adherence to recognized standards, particularly the ISA95 standard, our approach to the design and development of the HyperHub [14] is guided, ensuring a rigorous and industry-accepted methodology. Each phase is defined as follows.

2.2.1 Basic idea is formulating the possible solution to deal with problems which are highlighted by RW. For example, what are the best bots to use in the HyperHub or what is the best and most practical cell layout and intracell flow algorithm to minimize total movement in the system. This phase is responsible for providing basic ideas and definitions for the next phase regarding existing technologies and possible existing solutions based on the CM and CW. Figure 3 shows the possible basic idea for formulation of HyperHub. It highlights the types of cells and first step to formulized cell definition.

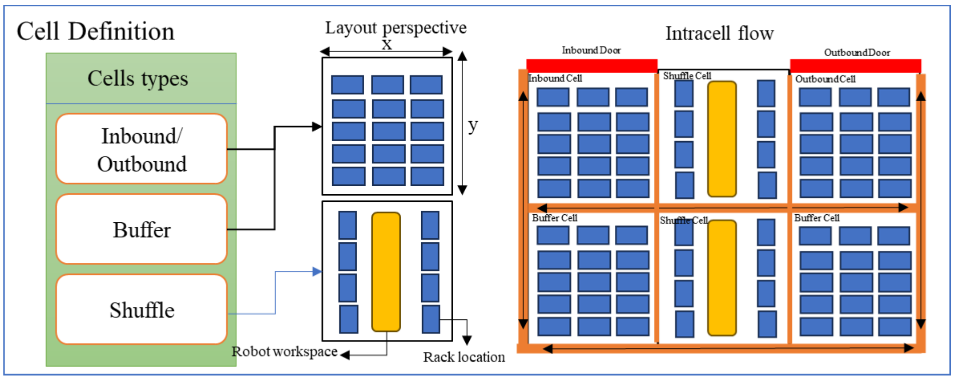


Figure 3 Basic cell definition of HyperHub

2.2.2 The requirement sets receive the output of the basic idea and RW and provides the set of the requirements of each resource, cells, and possible execution system. It is the conditions that a proposed requirements for a solution or applications must meet to solve the problem. Both scenarios based modeling and behavioral modeling are applied in order to extract the requirements of the cells in the HypreHub[6]. The main goal of the requirements set is to decompose the system in order to identify the initial problem domain, and solution domain. Figure 4 shows our method for capturing requirement sets.

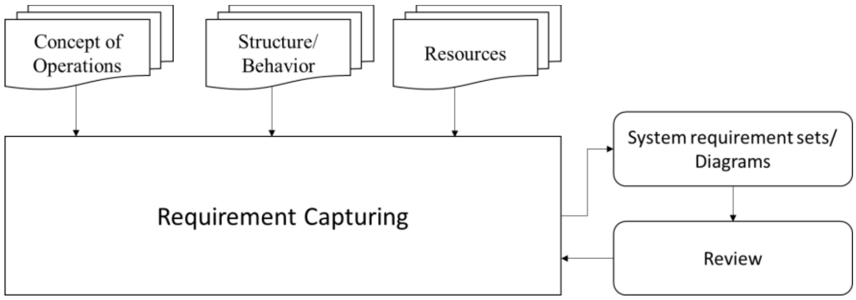


Figure 4 Steps in capture requirements

The cells in the HyperHub consist of structure and resources that act together to produce behaviors, or observable transformations. The cells and resources have their own behavioral capabilities which are invoked by execution system at the level of the cells and HyperHub. Such as resource for movement of racks (move bots or pallet jack), shuffling of PI-Boxes (shuffle bots or human) and loading or unloading rack to trailer (inbound bots or forklift). The resources may themselves contain sub resources, which will have their own structure, behavior and low-level control unites. Physical layout cells structures are also part of structure and behavior of Hyperhub. The structure and behavior of each operation with associate resources and physical layout of cells is to make sure that PI-Boxes from inbound racks are transferred to outbound racks, and the outbound racks loaded into the outbound trucks whose destination is the same as the truck's destination. System behavior and structure are based on the HyperHub main concept, which enables the system to be highly flexible in terms of agility and reconfiguration to handle different disturbances, such as demand disturbances. Figure 5 SysML requirement diagram of HyperHub based on the three main types of cells and its operation, physical layout and execution system.

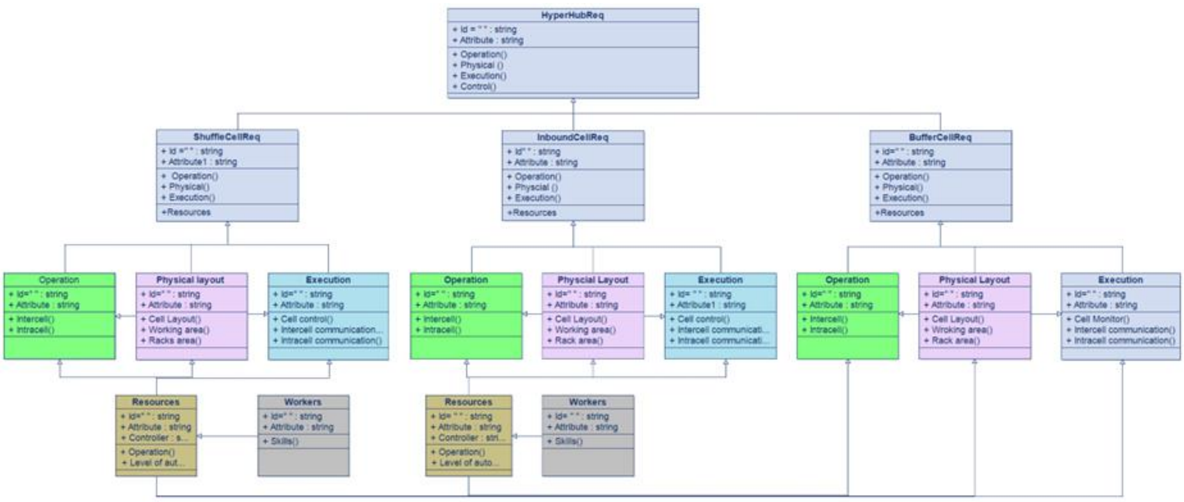


Figure 5 High level example of SysML requirement diagram for HyperHub

The HyperHub employs both active and passive resources and they are also clustered based on fully automated and human in loop perspective. The passive resources are the various PI-containers that are processed in the HyperHub. The three relevant concrete container types are the transport container, the rack, and the PI-box(tote), which are kinds of container and thus inherit all the properties of container.

2.2.3 Desing and development phase

The output of the requirement sets, encompassing both system and subsystem functionalities of the HyperHub, are inputted into the design and development phase. This process emphasizes the operational, structural, and behavioral characteristics of the HyperHub. A crucial aspect of the design and development phase is to furnish an abstract representation of the system's resources, activities, and decisions. To achieve this objective, we adhered to the ISA95 standard in designing the execution system for the HyperHub. This standard is divided into three main levels. In this context, Figure 6 illustrates the proposed architecture of execution system, which is aligned with the standard.

Level 1 encompasses physical resources such as robot and cell structures and pertains to the perception layer, or the types of sensors utilized in each resource. Level 2 addresses supervisory control or the types of internal controllers for each resource. Lastly, level 3 denotes the location of the execution system, which is responsible for executing tasks within the HyperHub. This architecture gives us a level of agents. The HyperHubs's execution system has three main agents with its operations and relations. Namely Hub controller agent, shuffle cell controller agent and inbound/ outbound controller agent. Both the inbound and outbound cells have a StagingZone where racks may be located after unloading or before loading. The activity and decision diagram of execution system is shown in Figure 7 and illustrates the flows between the three cells of operation as well as within the cells. There are three levels of decisions that exist in the HyperHub, hub level, shuffle center level and inbound/outbound level. The main decisions of HyperHub execution system highlighted at decision diagram based on the racks point of view. There are three levels of operational execution & control level, Figure 6 shows this level in the details.

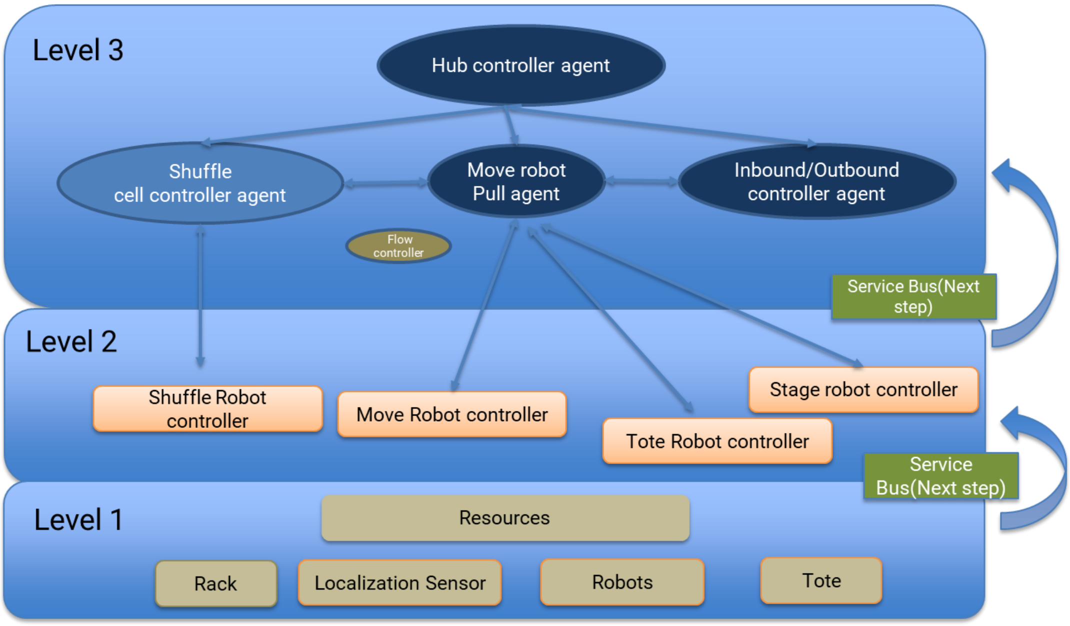


Figure 6 The proposed architecture of HyperHub's execution system

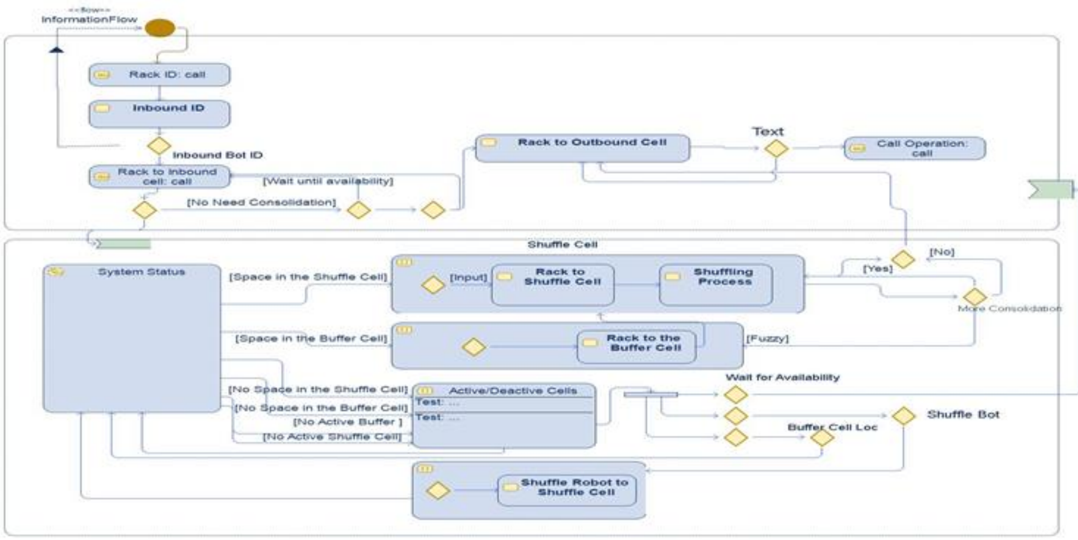


Figure 7 Activity and decision diagram of HyperHub's execution system

3 Cellular logistics hub

CLH receives knowledge and information from real-world and system design sections in order to create control systems and a digital model with its functionality and integration platform, key factors in the design and implementation of desired HyperHub goals. CLH consists of two main sections: the first section focuses on information integration to form cells and allocate resources, establishing direct or indirect relations between cells. This relationship, based on organized information, serves as the foundation for cell formation, moving to the next step of integrating modules together to run the system as a whole unit. Figure 8 shows the information and data integration framework with key modules that belong to CLH, namely, Layout Planning, Material Flow, Actors or Resources, Product, Control System, and Data Modules. All of these are integrated with each other through knowledge-based system integration to act as a union.

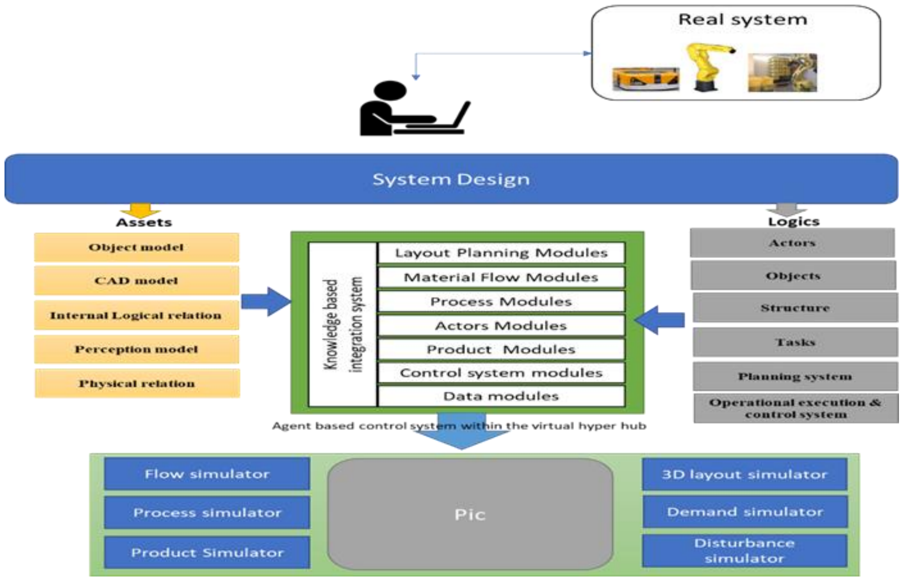


Figure 8 Framework for cellular logistics hub

The CLH was conceptualized as a virtual representation of a real factory, depicted through an integrated simulation model that encompasses the factory and its subsystems. In this regard, Table 1 illustrates the resources required at HyperHub.

Table 1 Resources in HyperHub

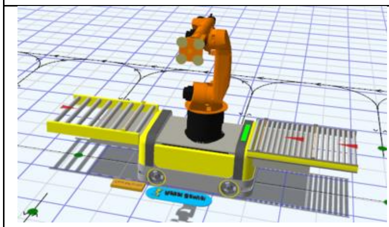
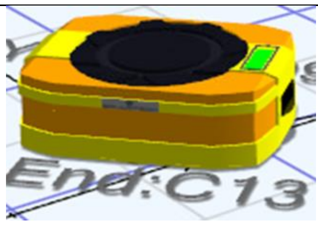
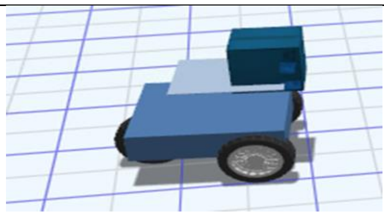
Shuffle Bot	Move Bot	Tote Bot
		
• Acceleration: 6.56 ft/s^2 • Declaration: 13.1 ft/s^2 Speed: 190 ft/min • Tote Capacity: 4 • Manipulator: Kuka600	• Speed: 196.8 ft/min • Declaration: 13.12 ft/s^2 • Acceleration: 6.5 ft/s^2 • Rack Capacity: 1	• Acceleration: 6.5617 ft/s^2 • Deceleration: 6.5617 ft/s^2 • MaxSpeed: 195 ft/min • Tote Capacity: 1
• Avoid Collision: True • Front Offset: 2 mm • Distance per charge: 60 km	• Avoid Collision: True • Front Offset: 2 cm • Front Sensor Range: 2 cm • Distance per charge: 100 km	• Avoid Collision: True • Front Offset: 1 cm • Front Sensor Range: 1 cm • Distance per charge:200 km

Figure 9 illustrates the implemented HyperHub through the proposed methodology. It comprises five shuffle cells, four buffer cells, and four inbound or outbound cells. While the cells are fixed, the system can add or remove new cells to the HyperHub with minimal changes in the control system, based on demand. Unity3D platform used as main platform for CLH and C# programming language was used for implementing proposed control system and functionality of subsystems.

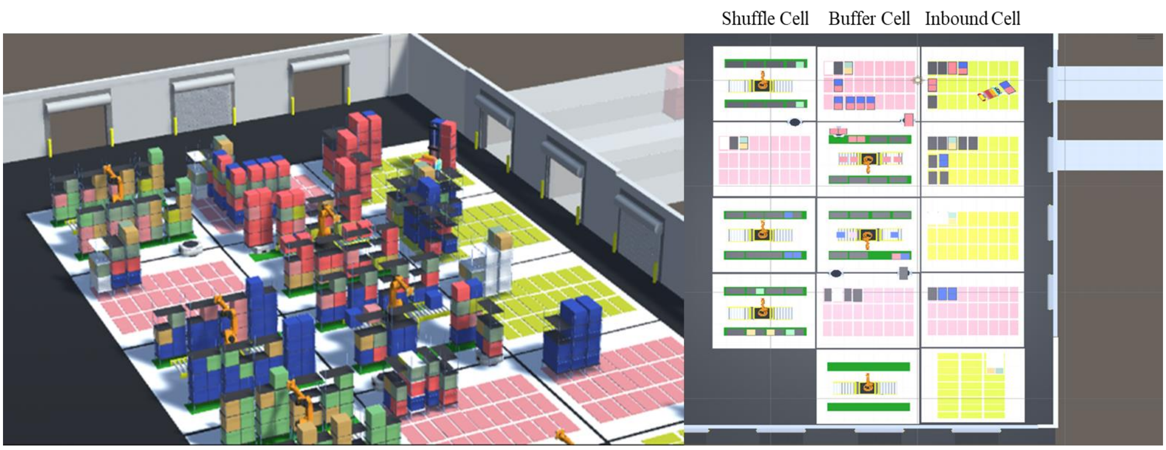


Figure 9 Developed HyperHub

Conclusion

A methodology based on digital twin for implementation of the HyperHub for early stage of design for parcel logistics has been presented in this paper. The digital twin cellular logistic hub concept has been introduced, which integrates real world and system design modelling into a virtual cell definition in order to realize the HyperHub within a system modeling environment. The DT-CLH concept introduced in this research serves to illustrate the use of digital twin to interface with existing modeling approach. Although each cellular logistic hub has been designed specifically for ISA95 standard and unity platforms, the methods presented here could be applied in general to other digital twin and multi-agent software development platforms.

The methodology outlined in this paper offers several contributions. It provides a systematic approach to HyperHub design and development, encompassing system design, real-world considerations, and cellular logistics hub components. Through the integration of digital twin technology, the proposed methodology enables adaptability to internal and external disturbances, allowing for the addition or removal of robotic systems and meeting diverse demands through system reconfiguration.

Furthermore, the paper introduces a conceptual architecture for DT-CLH, emphasizing system design phases such as basic idea formulation, requirement sets, and design and development. The DT-CLH framework integrates information from the real world to define cell structures, resource capabilities, and execution systems, facilitating a holistic approach to HyperHub implementation.

In conclusion, this paper lays the foundation for a robust methodology leveraging digital twin technology for the design and implementation of HyperHub in parcel logistics. While the presented approach is tailored to specific platforms and standards, its principles can be adapted to other digital twin and multi-agent software development environments, offering potential applications beyond the scope of this study.

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Resilient Logistics Flow Routing in Hyperconnected Networks

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Abstract: *Hyperconnected networks are prone to potentially wide variety of disruptions on daily basis that may impact their performance considerably. In this paper, we devise two combinatorial algorithms: a basic and an adaptive resilience-optimized algorithm to route commodities in large-scale hyperconnected networks that are robust against such disruptions. The basic resilience-optimized algorithm decomposes the total commodity routing based on each origin-destination (O-D) pair and then distributes this O-D commodity demand into multiple edge-disjoint paths. Alternatively, the adaptive resilience-optimized algorithm combinedly routes the commodity demand through multiple edge-disjoint paths without decomposing it separately for each O-D pair. Finally, we assess the efficiency and resiliency of routes obtained through resilience-optimized algorithms and benchmark them with routes generated through only considering efficiency on a hyperconnected network designed for finished vehicle logistics in Southeast USA. Benchmarking reveals enhanced capability of sustaining disruptions by the routes computed through the proposed algorithms as opposed to those generated through only efficiency consideration. Moreover, the results highlight the trade-off between efficiency and resilience in the generated routes.*

Keywords: *Hyperconnected Networks, Physical Internet, Resilience-Optimized Routing.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

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1 Introduction

The logistics and transport sectors, accounting for over one-third of global carbon dioxide emissions, stand as significant contributors and are at the forefront for the transition into a decarbonized future (IEA, 2022). Meeting global net-zero targets for 2030 necessitates a 20% reduction in emissions from this sector, urging an accelerated transition (Gould, 2023). While logistics service providers (LSPs) accept the responsibility of managing environmental impacts of their networks, the increased risk of disruptions and growing faster delivery expectations from customers may force some of them to drop their sustainable initiatives (Mari et al., 2014). Both individuals and businesses now want LSPs to provide higher level of transparency, flexibility and end-to-end digitization with aim for them to be resilient against disruptions. To address these changes and remain competitive, Montreuil (2011) suggests rethinking logistics and supply chain paradigms, leveraging the Physical Internet (PI). In principle, it notably means to move from closed logistic networks to more open networks with shared access to resources. Furthermore, by favoring shorter short-haul movement of modular containers between PI hubs for open consolidation, rather than direct long-haul drives as in traditional systems, PI effectively reduces driving distance, greenhouse gas emissions and improves the quality of life for truck drivers (Fazili et al., 2017). This approach paves way for hyperconnected logistics, encompassing multi-plane space structuring and multi-plane meshed networks, interconnecting hubs at multiple levels for efficient and sustainable logistics operations (Montreuil et al., 2018).

Hyperconnected Logistics promotes open sharing of existing assets such as logistic hubs and transportation services among stakeholders to achieve sustainability goals. For example, Naganawa et al. (2024) recently introduced a combinatorial optimization model achieving significant improvements in operational efficiency and a remarkable 52% reduction in CO_2 emissions by utilizing existing logistics facilities as nodes of PI without additional investments. However, they did not factor in the widespread disruptions daily faced by the PI network. Facing such disruptions unprepared induces service delays and increased freight-handling costs. Several works have tackled resilience in traditional supply chain and logistics networks under disruptions by employing strategies such as network topology optimization (Kim et al., 2015; Wang et al., 2023) and dynamic rerouting of commodities (Akyuz et al., 2023). Investigating how PI enabled freight transportation systems handle random disruptions, Yang et al. (2017) developed a multi-agent-based simulation model, focusing on fast-moving consumer goods (FMCGs) chains, highlighting superior performance of PI, even under significant capacity loss during worst-case disruptions. While these approaches enhance resilience, a significant portion of commodity flow remains to be impacted by disruptions. Moreover, the proposed solution approaches in these investigations work well in networks with limited degree of hyperconnectivity and fail to scale when applied to densely connected hyperconnected networks in large geographies. One way to tackle such a problem is to strategically route commodities within hyperconnected networks in the pre-disruption phase itself. Such an approach has the potential to ultimately reduce the portion of commodity flow susceptible to disruptions risks and provides an opportunity to improve operational resilience. As commodity routing tends to be challenging problems to solve, viewing it from a classical optimization lens provides approaches that lack practical scalability. To address such scalability concerns, although at a network design stage (Kulkarni et al., 2021; Kulkarni et al., 2022) proposed a modeling framework based on topology-based optimization. We leverage the core ideas from (Kulkarni et al., 2022) and devise commodity route generation approaches that reduce the commodity flow disruption risks and enhance operational resilience.

Specifically, this paper introduces a modeling framework tailored to enhance operational resilience and mitigate disruption impacts on commodity shipments within densely connected hyperconnected networks. We employ flow decomposition to build two combinatorial algorithms: basic resilience-optimized and adaptive resilience-optimized for commodity route generation. The underlying premise is that distributing commodity flow across multiple (edge-disjoint) paths, reduces the portion of flow impacted by disruptions while remaining efficient in nominal situations. Basic-resilience optimized restricts flow portions on each transportation arc to identify resilient commodity delivery paths and adaptive-resilience incorporates additional capacity constraints on arcs at a company level to select even-more resilient paths. Further, we evaluate the efficiency and resiliency of the generated commodity routes through a set of experiments performed on a case study of finished vehicle logistics in the Southeast USA. Especially, we focus on the freight flow at higher planes (inter-area and inter-regional hub networks), demonstrate the scalability of our algorithms, and showcase the efficacy of the generated routes by analyzing disrupted commodity flows.

The rest of the paper is organized as follows: Section 2 describes the problem setting and the proposed methodology in detail. Section 3 presents the set of experiments conducted with an illustrative case-study of car-hauling industry across Southeast USA. Section 4 provides concluding remarks and identifies promising areas of future research.

2 Resilient Route Generation

We consider a group of logistics companies that deliver commodities across a given geographical region. These companies are interested in devising commodity flow plans or routes that are both efficient in nominal operational conditions and resilient against a wide variety of disruptions.

Formally, we consider a set of locations $\mathcal{S}$ where the commodity demand originates and a set of locations $\mathcal{T}$ where the commodities are delivered. Let $\mathcal{P} \subseteq \mathcal{S} \times \mathcal{T}$ be the set of origin-destination (O-D) pairs of interest with each O-D pair $p \in \mathcal{P}$ having a commodity demand of D_p^1 units. As there are group of companies involved, let $\mathcal{B}$ be the set of these companies or company brands and $\mathcal{P}_{\mathcal{b}} \subseteq \mathcal{P}$ the set of O-D pairs of each brand b. So, for each brand b, its associated total commodity demand D_b^2 is then given by $\sum_{p \in \mathcal{P}_{\mathcal{b}}} D_p^1$ units.

These companies have together opened a set of logistics hub $\mathcal{H}$ at discrete locations which can be utilized to serve the O-D pairs. To this end, we consider the directed graph $\mathcal{G} = (\mathcal{S} \cup \mathcal{T} \cup \mathcal{H}, \mathcal{A})$, which represents a single plane of a hyperconnected network, where commodities are transported from origins $\mathcal{S}$ through logistics hubs $\mathcal{H}$ to finally be delivered at destinations $\mathcal{T}$ through available transportation arcs $\mathcal{A} \subseteq (\mathcal{S} \cup \mathcal{T} \cup \mathcal{H})^2$. Let Λ be the set of such paths which are used for commodity deliveries between these O-D pairs.

The logistics hubs $\mathcal{H}$ serve as locations where the commodities are sorted and shipped towards their respective destinations. As these commodities are not stored for a longer duration at these hubs, the hub capacities are not restrictive. So, we assume that hubs have sufficient capacities to sustain the logistics operations and satisfy the demand. Moreover, due to the huge volume of commodity flow that the network faces, the commodity flow costs can be approximated through linear flow function. So, we use transportation costs on each arc $(i, j) \in \mathcal{A}$ and assume it to be proportional to the travel distance of that arc (i, j).

In order to design commodity flow routes that are both efficient and resilient, we aim to distribute the commodity flow between each O-D pair among multiple paths. The underlying idea is that when a disruption occurs and renders a path unavailable for commodity delivery, only a fraction of total commodity demand is affected and majority of commodity demand gets delivered (Kulkarni et al., 2023). At its core, such a way of commodity flow routing will spread the risks of commodity flow being disrupted and in turn increase the chances of larger fraction of commodity demand fulfillment in timely manner. So, in this section, we present two algorithms (Algorithm 1 and 2) that generate such resilience-optimized commodity delivery routes on the hyperconnected network $\mathcal{G}$. Moreover, these algorithms also determine the commodity flow distribution on these routes for fulfilling the commodity demand D_p^1 between each O-D pair $p \in \mathcal{P}$.

2.1 Basic Resilience-Optimized Route Generation Algorithm

In order to devise such resilience-optimized commodity flow routes, we employ the principle of distributing the commodity flow across multiple edge-disjoint paths (Kulkarni et al., 2021). Whenever a transportation arc is disrupted which belonged to one of the commodity delivery paths, the above-described approach will guarantee the existence of an alternate commodity delivery path that doesn't utilize the disrupted arc at all.

Let $M_p \in [0,100]$ be the maximum allowable proportion of commodity flow between O-D pair $p \in \mathcal{P}$ on each transportation arc. Then, the aim here is to devise $k_p = \lceil 100/M_p \rceil$ edge-disjoint path for commodity flow of O-D pair $p \in \mathcal{P}$. Due to absence of hub capacity restrictions, the task of finding k_p edge-disjoint paths can be computed independently for each O-D pair $p \in \mathcal{P}$. Rather than formulating an optimization problem that finds k_p edge-disjoint paths, we utilize a combinatorial algorithm instead. One of the major benefits of this choice is its vast scalability, especially in very dense networks such as hyperconnected networks. The detailed pseudocode for this basic resilience-optimized route generation algorithm is provided in Algorithm 1.

Algorithm 1: Basic Resilience-Optimized Route Generation

Input : Original Graph $\mathcal{G} = (\mathcal{S} \cup \mathcal{H} \cup \mathcal{T}, \mathcal{A})$, Set of O-D Pairs $\mathcal{P}$, Commodity demand $(D^1)_{p\in\mathcal{P}}$, Maximum allowable proportion of commodity flow on each arc $(M)_{p\in\mathcal{P}}$

Output : Vector of flow on each arc for each commodity $(\boldsymbol{f})_{(i,j)\in\mathcal{A},p\in\mathcal{P}}$

Initialize: Vector of flow $\boldsymbol{f} \leftarrow \{0\}^{|\mathcal{A}|\times|\mathcal{P}|}$, # of edge-disjoint paths $(k_p \leftarrow \frac{100}{M_p})_{p\in\mathcal{P}}$;
for every $p \in \mathcal{P}$ **do**
  Initialize: $\ell_p \leftarrow 0$, $\mathcal{G}_p \leftarrow$ Copy of graph $\mathcal{G}$;
  while $\ell_p \leq k_p$ **do**
    $\lambda_{\ell_p} \leftarrow$ Shortest path on $\mathcal{G}_p$ using Dijkstra's Algorithm ;
    for every $(i,j) \in \lambda_{\ell_p}$ **do**
      $f^p_{i,j} \leftarrow M_p \cdot D_p$, $\mathcal{A}_p \leftarrow \mathcal{A}_p \setminus \{(i,j)\}$;
    $\ell_p \leftarrow \ell_p + 1$;
return $\boldsymbol{f}$

Algorithm 1 distributes the commodity demand into multiple edge-disjoint paths effectively. However, in practice, a transportation arc capacity for each O-D pair is not sufficient. A company (or company brand $b \in \mathcal{B}$) usually has a transportation arc restriction for all its O-D pairs ($\mathcal{P}_{b}$) together because of the associated contracts with truckers for their travel on each arc. Such a caveat is not captured by Algorithm 1. Hence, next we modify Algorithm 1 to capture such technicality more realistically.

2.2 Adaptive Resilience-Optimized Route Generation Algorithm

Let N_b be the maximum allowable proportion of brand-based commodity flow on each transportation arc for each company brand $b \in \mathcal{B}$. Due to this brand-based arc capacity restriction, the independence of devising commodity delivery routes for each O-D pair separately is not present anymore, although exists at each brand level. So, we compute the commodity delivery routes (through utilizing a combinatorial algorithm) of all the O-D pairs $\mathcal{P}_{b}$ that belong to a brand $b \in \mathcal{B}$ together. Precisely, we process the O-D pairs $p \in \mathcal{P}_{b}$ in decreasing order of their associated demand D^1_p. The detailed pseudocode for such adaptive resilience-optimized route generation algorithm is provided in Algorithm 2.

We note that one of the major advantages of adaptive resilience-optimized route generation for commodity delivery other than it able to capture the logistics operational constraints more realistically is that it provides more resilient commodity delivery paths than the basic resilience-optimized algorithm. This happens because of an additional capacity restriction on each transportation arc which leads to distribution of commodity flow to even larger number of (edge-disjoint) paths.

Algorithm 2: Adaptive Resilience-Optimized Route Generation

Input : Original Graph $\mathcal{G} = (\mathcal{S} \cup \mathcal{H} \cup \mathcal{T}, \mathcal{A})$, Set of O-D Pairs $\mathcal{P}$, Set of Brands $\mathcal{B}$, Set of O-D pairs in each brand $(\mathcal{P}_b)_{b\in\mathcal{B}}$, Commodity demand $(D^1)_{p\in\mathcal{P}}$, Maximum allowable proportion of commodity flow on each arc $(M)_{p\in\mathcal{P}}$, Maximum allowable proportion of brand-based commodity flow on each arc $(N)_{b\in\mathcal{B}}$

Output : Vector of flow on each arc for each commodity $(\boldsymbol{f})_{(i,j)\in\mathcal{A},p\in\mathcal{P}}$

Initialize: Vector of flow $\boldsymbol{f} \leftarrow \{0\}^{|\mathcal{A}|\times|\mathcal{P}|}$, Brand-based Commodity demand $D_b^2 \leftarrow \sum_{p\in\mathcal{P}_b} D_p^1$;
for every $b \in \mathcal{B}$ **do**
  Sort $\mathcal{P}_b$ based on decreasing of D^1, $\mathcal{G}_b \leftarrow$ Copy of graph $\mathcal{G}$, Brand-based arc capacity $(C^b \leftarrow N_b \cdot D_b^2)_{(i,j)\in\mathcal{A}}$;
  for every $p \in \mathcal{P}_b$ **do**
    Initialize: $\mathcal{G}_p \leftarrow$ Copy of graph $\mathcal{G}_b$, Commodity flow yet to be routed $R_p \leftarrow D_p^1$, O-D pair-based arc capacity $(C^p \leftarrow M_p \cdot D_p^1)_{(i,j)\in\mathcal{A}}$, $\ell_p \leftarrow 0$;
    while $R_p > 0$ **do**
      $\lambda_{\ell_p} \leftarrow$ Shortest path on $\mathcal{G}_p$ using Dijkstra's Algorithm ;
      $q_p \leftarrow \min_{(i,j)\in\lambda_{\ell_p}} \left\{ \min\{R_p\,, C_{i,j}^p\,, C_{i,j}^b\} \right\}$;
      for every $(i,j) \in \lambda_{\ell_p}$ **do**
        $f_{i,j}^p \leftarrow q_p$, $C_{i,j}^p \leftarrow C_{i,j}^p - q_p$, $C_{i,j}^b \leftarrow N_b \cdot D_b^2 - \sum_{p\in\mathcal{P}_b} f_{i,j}^p$;
        if $C_{i,j}^p = 0$ **then**
          $\mathcal{A}_p \leftarrow \mathcal{A}_p \setminus \{(i,j)\}$;
        if $C_{i,j}^b = 0$ **then**
          $\mathcal{A}_b \leftarrow \mathcal{A}_b \setminus \{(i,j)\}$;
      $\ell_p \leftarrow \ell_p + 1$;
return $\boldsymbol{f}$

3 Computational Study

3.1 Case Study

In this section, we design commodity flow routes within hyperconnected hub network for finished vehicle logistics across US Southeast through proposed algorithms and assess their efficiency and resiliency. The hyperconnected network is designed through principles mentioned in (Montreuil, 2011; Kulkarni et al., 2024).

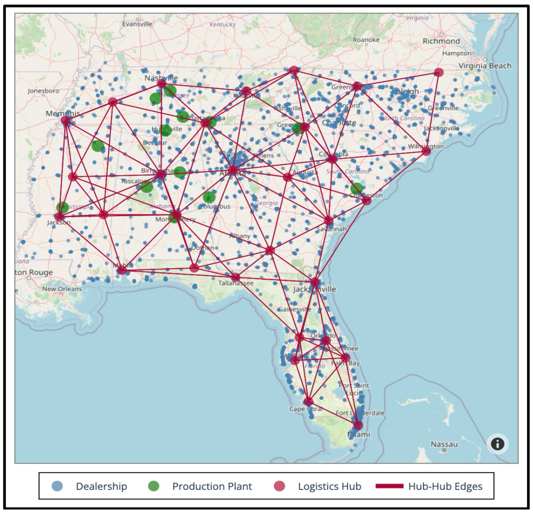


Figure 1: Hyperconnected Hub Network for finished vehicle logistics in the Southeast USA.

Figure 1 represents the hyperconnected network utilized for computational purposes. Here, each node in the network represents the centroid of a cluster of hubs located around the sites with logistics significance such as those having an easy access to boulevards, highways, airports, railway infrastructures, and waterways (Grover et al., 2023). Aligning with the core idea of hyperconnected logistics underpinning the Physical Internet, these hub networks are shared by multiple brands to move thousands of finished vehicles from their production plants to partnered dealerships over large regions. In the interest of this case study, we purposefully assume that these hubs are only used for transporting finished vehicles while it can be utilized by logistics service provides to move other types of freight. In compliance with the regulations imposed by the government stipulating a maximum driving time of 11 hours per day for a truck driver, we restrict the transportation arcs in the network to be within 5.5 hours of drive time. This policy ensures that the drivers can conclude their journeys and return home daily without violating their daily driving limit. Additionally, it's presumed that production plants employ hub network for shipments to dealerships situated more than 5.5 hours away in terms of travel time. This strategic decision aims at capitalizing the advantages of consolidation at hubs for shipments requiring longer travel, thereby achieving greater economies of scale.

3.2 Computational Results

The proposed algorithms and network simulations are implemented in Python v3.11.4 on a laptop with Apple M2 Pro chip (Apple, Cupertino, CA, USA) with 10-core CPU and 16GB unified memory.

First, we generated resilience-optimized flow routes through hyperconnected network for each O-D pair using basic resilience-optimized route generation algorithm as described in Section 2.1. Particularly, by setting the maximum proportion of commodity flow per O-D pair on each transportation arc $M_p = 50\%$, we decomposed the flow through two edge-disjoint paths. Next, we also generated commodity flow routes through adaptive resilience-optimized algorithms by setting maximum allowable proportion of brand-based commodity flow on each transportation arc $N_b = 20\%$ for each brand $b \in \mathcal{B}$ in addition to setting $M_p = 50\%$. To benchmark the efficiency and resiliency of the computed commodity flow routes, we also calculated efficiency-optimized routes for each O-D pair through hub network. The underlying reasoning for computing such routes is that they follow the minimum cost-paths which in turn minimizes the operational expenses in the absence of disruptions.

Figure 2 (a), (b) and (c) presents the commodity flow routes generated using the three algorithms for shipments from a plant located in Mississippi to a dealership in Georgia. Efficiency-optimized methodology select the shortest path via the hub in Birmingham to route the associated O-D flow while resilience-optimized algorithms select two edge-disjoint paths based on set parameters. One interesting observation is that the two edge-disjoint flow routes generated in basic and adaptive resilience-optimized algorithms are different. Basic resilience optimized methodology chooses first two minimum-cost edge-disjoint paths by independently solving for each O-D pair. However, since the adaptive resilience-optimized methodology restricts flow on arc based on brand and solves O-D pairs within brand together in decreasing order of flow, the arc from plant to Birmingham and Montgomery are allocated to O-D pairs with higher flow.

Under the scenario that the transportation arc from plant to Montgomery is disrupted, the entire O-D flow is impacted in efficiency-optimized while 50% flow reaches the dealership on time in case of basic resilience-optimized and 100% flow delivered on time in case of adaptive resilience-optimized. This clearly showcases that the adaptive resilience-optimized can distribute flow to wider range of edge-disjoint paths, leading to generating more resilient flow routes for commodity shipments. In next subsections, we compare the efficiency and resiliency of routes generated by resilience-optimized methodologies by setting $M_p = 33.4\%$ and $N_b = 20\%$ for each brand $b \in \mathcal{B}$, to decompose flow into 3 edge disjoint paths for each O-D pair.

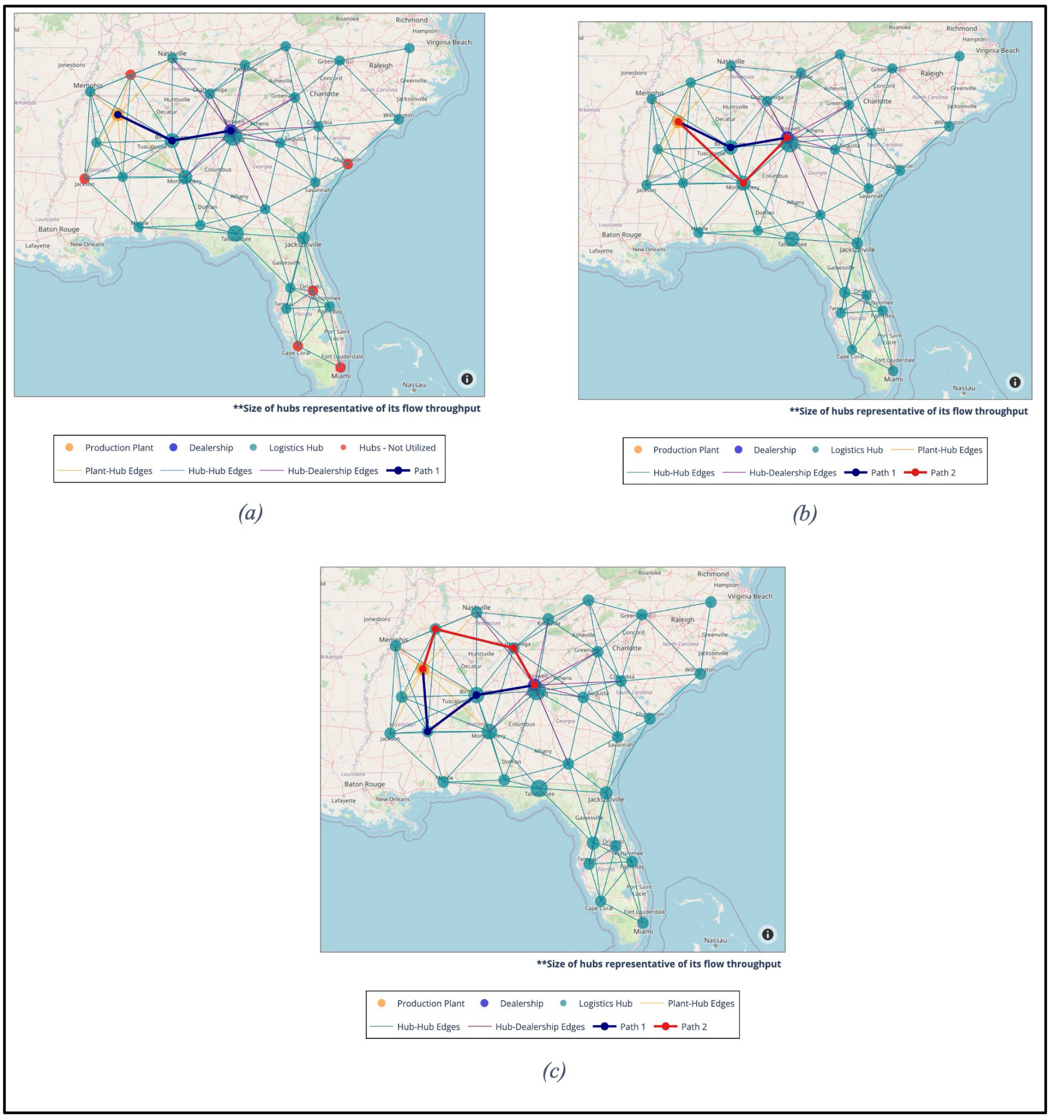


Figure 2: Flow Routes generated for an O-D pair by: (a) Efficiency-Optimized (b) Basic Resilience-Optimized (c) Adaptive Resilience-Optimized algorithms

3.2.1 Efficiency Comparison

To compare the efficiency of proposed algorithms, we calculate an efficiency metric as the ratio of sum of travel times in path weighted by its associated flow to the sum of travel times in minimum cost path weighted by its associated path-flow and shown in Figure 33. In case of routes generated through basic resilience-optimized algorithm, we observe that the induced travel time for all O-D pairs is not more than 20% as that of the routes obtained from efficiency-optimized routes. This depicts the strong hyperconnectivity in hub network and showcases that the resilience-optimized routes generated by basic resilience algorithm are highly efficient under nominal operating situations.
However, in case of routes obtained from the adaptive resilience-optimized algorithm, we find that ~13% of O-D pairs have an induced travel time of greater than 20% and 3% of O-D pairs

taking more than 40% than the efficiency-optimized routes. One potential reason for such occurrence lies in the fact that Algorithm 2 prioritizes O-D pairs with higher flows within each brand, and consequently, the O-D pairs with lower commodity demand have to take considerably longer routes.

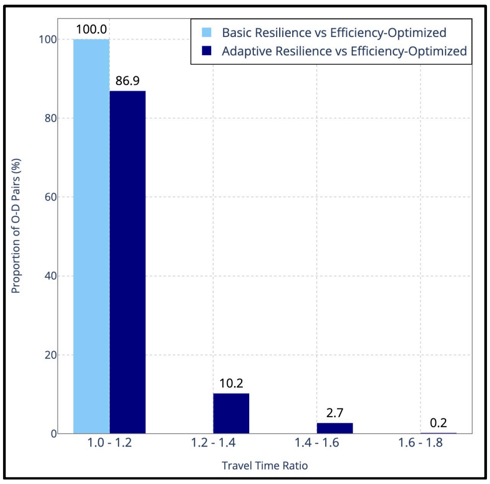


Figure 33: Travel Time Ratio of proposed algorithms with Efficiency-optimized routes

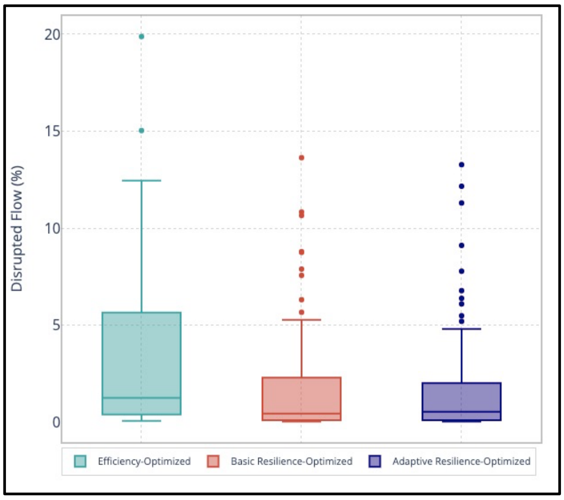
3.2.2 Resiliency Comparison

To assess the resilience of the routes generated by resilience-optimized algorithms against efficiency-optimized ones, we conduct two types of worst-case disruption experiments where we disrupt either a single edge or a single hub randomly. By “worst-case disruptions”, we refer specifically to disruption of transportation arcs (or) hubs that are employed for routing the flow from plants to dealerships under different algorithms (Kulkarni et al., 2023). For these disruption experiments, we suppose that the consolidation plans are fixed a priori and cannot be substantially changed upon the realization of a disruption scenario.

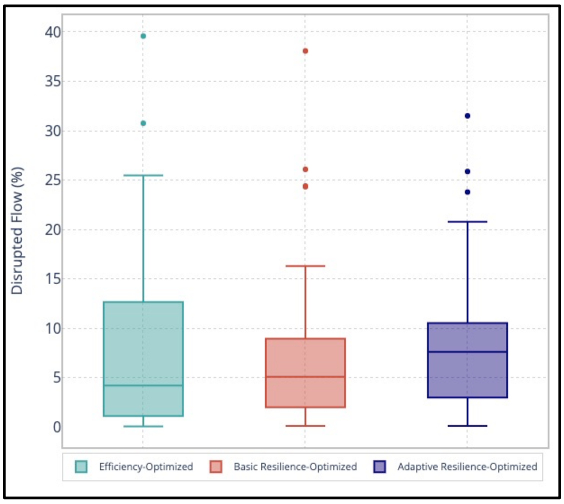
The results from the random 1-edge disruptions are shown in Figure 44(a). In the case of efficiency-optimized routes, the distribution of flow for all O-D pairs in network is highly concentrated on a fewer number of critical edges. These edges are critical in nature as they are being utilized to route associated demand of a large proportion of O-D pairs. When they are disrupted, a substantial flow is affected, leading to a significant increase in freight operational expenses and delayed deliveries for a larger proportion of total flow. On the contrary, in resilience-optimized algorithms, the proportion of flow is well-distributed across the transportation edges and any disruption in these edges affects a lesser proportion of overall flow, thereby depicting higher operational resilience. In particular, the flow is evenly distributed to multiple edges in adaptive resilience-optimized routes enabling a major proportion of flow to reach destination on time even under such worst-case disruptions.

Next, we randomly disrupt 1-hub and the results regarding the disrupted flow are shown in Figure 44(b). Similar to the trend observed in 1-edge disruptions, distribution of flow is more concentrated on a few hubs in efficiency-optimized methodology, with almost 40% flowing through one hub. This hub is consistently utilized for over 30% of flow in resilience-optimized cases, indicating its criticality in the network. Moreover, in the case of efficiency-optimized, more than 50% of the hubs have higher throughput flow compared to resilience-optimized, signifying that on an average higher proportion of O-D flow is likely to be affected under worst-case hub disruptions.

We note an interesting aspect which lies in the context of adaptive resilience-optimized routes. Despite achieving higher resilience under edge disruptions by limiting the proportion of flow on edges by brand, it introduces a trade-off. The selected edge-disjoint paths exhibit more intersections of nodes, rendering the system less resilient under hub disruptions compared to the basic-resilience optimized algorithm.



(a)



(b)

Figure 44: Comparison of disrupted flow % across methodologies under random (a) 1-Edge Disruption (b) 1-Hub Disruption

4 Conclusion

In this article, we ascertained the need for and importance of devising commodity delivery paths across hyperconnected networks that are both efficient in the absence of disruptions and resilient to sustain a wide variety of disruptions. To this end, we devised two algorithms: basic and adaptive resilience-optimized for commodity route generation. These algorithms distribute commodity flow smartly across multiple (edge-disjoint) paths while respecting the constraints of logistics operations realistically. Comparison results depicted enhanced capability of sustaining disruptions by the routes computed through proposed algorithms as opposed to that generated through only efficiency considerations. We observed that the routes generated through basic resilience-optimized were more efficient than those of adaptive resilience-optimized algorithm. In terms of resiliency, we witnessed the opposite trend of that observed for efficiency comparison. Overall, a classic trade-off between efficiency and resiliency is observed in all the routes generated through the proposed algorithms.

The current work opens multiple avenues of research. These algorithms, although scalable, are still heuristic ways to devise resilience-optimized commodity delivery routes. The first avenue is to explore optimization-based modeling framework for the same problem and devise exact solution approaches for it. Second, instead of devising edge-disjoint commodity delivery paths, non-edge-disjoint paths can be computed. Such an approach, although less capable of sustaining disruptions, is indeed more efficient in nominal operating conditions. This will require exponential-sized optimization models and sophisticated solution techniques such as column generation to devise good quality routes. Finally, regarding evaluation of such routes, a more comprehensive set of disruption experiments can be conducted. This could involve simulating other types of disruption scenarios such as multiple edge and hub disruptions, localized disruptions, and adversarial type of disruptions.

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Hyperconnected Urban Delivery with synergized public transportation options and containerization.

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Abstract: *This paper investigates a comprehensive exploration of a hyperconnected urban delivery system that synergizes public transportation options with containerization for efficient parcel logistics. The study focuses on optimizing the urban middle-mile segment of parcel delivery, emphasizing the integration of freight operations into existing public transport networks. This paper applies three means & ways concepts from the Hyperconnected City Logistic framework: open response planning, open resource deployment, and open capability enablement and adapts them. These three groups of decisions are interconnected, each influencing and complementing the others to enable the creation and efficient use of an urban logistics system using public transport and containerization.*

Keywords: *Physical Internet, Hyperconnected City Logistics, Freight transportation, Urban mobility, Public Transportation.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☐ PI Networks, ☒ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

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1 Introduction

1.1 Motivation

Since the COVID-19 crisis, the growth of Annual e-commerce sales in France has been significant: annual e-commerce sales have risen from €103.4 billion in 2019 to €146 billion in 2022, an increase of 41% (Fevad, 2023). This increase has led to a significant rise in the number of deliveries of different types and sizes in the city's various areas. In addition, the consumer desire for speed is constantly evolving, and same-day deliveries are more and more popular for the consumer, involving more resources, more saturation in city centers, and creating congestion and pollution by using more and more urban vehicles. Simultaneously, the increasing urban population density creates important passenger flows with their own operating network with dedicated resources (private like cars and public like buses and tramways) and infrastructures (roads, rails). Within urban areas, many public transport services are available, making it possible to reach pedestrian zones in the city centers that are inaccessible to freight vehicles. Often full during rush hour, public transport provides underutilized spare capacity during off-peak hours.

Despite similarities between freight network and people mobility within the same urban environment, the conventional practical framework imposes a separation in terms of flows, infrastructures, and resources. It is in this context of network separation that the physical Internet (PI) (Montreuil, 2011) is emerging, removing the separation between the two networks by connecting people, objects, stakeholders, and networks in a unified, open, interconnected system. When applied to urban environments and city logistics, PI emerges the concept of Hyperconnected City Logistics (HCL) (Crainic et al., 2016). HCL aims to create new urban logistics and transportation systems that are more efficient and sustainable. HCL framework gives several concepts, this study integrates the concept of integration and interconnection of passenger and freight movements. This concept establishes synergies between public transportation infrastructures dedicated to passenger mobility and freight networks characterized by hyperconnectivity and synchromodality (Labarthe et al., 2024).

Figure 1: TRAM-FRET Pilot, Bordeaux, France, 2015 (Source: Kedge)

Figure 2: KombiBus, Germany, since 2010 (Source: KombiBUS Gruppe)

Figures 1 and *2* illustrate projects combining one type of public transportation with freight. To facilitate movement within the public transport system, parcels are grouped together. Containerized parcels save space inside the public transportation and time to load/unload it.

In our work, we investigate combined systems, considering multimodal transportation, particularly public transportation modes, to transport part of goods in the context of HCL using parcel containerization.

1.2 Business Context

We consider the practice of consolidation and containerization. To unify the handling, loading, and unloading process at hubs for the parcels, they are grouped into containers when they are traveling in the same direction (Kaboudvand et al., 2021). Figure 3 illustrates the containerization and consolidations.

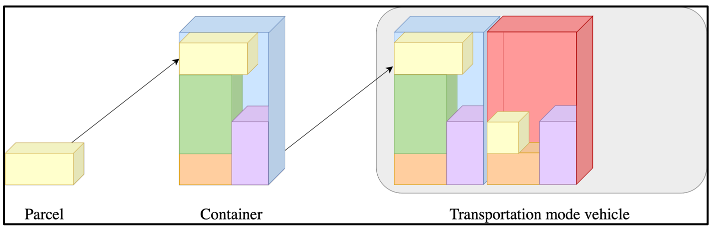

Figure 3: consolidation

In the urban context, demand is considered as a volume of parcels with an origin and a destination. Demand is available at a given time in an area and must reach its destination within a given time. To achieve this, we consider a Hyperconnected Urban Delivery System (HUDS) with three tiers: urban first-mile, urban middle-mile, and urban last-mile (*Figure 4)*. Our HUDS network is made of different logistic urban vehicles from the urban freight network and public transportation modes from the people mobility network.

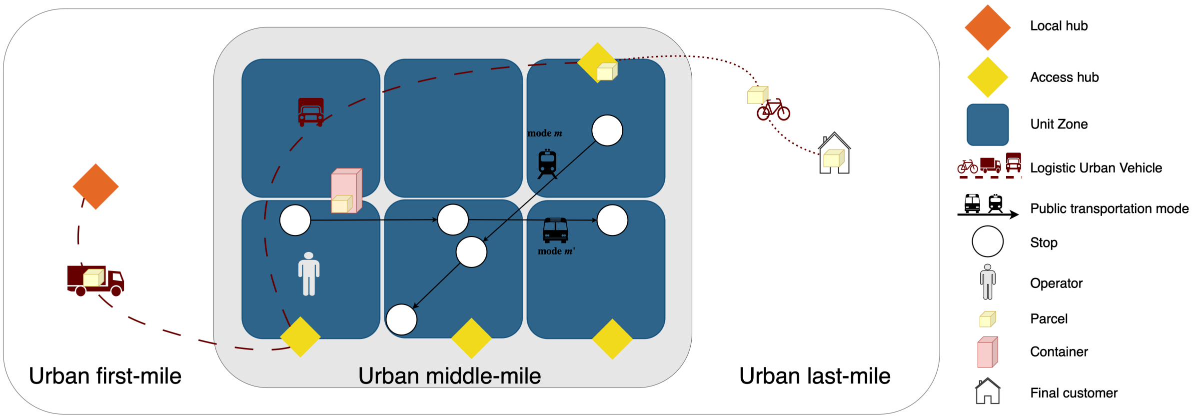

Figure 4: Hyperconnected Urban Delivery System description

The urban first-mile corresponds to the movement where an urban vehicle transports the parcel from a local hub to an access hub near the public transport network. Conversely, the urban last-mile corresponds to the last step, where the urban logistics vehicle delivers the parcel to its final customer. In this paper, we focus on the urban middle-mile. Assuming that demand is available at an access hub and must reach another access hub destination, we want to use our HUDS network at our disposal to demonstrate the efficiency of public transport in urban delivery. We, therefore, assume that at access hubs, urban logistics vehicles are perfectly synchronized with our urban middle-mile tiers to ensure that parcels are available on time. In cases where demand cannot reach the access hub destination by public transport within the required timeframe, we use an emergency urban logistics vehicle capable of reaching the destination directly. To move inside the public transport network, parcels are consolidated in containers to facilitate their transport. The urban area is divided into zones containing stops. Operators can be assigned to zones to authorize consolidated parcels evolving within the network. By consolidating transportation needs and using shared resources, the HUDS can achieve the same level of service with fewer resources, resulting in reduced gas emissions and pollution (Bektas et al. 2015). Additionally, managing the integration of various transportation public modes with urban freight networks opens additional business opportunities.

Recently, several studies have investigated urban parcel delivery systems with public transportation options. (Yang et al. 2024) propose a co-modality system, passenger-freight, in which passengers on the public transport network can carry parcels from the freight network, and these passengers are synchronized with the freight service. (Delle donne et al. 2023) propose the strategic integration of freight and passengers inside public transportation; however, transshipment operation isn't authorized in this study. In contrast, (Li et al. 2024) integrate freight transportation into the underground city logistics system, authorizing operations on train units. Regarding consolidation and containerization, (Kaboudvand et al. 2021) study containerized consolidation inside a Hyperconnected Parcel Logistics. The latter work doesn't consider public transportation services.

Our research contributes to the field of urban parcel logistics by integrating the Hyperconnected City Logistics framework into a hyperconnected urban network using public transportation infrastructure. Focused on the middle-mile segment of parcel delivery within urban areas, our study proposes a combined transportation system that merges passenger mobility with freight movements. A key aspect of our approach is the adoption of containerization practices, whereby parcels are consolidated within, allowing them to move inside the public transport network, changing lines an unlimited number of times with the support of the workforce.

This paper is organized as follows. In Section 2, our proposed approach is presented to answer the business context. Section 3 is dedicated to discussing and modeling our adaptation of three core concepts of the Hyperconnected City Logistic framework. Finally, the conclusion and perspectives are discussed.

2 Proposed approach

We are interested in the means & ways category of the Hyperconnected City Logistic framework (Crainic et al., 2023) enabling and leveraging logistic Hyperconnectivity. Our proposed approach focuses on an application of three of the fourteen core concepts of the HCL framework, *Figure 5*.

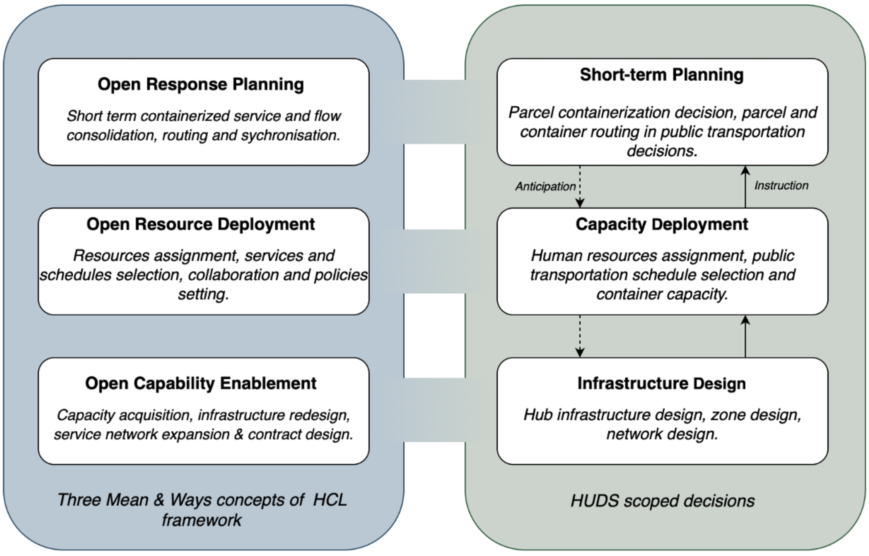

Figure 5: Scoped decisions adapted from (Crainic et al. 2023)

To create an effective Hyperconnected Urban Delivery System (HUDS), we consider three types of decisions adapted from the HCL framework: short-term planning, capacity deployment, and infrastructure design. Each decision is linked to the others, and together, they create a network that allows the joint optimization of these decisions.

The decision on *infrastructure design* is the one made upstream, as it takes place seasons or years before implementation. It corresponds to the "open capability enablement concept" for our HUDS. A service network design is established, focusing on the delivery network design, selecting the infrastructures (hub and transportation mode) to be utilized or created, and their role. Then comes the decision on *capacity deployment*, which is considered to take place weeks or months before. Capacity assignment of a hyperconnected network in parcel logistics is imperative to define because it delineates the boundary of feasible activity within a technological system. It is adapted from the "open resource deployment" consisting of allocated capacity as the human resources required to carry out consolidation operations, the public transportation frequency, and container characteristics. Finally, the decision on *short-term planning* is made shortly before execution, days or even hours in advance. This decision is adapted from the "open response planning" concept and consists of studying the flow of parcels and their consolidation into containers within various modes of public transportation.

The outcome of each decision serves as the basis for the next, creating a loop where the results of one decision provide the input instructions for the next. The model of the previous decision acts as a simulation, guiding the formulation of subsequent decisions and enabling the model to be adapted. This process ensures that each decision contributes to the overall efficiency of the HUDS. To ensure that it is adapted to the specific needs and challenges of urban delivery, it is necessary for each decision to define the objectives, constraints, and information available. This is the subject of the next section.

3 Discussion and modeling

3.1 Short-term Planning

To implement the short-term planning model, it is imperative to initiate the decisions made at the two other levels: capacity deployment and infrastructure design. Infrastructure design provides the network structure with zone configurations, specifying the number of lines and stops used. The capacity deployment model provides instructions on operator allocation and determines the number of operations authorized in each zone. It sets limits on the number of containers per public transportation mode and establishes fixed transport frequencies.

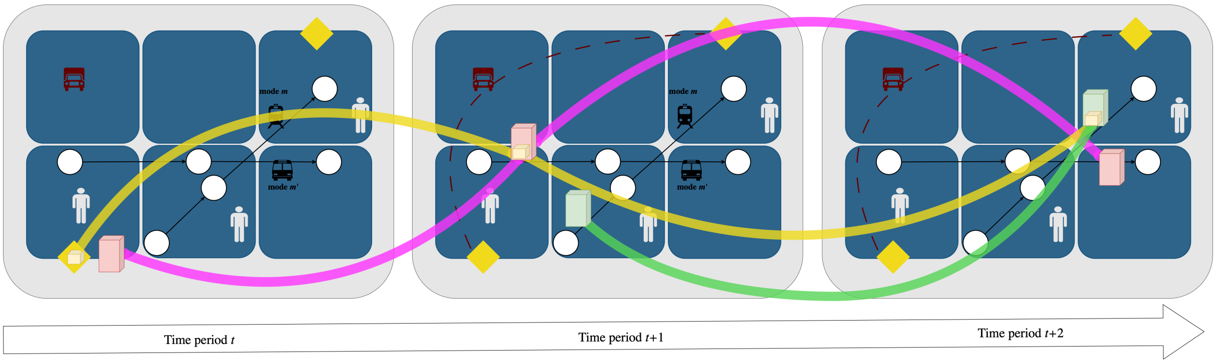

Figure 6: Parcel and container routes planning.

Figure 6 highlights route planning for parcels and containers during different periods. The objective of short-term planning is to assign each parcel a route composed of containers and transportation modes. In this model, decisions focus on planning routes of parcels and containers in our HUDS while ensuring efficient coordination between them to apply containerization.

Parcel routing and container consolidation represent interconnected decision problems (Kaboudvand et al., 2021). Parcels cannot travel independently and must be contained inside containers. Time constraints are important, as they dictate when parcels are available at their origin hub and when they must reach their destination hub. It is essential to consider these time intervals to ensure timely delivery within designated time frames. The last constraint to add is during specific freight operations, and careful consideration must be given to the time required between the various modes engaged in the process. If modes are not synchronized, a reasonable waiting period should be added in to ensure smooth operations.

3.2 Capacity deployment

To ensure efficient parcel and container movement, it is important to optimize the allocation of resources and capacity within the network. The aim is to allocate capacity while maximizing utilization and minimizing costs. For this purpose, we have information from the other decision level: infrastructure design. This includes instructions on the network's design, such as zone configurations and the number of lines and stops used. The short-term planning model, as it takes effect earlier, can be used to simulate the results found in the capacity deployment model. In our capacity deployment problem, we consider levels of demand that evolve throughout the day. For each demand, a time of availability at its source is known, as well as the time at which the demand must be at its destination.

The decisions associated with capacity deployment focus on human capacity allocation, PI-container characteristics, and public transport scheduling. These three decisions can be handled separately.

Human capacity allocation

To enable demand to evolve in the network and reach its destination with public transport, the quantity of workforce assigned to a unit zone at a time interval must be chosen. Operators can have short or long-term contracts, as already deployed in Bordeaux with (ELISE), which hires people on long-term contracts with disabilities or integration difficulties. Each operator's schedule must be known daily, so an operator can be either assigned inside a unique zone or deployed in several different zones at different times while ensuring that the travel time between the two zones is feasible. In the *Figure 6* example, the same operator is deployed in different zones at different times allowing different operations in each zone.

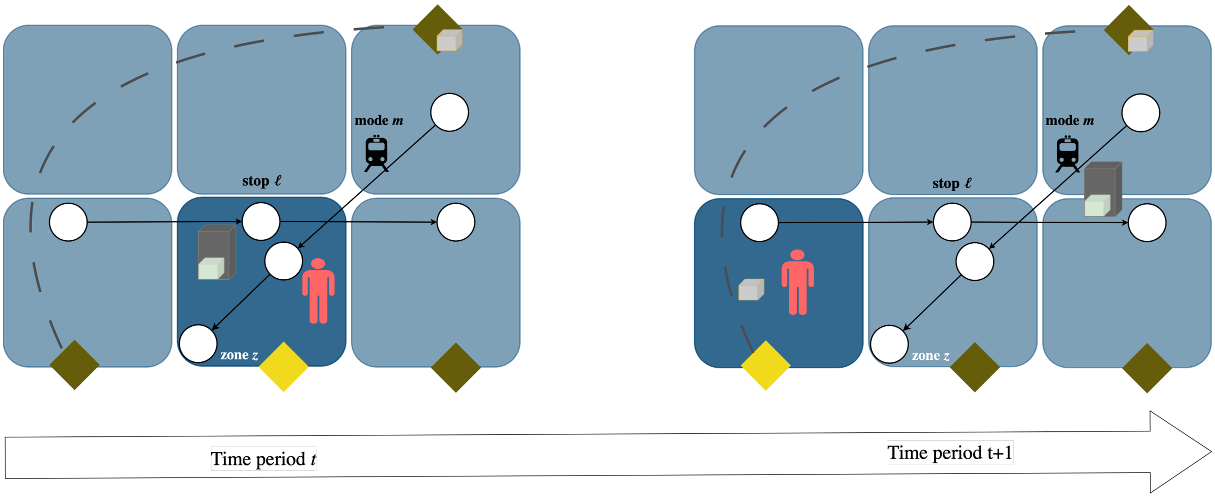

Figure 6: Time Capacity allocation

Time is an important factor to consider when allocating human resources. If an operator can be assigned to several different zones during his working day, it is important to specify the discretization of this day to have a decision by time interval. Flexibility in operators' working hours can be considered to meet fluctuations in demand throughout the day. This could involve flextime, rotating shifts, or overtime as required. The number of operators deployed in each zone also needs to be defined, as this will determine the network's capacity to handle parcels and containers.

PI-container characteristics

The quantity of containers, their origin and destinations, and their volume are decisions of the model as they fix the available capacity for parcels. The quantity of containers circulating inside the network should align with demand levels. The origin and destination zones of containers must be situated within areas with deployed workforce. Container volume plays a pivotal role in decision-making (Mohri et al. 2024) presents various containers of varying sizes and capacities, and it is possible to use different volumes and types of PI containers (Ben Mohamed et al. 2017). Moreover, container dimensions must be compatible with the height and width of public transport doors.

Public transport scheduling

As part of our HUDS, public transport scheduling plays a crucial role in capacity allocation. The availability and regularity of public transport determine the network's ability to transport passengers and goods efficiently. The public transport scheduling is a key decision. A high frequency allows more trips to be made in each time, reducing waiting times and improving the accessibility of the network for parcels. On the other hand, low frequency can lead to longer waiting times at stops, which can remove possible operations for operators and result in under-utilization of available capacity. It is also possible to consider variable frequencies (Ghilas et al. 2013).

3.3 Infrastructure design

Strategic infrastructure design and redesign are essential to integrate freight logistics into existing public transport systems inside a Hyperconnected City Logistics network. The decisions focus on optimizing line and stop selection, creating new infrastructure where necessary, and defining zones for efficient freight transportation. Constraints include considerations for passenger mobility, resource utilization, and network connectivity. The objective of infrastructure design is to create a network that is efficient, adaptable, and integrated with existing urban infrastructure. The results network will be inserted into the other two decision models to provide an efficient and complete HUDS. Two sets of decisions need to be made in this infrastructure design phase. The first concerns the design of the public transport network, and the second is the service and zones network design.

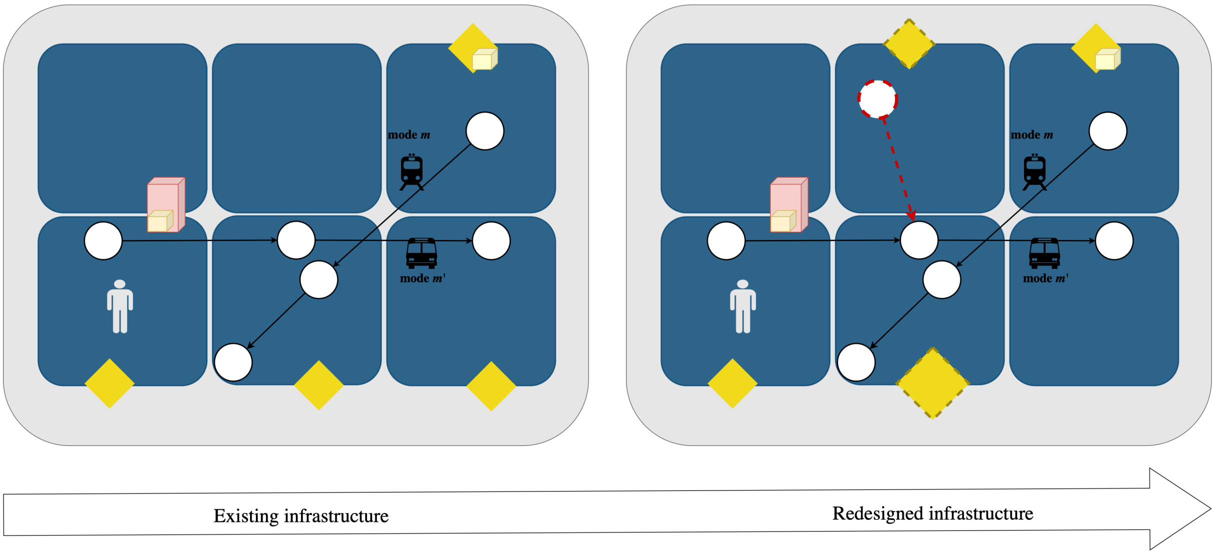

Figure 7: infrastructure redesign.

Figure 7 illustrates the difference between the existing and modified networks. The redesigned one contains a new stop with a new line, and one hub have been added and one expanded. This highlights the decisions to be made in the infrastructure design model.

Public network design

This model aims to strategically design public transport network by selecting bus routes and stops existing and potentially creating new stops or lines. To improve network connectivity, reduce delivery times, and optimize resource utilization for HUDS.

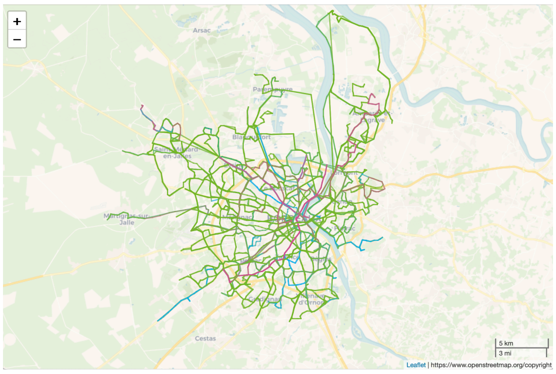

Figure 8: Lines public transportation Network, city of Bordeaux.

The decision to integrate either the entire existing public transport network or specific lines into our combined freight delivery and passenger system is pivotal for optimizing urban logistics. For instance, insights from (Diego Delle Donne et al. 2023) highlight the strategic significance of this decision by choosing the bus routes and stops to be used for delivery. The number of lines selected influences the total network's connectivity, as mentioned in *Figure 8* the entire network may be large, and not all lines will be used. *Figure 8* representing public transportation network of the city of Bordeaux is obtained by using OpenData website shared by Bordeaux public authorities (L'atelier Opendata). Opting for a subset of lines rather than the entire network for freight delivery integration can strike a tradeoff between passenger mobility and freight transportation efficiency. It's also essential to determine the number and location of stops to be used in the delivery network. Integrating into the network stops located in the main urban nodes can maximize their usefulness and facilitate efficiency. There are stops where several public transportation modes pass through. These stops are important because many operations can take place, and they contribute to the connectivity of the overall network.

Additionally, it is worth considering the possibility of creating new stops (dedicated to freight or serving both freight and passengers) or public transport lines at strategic locations. This approach can bring improvements to both networks simultaneously by enhancing connectivity, reducing delivery times, and optimizing resource utilization. By placing new lines or stops, cities can address specific freight delivery needs while also improving overall public transportation accessibility and efficiency.

Service network design and Zone configuration.

The objective of this model is to optimize the zone and service by strategically dividing space and creating or modifying hubs.

A zone corresponds to a division of space comprising one or more stops, and some zones may contain hubs. Inside zones, when manpower is assigned, we can carry out the various operations. In the context of Hyperconnected Urban Delivery with synergized public transportation options and containerization, the creation of zones is a crucial aspect for ensuring efficient and effective freight transportation. One approach to defining these zones involves leveraging classical clustering methods, which group stop stations based on geographical proximity, demand patterns, or other relevant factors. However, more sophisticated zone design methodologies exist, such as those discussed in the literature by (Huang et al. 2018) in their article on designing logistics systems for home delivery in densely populated urban areas, offer additional insights and considerations. These advanced techniques go beyond simple proximity-based clustering and consider indivisible micro-cells in the city merged into blocks, including geographical barriers.

To improve the design of zones within the delivery network, it's essential to consider the internal structure of these zones, including the installation of hubs or lockers. Strategic placement of these facilities can significantly impact the overall network design and cost performance (Janjevic et al. 2019). It is imperative to consider not only the location of infrastructures such as hubs or lockers but also their size and type of storage. The right placement of infrastructures in a zone can improve the fluidity of delivery operations by reducing waiting times and travel distances. In addition, the size of the infrastructure must be adapted to the volume of parcels handled. Finally, the choice of storage type - whether secure lockers, warehouses, or other solutions - depends on the specific characteristics of the zone. These characteristics must not deteriorate the passenger mobility network already deployed and must not affect passengers' appreciation of the network. By incorporating these considerations into the design of the delivery zone, it is possible to create a network that is more efficient and adaptable to the changing needs of the urban area.

Conclusion

Our study presents a comprehensive framework for enhancing urban parcel delivery systems by integrating three key decisions from the Hyperconnected City Logistic Framework: open response planning, open resource deployment, and open capability enablement. Through the adaptation of these decisions into short-term planning, capacity deployment, and infrastructure design, we have developed an integrated approach aimed at optimizing the efficiency of urban logistics using public transportation. These three decisions - short-term planning, capacity deployment, and infrastructure design – are interconnected, each influencing and complementing the others to create an efficient HUDS.

The first decision of our approach concerns the optimization of parcel and container routing, which directly addresses the concept of open response planning. By planning the movement of parcels and containers within the urban delivery network, we aim to minimize delivery times and maximize resource utilization. This involves coordinating the routes of parcels and containers considering containerization. Capacity deployment inspired by Open Resource Deployment is the second decision of our framework focuses on the efficient allocation of human resources and container characteristics. By assigning a workforce, optimizing container volume, and line scheduling, we enhanced overall efficiency and performance. Once Capacity deployment is fixed, the short-term planning can be used as a simulation to validate the solution's feasibility. The redesign or selection of public network infrastructure and zone design emerged as key factors in optimizing system efficiency, aligning with the Open Capability Enablement concept. This third decision consists of selecting optimal lines and stops within the public transport network, as well as strategically placing hubs and lockers in delivery zones. Together, these interconnected decisions offer a solution to the challenges of urban parcel delivery using public transportation with containerization.

Further research avenues include calculating the economic and ecological benefit for the city stakeholders of using the HUDS. To test the model and develop it, a case study for the city of Bordeaux, France, can be built using data available in open data.

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Strategic Network Design for Hyperconnected Mobile Supply Chains

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Abstract: *In today's competitive world, businesses must offer high-quality products that can be delivered fast and cheaply. Three main strategies have been identified to solve this challenge: fast delivery, deploying inventory near to customers, and distributed production near to customers. Using Physical Internet concepts of resource sharing and flow consolidation leveraging modularization, standardization, interfaces, and protocols, Marcotte and Montreuil were the first to introduce the concept of Hyperconnected Mobile Production to contribute to the distributed production near-to-customers strategy. But their work only considered single tier supply chain. In this paper, we introduce Hyperconnected Mobile Supply Chains, a hyperconnected multi-party open hub network with plug-and-play modular mobile production units for the multi-layers involved across the supply chain system. We propose a decision-making framework for the strategic network design of hyperconnected mobile supply chains, for selecting the location, size, and number of facilities for open-hub network, leveraging capacity pooling and plug-and-play modular mobile production unit.*

Keywords: *Physical Internet, Strategic Network Design, Hyperconnected Network, Mobile Production, Modular capacity, Sustainability*

***Physical Internet (PI) Roadmap Fitness**: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☒ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

***Targeted Delivery Mode-s**: ☒ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation*

1 Introduction

In recent years, the concept of containerized production, i.e. encapsulated production lines capable of producing a product in its entirety, has gained momentum. Notably, the F3 Factory project, a major European public-private sector initiative for the chemical industry, was launched in 2009 to investigate the potential impact of containerized production in the chemical industry. The results published in 2014 highlighted considerable benefits, including a reduction in capital expenditure by 40%, operational expenditure by 20%, energy consumption by 30%, required footprint by 50%, the number of equipment required by more than 60%, and a decrease in product's time to market, while increasing production yield and capacity by more than 20% (EU Commission Cordis's website). This first major research led companies like Bayer to develop containerized production units, as shown in Figure 1.

Figure 1: Containerized production unit in operation (left) during loading/unloading (right)

Source: Kessler.S, 2015

Containerized production and mobile supply chains broadly address the lack of flexibility, adaptability, and robustness of traditional supply chains. As described by Jabbarzadeh et al. (2016) traditional supply chains often rely on a small number of fixed production sites producing a wide range of products that will be delivered to the customer through a distribution network. While this centralized vision allows for economies of scale and better management of production sites, it has the drawback of poor flexibility, adaptability, and robustness (Shahmoradi-Moghadam and Schönberger, 2021). Another crucial motivation for mobile supply chains is sustainability. With global demand increasing, companies traditionally preferred production in economically advantageous locations to maximize profit. However, societal pressures for more sustainable production and processes are pushing for a shift toward more environmentally responsible and closer-to-market production.

An aspect yet to be addressed in the current perception of mobile supply chain is resources and information sharing across multiple tiers. To the best of our knowledge, literature is scarce regarding multi-tier mobile supply chains.

The rest of this paper is constructed as follows: we begin with a literature review to depict the state-of-the art regarding mobile supply chains. We then introduce the concept of a hyperconnected mobile supply chain and propose a strategic network design formulation aimed at minimizing total cost and environmental footprint. Finally, we demonstrate the cost reduction of the proposed model in a case study in the realm of modular construction.

2 Literature Review

As described by Jabbarzadeh et al. (2016), traditional supply chains are centralized: a small number of fixed production sites produce a variety of products that will be delivered to the customer through a distribution network. While allowing economy of scale and efficient management of production sites, this centralized concept suffers from low flexibility, adaptability, and robustness. (Shahmoradi-Moghadam and Schönberger, 2021). To address these limitations, the concept of Distributed Manufacturing Systems (DMS) has emerged (Matt et al., 2015).

Mobile Supply Chains (MSC) is an evolution of DMS, aiming to overcome the lack of flexibility, adaptability, and robustness of traditional fixed supply chains. Shahmoradi-Moghadam and Schönberger (2021) described MSC as focusing on producing as close as possible to markets to enhance service levels and fast-deployment of production units into vast geographical regions. This mobile concept also allows for better management demand fluctuations, facilitates mass customization, and reduces asset investment and logistics costs. A popular application of Mobile Supply Chains is Modular Manufacturing. Because the container contains everything that is required for production, companies are capable of better responding to variations in demand, reducing financial risks, and increasing profits (Baldea et al., 2017).

However, most of the literature related to Mobile Supply Chains and Mobile Manufacturing focuses on Vehicle Routing Problems with predetermined networks (Shahmoradi-Moghadam, H. and Schönberger, J., 2021; Halper et al., 2011), single-tier network design (Jena et al., 2015) and does not leverage the concept of an open network (Dotoli et al., 2005)

Marcotte and Montreuil (2016) were the first to introduce the concept of Hyperconnected Mobile Production. This concept, emerging from the convergence of eight production threads, leverages a network of open certified production facilities interconnected by a hyperconnected transportation for fulfillment and shipping, businesses will have real-time access to all relevant data about their hyperconnected mobile production modules, including information on the next location of the module or the next production program. Consequently, they are capable of dynamically expanding and contracting their production capacity in regions, enhancing flexibility and responsiveness within the supply chain. For such type of production, Fergani et al. (2020) developed a tactical network design using a multi-objective optimization model that minimizes costs and environmental impact of the network for this Single-Tier problem, using a predetermined network of open fabs was predetermined.

3 The concept of hyperconnected mobile supply chains (HMSC)

In traditional supply chains, every tier is mostly centralized in a few locations. Stakeholders from each tier ship from their own facility(ies) or leverage a 3PL network. While this strategy allows each player to leverage economies of scale and better handle processes, it also implies low flexibility, agility and, in the worst case, possibly results in substantial transportation costs if demand points are far from the location.

As previously discussed, mobile supply chains (MSC) already aim to address such issues. However, to the best of our knowledge, most applications of MSC and hyperconnected mobile production have focused on single-tier supply chains (Marcotte and Montreuil, 2016; Fergani et al., 2020) or in support of existing supply chain systems and networks (Shahmoradi-Moghadam and Schönberger, 2021).

Nonetheless, real-world supply chains are complex, interconnected multi-tier systems, in which pairwise relationships exist between the production steps of each tier. To tackle those issues, we propose the concept of hyperconnected mobile supply chains. It can be understood as a multi-party open hub network where each actor can deploy its hyperconnected plug-and-play modular mobile production units. Leveraging the Physical Internet concepts of hyperconnected transportation, open network, resource sharing, and hyperconnected production, hyperconnected mobile supply chains are designed to ensure flexible, agile, and robust operations, facilitating optimal information sharing between each tier and ultimately benefiting both customers and supply chains.

Compared to integrated supply chains - where each stakeholder has its own supply chain - or collaborative supply chains - where stakeholders try to establish strategic alliances - in hyperconnected mobile supply chains, alliances between stakeholders are not required to share resources or information, as the open network is composed by certified open facilities that can host any containerized production module and be used by any current or new certified actor.

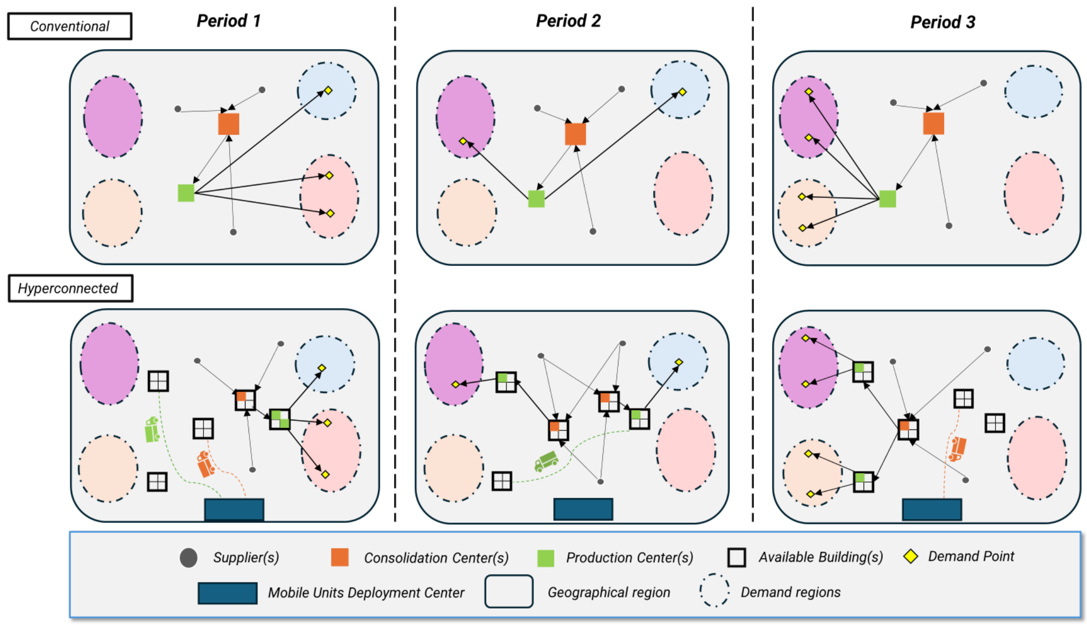

Figure 2 : Comparison between Conventional and Hyperconnected Mobile Supply Chains

Indeed, in a conventional supply chain, a unique (or multiple) fixed facility(ies) for each tier will serve the demand of the different geographical areas. In a hyperconnected mobile supply chain, whenever a demand point appears, if there is already production capacity available nearby, the demand will be assigned to the corresponding facility. If not, then production capacity will be deployed by each tier near the demand point. Such dynamic deployment is feasible thanks to the hyperconnectivity of the mobile production module, which implies that each stakeholder has access to an accurate demand forecast to plan a robust deployment and guarantee a sufficient service level. As illustrated in Figure 2, hyperconnected mobile supply chains aim at reducing delivery distances and enhance ability to capture demand, as capacity can be distributed across the network of open hubs. Thus, finding the optimal pool of open hubs is critical to guarantee the efficiency of the proposed supply chain.

4 Problem description and Methodology

4.1 Problem description

We consider a context where there is a deterministic demand for a given number of products m at period t in a market α. To satisfy this demand, we aim to leverage the hyperconnected multi-tier mobile supply chains network structure, with in our case four tiers. The first tier will consist of all demand points. The second tier will be the hyperconnected production facility network, referred to as tier-1 production, responsible for producing products based on the demand from the first tier and utilizing shipments from the third tier. The third tier will be the hyperconnected consolidation facility network, referred to as tier-2 production, responsible for receiving components from suppliers and consolidating shipments toward the second tier. The fourth and final tier will be the suppliers' network.

In such a multi-tier network, our aim is to determine at the strategic level, for each period t (from the set of periods T), a set of facilities to open from the set of potential facilities L, for how many time periods, as well as their corresponding size and capacity. The last two decisions will be made by assigning the two types of production capacity, tier-1 and tier-2 respectively, to facilities. Another decision will be the volume of products that will be shipped to downstream tiers and the quantity that is asked to upstream tiers.

This set of decisions is made considering that all the demand for a market α for product m during period t is satisfied while respecting capacity constraints at each facility (i.e. the square footage used by the assigned production capacity doesn't exceed the size of the facility). Note that for each tier, the outbound quantity of products needs to satisfy the requirements of the downstream tier.

In our context, we identified two objective functions: minimizing the total cost (operating, opening, and transportation costs) and the environmental footprint of the network.

4.1.1 Economic cost Objective F_1

The first objective function is related to the total cost induced by the network, including the operation cost for a facility of tier 1 and 2 operating at a capacity c during a period t, the opening cost of opening a facility for production of tier 1 or 2 at time t until time t', the transportation cost of product from a facility of tier 1 to market, the transportation cost of products from a facility of tier-2 to a facility of tier 1 and the transportation cost of components from suppliers to tier-2 facility.

4.1.2 GHGs emission Objective F_2

The second objective function is about the GHCs emissions. We considered the emissions of GHGs associated with the tier-1 and tier-2 production at capacity c, the GHCs emissions linked with the transportation of product between a facility with tier-2 production capacity to tier-1 facility, and the GHCs emissions associated with the transportation of product from a facility with tier-1 production to market. As we want to consider GHC emission related to transportation at a strategic level, we considered the average distance between the chosen facility and the market, not optimizing the routing.

The mathematical formulation of our model can be found in Appendix 1.

5 Preliminary results and discussions

To illustrate our concept, we leverage data collected in the context of a research project with a global construction company interested in innovation in the field of Modular Construction. Hyperconnected Mobile Supply Chains is a concept of interest in such a field. Indeed, it implies that modules are produced in factories before being delivered to erection sites, i.e. demand points. Given the strategic level of our decision, we choose a period of one month (t) with a planning horizon of one year.

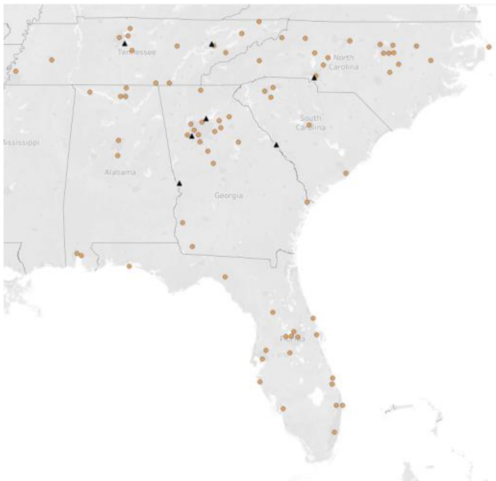

Figure 3 : Set of demand points (orange) and suppliers (black)

For this case study, we considered two scenarios: Traditional Distributed and HMSC. In the former, our network is composed of two tier-1 facilities fulfilled by one tier-2 facility, linked to the closest supplier. All demand points will be served by the closest of the two tier-1 facilities. For the latter scenario, we identified a pool of 142 potential facilities where tier-1 and/or tier-2 production capacities can be deployed near the demand points.

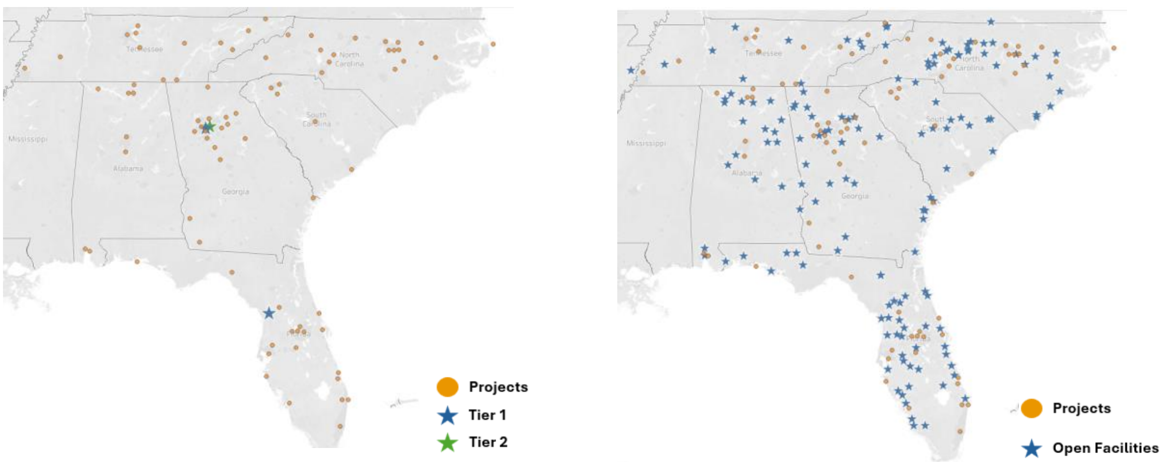

Figure 4: Set of locations for Traditional Distributed (left) and HMSC (right)

In a first attempt, we solved the problem only considering the economic cost objective F_1.

All calculations were performed on an AMD Ryzen 5 5600H (3.3 GHz) with 16GB RAM. The mathematical model was solved by using GUROBI 11.0.0, with an optimality gap set to 3%.

Compared to the base case of Traditional Distributed, we found that HMSC used a maximum of 32 smaller-sized facilities and induced a smaller average traveled distance for each tier of the supply chains, as illustrated in Table 1. This can be explained by the flexibility in terms of locations and capacity levels of HMSC. Indeed, this concept enables the use of multiple smaller -sized facilities closer to demand points, and the dynamic deployment of capacity when needed. The capabilities of the network reflects on the average distance traveled and deployed capacity for each tier.

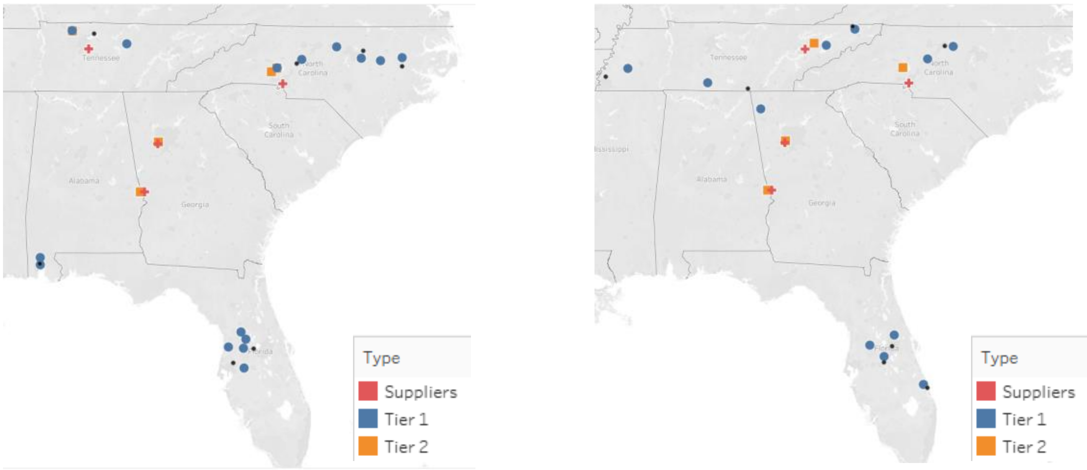

Figure 5: HMSC in Period 8 (left) and Period 9 (right) with projects (black)

Table 1: Summary of Base case vs HMSC computations

	Scenario		Improvement
	Base	HMSC	
Avg. Distance Travelled Tier 1 (miles)	172	51.2	70,2%
Avg. Distance Travelled Tier 2 (miles)	244.8	155.6	36,4%
Avg. Distance Travelled Suppliers (miles)	47,8	19,2	59,9%
Average Deployed Capacity Tier 1 (unit/day)	27	2,3	91,2%
Average Deployed Capacity Tier 2 (unit/day)	21	6,5	69%

6 Conclusion

This paper introduces the concept of hyperconnected mobile supply chains, leveraging the full potential of the Physical Internet within the framework of multi-tier supply chains. We have laid the groundwork by developing an initial bi-objective mixed integer programming formulation for the strategic network design of a hyperconnected mobile supply chain, considering both financial cost and environmental impact.

While our preliminary study only considered the economic objective, it was an important first step in demonstrating that the concept of hyperconnected mobile supply chains, leveraging an open network and distributed logistics, has a powerful impact on the flexibility, agility, and cost of multi-tier supply chains. Our future research involves evaluating the output from the proposed model using tactical planning models, studying potential interactions and feedback between the two levels, and developing the bi-objective version of the model.

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Appendix 1

Indices:

- α: Market
- m : Module
- l : Location
- t : Period
- i : Tier in network, $i \in [\![1,2]\!]$
- p : Type of truck

Mathematical Sets:

- D_{mt} : Set of demand of module m in market α at period t
- M : Set of Products m
- R:Set of components required for kit k
- L : Set of Locations l
- C^i: Set of capacity for module of tier i, $i \in [\![1,2]\!]$
- T : Set of Periods
- S: Set of suppliers

Parameters:

- a_i : Area required for a production module of Tier i
- A_l: Available area at location l
- $C_{l,c}^{opex}$: Operating cost of capacity level c for facility l
- $C_{l,c}^{open\ tier\ i}$: Opening cost of capacity level c for Tier i at facility l
- $\bar{C}_{m,l,\alpha}$: Transportation cost to ship a module m from facility l to market α
- $\bar{C}_{k,l,l'}$: Transportation cost to ship a module kit k from facility l to facility l'
- $\bar{C}_{s,l}$: Cost of transporting a component between supplier s and facility l
- c_p^{truck}: Capacity of truck type p for transporting modules
- e_p: Carbon emissions for a truck type p used for module kits
- $E_{l,c}^{opex\ i}$: Carbon emissions for operating a module of Tier i at facility l
- $ds_{l,\alpha}$: Distance between location l and market α
- $ds_{l1,l2}$: Distance between facility $l1$ and facility $l2$
- $ds_{s,l}$: Distance between supplier s and facility l :
- $\lambda_{r,k}$: quantity of component r used for kit k
- $\theta_{k,m}$: quantity of kit k used for module m
- $d_{m,\alpha,t}$: Demand of module m in market α at period t
- ρ_i: Production capacity of a production module of Tier i
- $Z_{r,s,k}$: Quantity of component r supply from supplier s shipped for kit k
- w_c^i : Corresponding capacity level for module of tier i (range 2 to 16)

Decisions variables:

- $X_{l,c,t}^i$: binary variable equals to 1 if facility l has a capacity c for tier i at period t.
- $Y_{l,c,t,t'}^i$: binary variable equals to 1 if facility l is activated for tier i at max capacity c during period t to t'.
- $F_{m,l,\alpha,t}$: Quantity of module m shipped from facility l to serve market α at period t
- $V_{k,l,l',t}$: Quantity of kit k shipped from fracility l to serve facility l' at period t
- $Z_{r,s,l,t}$: Quantity of component r shipped from supplier s to facility l at period t
- $N_{l,\alpha,t}^1$: Number of trucks of Tier 1 leaving facility l for market α at period t
- $N_{l,l',t}^2$: Number of trucks of Tier 2 leaving facility l for facility l' at period t
- $N_{s,l,t}^{supplier}$: Number of trucks for components leaving supplier s for facility l at period t

Objective functions:

$$F_1 = \sum_T \sum_L \sum_C C_{l,c}^{opex} X_{l,c,t}^1 + \sum_T \sum_L \sum_C C_{l,c}^{opex} X_{l,c,t}^2 + \sum_{(t,t')\in T} \sum_L \sum_C C_{l,c}^{open\ type\ 1} Y_{l,c,t,t'}^1 + \sum_{(t,t')\in T} \sum_L \sum_C C_{l,c}^{open\ type\ 2} Y_{l,c,t,t'}^2 + \sum_T \sum_M \sum_L \sum_D \overline{C}_{m,l,\alpha} N_{l,t}^1 + \sum_T \sum_K \sum_L \overline{C}_{k,l,l'} N_{l,t}^2 + \sum_T \sum_S \sum_L \overline{C}_{s,l} N_{s,l,t}^{supplier}$$

$$F_2 = \sum_T \sum_L \sum_C E_{l,c}^{opex\ 1} X_{l,c,t}^1 + \sum_T \sum_L \sum_C E_{l,c}^{opex\ 2} X_{l,c,t}^2 + \sum_T \sum_D \sum_L \sum_M ds_{l,\alpha} * e_{type1}^{transport} * N_{l,t}^1 + \sum_T \sum_K \sum_L ds_{l,l'} * e_2 * N_{l,t}^2 + \sum_T \sum_S \sum_L ds_{s,l} * e_1 * N_{s,l,t}^{supplier}$$

Mathematical model:

$$Min\ F(x) = \left(F_1(x), F_2(x)\right)$$

s.t

$\sum_L V_{k,l,l',t} \geq \sum_\alpha \theta_{k,m} F_{m,\alpha,l',t}\ ;\forall\ l', m, k, t$ (1)

$\sum_S Z_{r,s,l,t} \geq \sum_K \sum_L \lambda_{r,k} V_{k,l,l',t}\ ;\forall r, l, t$ (2)

$\sum_l F_{m,\alpha,l,t} = d_{m,\alpha,t}; \forall m, \alpha, t$ (3)

$\left(\frac{w_c^2 X_{l,c,t}^2}{\rho_2} * a_2 + \frac{w_c^1 X_{l,c,t}^1}{\rho_1} * a_1\right) \leq A_l\ ;\forall\ l, t$ (4)

$N_{l,\alpha,t}^1 \geq \frac{\sum_m F_{m,\alpha,l,t}}{c_1^{truck}}\ ;\forall l, \alpha, t$ (5)

$N_{l,l',t}^2 \geq \frac{\sum_k V_{k,l,l',t}}{c_2^{truck}}\ ;\ \forall l, l', t$ (6)

$N_{s,l,t}^{supplier} \geq \frac{\sum_r Z_{r,s,l,t}}{c_2^{truck}}\ ;\ \forall s, l, t$ (7)

$\sum_K \sum_{l'} V_{k,l,l',t} \leq \sum_C \sum_K \sum_M \theta_{k,m} w_c^2 X_{l,c,t}^2\ ;\ \forall l, t$ (8)

$\sum_{m,\alpha} F_{m,\alpha,l,t} \leq \sum_C w_c^1 X_{l,c,t}^1\ ;\ \forall l, t$ (9)

$\sum_L \sum_C X_{l,c,t}^i \leq 1\ ;\forall t, i$ (10)

$X_{l,c,t}^i \leq \sum_{\tau=1}^{t} \sum_{\epsilon=t}^{T} Y_{l,c,\tau,\epsilon}^i;\ \forall l, c, t, i$ (11)

$\frac{c}{2} * a_1 * Y_{l,c,\tau,\epsilon}^i \leq A_l\ ;\forall l, i, c, \tau \in [1, t], \epsilon\ \in [t, \mathrm{T}]$ (12)

$\mathbb{X}, \mathbb{Y}\ \in \{0,1\}$ (13)

$N_{l,t}^i \in\ \mathbb{Z}_+\ ;\ \forall l, t, i$ (14)

$N_{s,l,t}^{supplier} \in\ \mathbb{Z}_+\ ;\ \forall s, l, t$ (15)

$V_{k,l,l',t} \in\ \mathbb{Z}_+\ ;\ \forall k, l, l', t$ (16)

$F_{m,l,\alpha,t} \in\ \mathbb{Z}_+\ ;\ \forall m, l, \alpha, t$ (17)

$Z_{r,s,l,t} \in\ \mathbb{Z}_+\ ;\ \forall r, s, l, t$ (18)

Constraints (1) and (2) ensure that tiers 1 and 2 receive enough products for production. Constraint (3) ensures that all the demand is satisfied. Constraint (4) ensures that the square footage of the assigned production capacity doesn't exceed the size of the facility. Constraints (5), (6) and (7) compute the number of trucks required between each tier. Constraints (8) and (9) ensure that we assign production only to open facilities. Constraints (10) ensure that each facility is open at one capacity level at each period. Constraints (11) ensure that a production capacity is assigned to a facility during a period only if the facility is open at this period. Constraints (12) ensure that the maximum capacity at which a facility is opened during a time interval doesn't exceed the size of the facility. Constraints (13) ensure that $\mathbb{X}, \mathbb{Y}$ are binary variables. Constraints (14) to (18) ensure that the other decision variables are integers.

A framework for risk assessment of ammonia storage and bunkering at ports

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Abstract: Ammonia stands out as a promising option for maritime fuel, offering the potential to reduce greenhouse gas emissions. However, its adoption comes with inherent risks, including: toxicity, flammability, corrosiveness, and odor. As the maritime industry is in the initial stages of the exploration of using ammonia as fuel, it is imperative to acknowledge and address these risks. This work focuses on the acknowledging port authority and terminal operators, whose responsibilities are a safe and efficient facilities construction and inter terminal fuel transportations. This profound risk assessment should be conducted in advance to identify risks alongside with potential consequences. In this article, we provide a risk assessment framework consisting of qualitative and quantitative assessment tools. This framework can facilitate the responsible integration of ammonia as a maritime fuel at the port level. In particular, it can provide the port authorities with meaningful guidance for the prevention and risk mitigation strategies for ammonia storage and bunkering to the vessels. This work aligns with the concept of physical internet nodes, as it illustrates how an emerging application such as alternative fuel is embedded and integrated into a connected multi-machine system like inter-terminal logistics

Keywords: *Physical Internet Port, Ammonia, Risk assessment Framework, Bow tie diagram, Bayesian network*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan:* ☒ *PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories),* ☐ *Transportation Equipment,* ☐ *PI Networks,* ☐ *System of Logistics Networks,* ☐ *Vertical Supply Consolidation,* ☐ *Horizontal Supply Chain Alignment,* ☐ *Logistics/Commercial Data Platform,* ☐ *Access and Adoption,* ☐ *Governance.*

Targeted Delivery Mode-s*:* ☒ *Paper,* ☐ *Poster,* ☐ *Flash Video,* ☒ *In-Person presentation*

1 Introduction

New energy is currently seen as one of the most important measures to reduce the negative impact of transportation to the environment. Ammonia has caught significant attention due to its carbon-free composition and relatively higher energy density compared to liquefied hydrogen. At the same time, ammonia has its own hazardous characters of corrosive, toxic and odor. Compared to conventional fossil fuel, ammonia storage and bunkering is associated with possible risks related to cryogenic liquid/high-pressure liquid transfer and vapor return. This risks are hurdles and challenges in the adoption of ammonia as a maritime fuel.

To be technically ready to use ammonia as a maritime fuel, the port authorities should preliminary be aware of the operation procedures. Ammonia operation procedures at the port area mainly relates to three processes: storage, bunkering process, and the inter-terminal logistics among different locations. Bunkering is the process of transferring fuel from a supplier or storage to the fuel receiving ship. These three processes can be similar to conventional fuel, but variations arise in the extra effort to liquification and its hazardous characteristics. By recognizing these similarities and differences, port authorities can accordingly plan the infrastructures constructions and equipment purchase. Taking into account the lead time of infrastructure construction, these activities should be conducted in the early stages. Meanwhile the bunkering and inter terminal logistics operations should be regulated in advance before the real application.

This integration of safety handling into a hyperconnected network mirrors the principles of the physical internet, emphasizing the efficient flow of goods and information across interconnected nodes (Ballot and Fontane, 2008, Montreui 2011).

These hazardous characteristics and corresponding risks can be understood, prevented or mitigated accordingly. The ammonia-related risks have been studied in existing literature from different angles, e.g. from the perspective of historical accidents analysis (Duong et al. 2023, Machaj et al. 2022), from experimentation at lab, or from simulation via specific software(Ng et al. 2023). However, the acknowledgement of the risky characteristics remains insufficient since the data of ammonia pertains as agriculture fertilizer or small-scale simulations are adopted. The transshipment of ammonia as freight (fertilizer) and its usage as a maritime fuel requires vastly different location distributions inside the port and time requirements. This leads to consider the question: How can these risk studies inform the planning of infrastructure construction and inter terminal fuel logistics to ensure safety storage and bunkering? The interpretation is the indispensable link in between. However, The risk assessment from the view point of inter terminal logistics side is still an open field. Both industry and academic are at the beginning stages of using ammonia as fuel.

This work provides a risk assessment framework of ammonia as a fuel, aiming to offer decision support to port authorities in the strategical planning and terminal operators in the operational regulations. The framework consists of two perspectives: qualitative and quantitative. The qualitative risk assessment aims to draw efficient and direct conclusions based on qualitative characteristics such as descriptions, categories, and expert judgments. On the other hand, the quantitative assessment further involves the objective measurements and risk analysis using numerical data and mathematical models to estimate probabilities, consequences, potential impacts of prevention and mitigation events.

The contributions of this work are as follows. First, in section 2, we summarize the facilities and inter terminal logistics to be conducted at the port for using ammonia as a maritime fuel. The corresponding risks are intensively studied via literature, historical documentations and some industry regulations, which are interpreted from the logistics viewpoint. We also highlight the necessity of a comprehensive risk assessment to interpret the chemistry characteristics to port infrastructure planning and logistics management. Second, we develop a risk assessment framework based on the previous analysis in Section 3. The assessment methodology resorts to both qualitative and quantitative assessments utilizing Bow tie diagrams and Bayesian networks. This article concludes with a summary and outlook in section 4.

2 Ammonia operations and associated risks

In this section, we first describe the ammonia operations at the terminals, which includes the storage, bunkering and transshipment in between. Next, we review the ammonia hazardous characteristics, and discuss possible risks in the described operations. We compare and highlight distinctions from the inter terminal logistics of conventional combustion fuel. Lastly, we identify research gaps and lay the foundation of what to expect from the risk assessment framework.

2.1. Ammonia storage, bunkering and the transshipment

This subsection reviews the operations of ammonia at the port area. The processing encompasses various stages, including the receiving, storage, fuelling, and internal transportation within the terminal, as described in Figure 1. We concentrate on the utilization of ammonia as a fuel, thus omitting the cracking related operations.

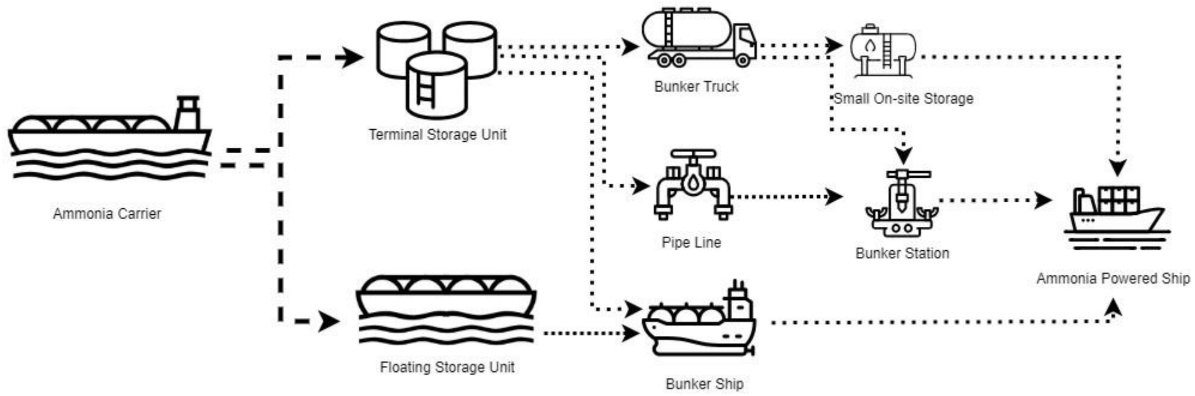

Figure 1: The ammonia flow inside the port, resource the authors

To make efficient usage of ammonia, it is generally compressed into liquid phase, relying on refrigeration (-33 ◦C) or pressurisation (around 10 bar pressure). In most literature (Duong et al. (2023), Machaj et al. (2022), Yang and Lam (2023)) and some industry reports (MAGPIE (2023), Global Centre for Maritime Decarbonisation (2023)) the refrigeration is more economic efficient and currently chosen in Port of Singapore and Port of Rotterdam.

Before diving into the detailed description, it is important to establish some definitions that will be frequently used. There are three primary types of ships involved in the ammonia operations at port: ammonia carrier vessels, ammonia powered ships, and ammonia bunker ships. Figure 1 depicts these three ships. Ammonia is usually not produced at the port but carried to the port by **carrier vessels**. These already exist since ammonia has been widely used as fertilizer for a long time (Machaj et al. (2022)). The ammonia powered ship are those that use ammonia as fuel resource. Bunker ships transfer the ammonia from the storage place to the ammonia powered ship. Presently, there are only a few bunker ships and ammonia powered ships operating in Singapore (Duong et al. (2023), Global Centre for Maritime Decarbonisation (2023)) .

Upon the carrier vessel's arrival at the port, the ammonia will be off loaded and stored, for the next step utility. There are two types of large scale storage: **terminal storage unit** at land side and **floating storage unit** offshore. Besides, there will also be a **small on-site storage unit**, which typically is in the form of bullet tanks.

Ammonia bunkering for commercial purposes contains various methods, including ship-to-ship, truck-to-ship (Duong et al. (2023), Yang and Lam (2023)) and pipe to shipe. **Ship-to-ship** bunkering was the most commonly employed method of delivering marine fuels to ships (Yang and Lam (2023)). Calderon et al. (2016) evaluated the ship-to-ship bunkering as an attractive LNG bunkering solution. The reason was four folded: (1) no expensive infrastructure; (2) bunker ships offer high flexibility; (3) high utilisation rates from the flexibility; (4) ships to be fuelled were often hard to manoeuvre, the bunker ships could improve efficiency by supplying the bunker fuel. This provides referential value to the ammonia bunkering.

Truck-to-ship bunkering is conducted by trucks carrying the ammonia storage tank. As pointed out by Global Centre for Maritime Decarbonisation (2023), this required road access to the berth, and vehicle access near the storage tank area. Leveraging existing ammonia tanks and supporting infrastructure could reduce the impact on the current operations and development costs.

The ammonia **pipeline transportation** is via carbon steel pipelines about 0.15-0.25 m diameter and with a pressures of around 17 bar (Papavinasam (2014)). According to Fertilizers EU (2013), the ammonia pipeline has been operating for decades for the agricultural fertilizer in America. In Europe only short pipeline systems were in operational at that time, the largest being 74km in Italy. According to a simulation result of Schotman (2023), pipe to ship indicates a higher bunkering efficiency and a lower operating cost in medium and large sized port.

Summarizing, facilities for storage and bunkering can take different combined forms. The most suitable solution depends on port storage and bunkering demand and site-specific factors. The size and amount of large storage units should be calibrated to ensure sufficient inventory for the bunkering and cracking demand. The flexible storage are strategically located nearby the bunker site to ensure a short bunker time. bunkering facilities should meet the volume of fuel demand, being accessible at the chosen bunkering methods, and fitting into existing infrastructures. The site of storage and bunkering are the originals and destinations of inter terminal fuel transportations, the distance among which directly affects the operating time and cost. Meanwhile their sites selection can be restricted to land availability and hazardous exclusion zones.

2.2. Ammonia Risks

Ammonia is characterized by flammability (Park et al. (2023)), toxicity (Duong et al. (2023), Ng et al. (2023), Park et al. (2023)), corrosiveness (Duong et al. (2023)), and odor (Machaj et al. (2022), Park et al. (2023)), making safety a challenge. To address these risk, we provide an review of the corresponding literature, industry reports and regularities.

Ammonia does not burn readily thanks to its narrow **flammability** range, high ignition temperature and low laminar burning velocity. The risk of an ammonia fire is lower compared to other fuels. The **corrosive** effect of ammonia is due to possible reaction with water and form ammonium hydroxide. It can cause damage to various materials, such as metals, plastics, and rubber. Corrosivity can be avoided by cautious handling and appropriate precautions to prevent materials' exposure. This includes proper storage and handling procedures, as well as the use of protective coatings and materials that are resistant to alkaline substances.

Toxicity was regarded as the greatest risk for liquid ammonia storage (Yang et al (2023), Zhang et al. (2023)) and bunkering (Ng et al. (2023), Yang and Lam (2023), Fan et al. (2022)). In this regard, special safety precautions are necessary to prevent **leakage** and subsequent **dispersion**. Ng et al. (2023) simulated how key operational parameters affect ammonia dispersion. Yang and Lam (2023) also studied the environmental impacts of ammonia bunkering. The effects of large spills of ammonia on people and ecosystems are still relatively unknown and based on limited case studies.

There are several risk prevention and mitigation methods against the leakage during the storage and bunkering process. Those methods involve **double-walled storage** tanks, implementing a **safe zone,** and completing **safety regulations** for the storage and bunkering. Ammonia in large quantities is refrigerated in cylindrical double-walled storage tanks (Ikaheimo et al. (2018)). Ng et al. (2023) stated that it was the safest to store ammonia fuel in fully-refrigerated tanks as an atmospheric pressure saturated liquid. Figure 2 shows a typical storage tank. Recommendations of Duong et al. (2023) based on a review of a number of research papers, emphasized the importance of regulations and guidelines, setting a **safety zone,** and completing **safety regulations**. The safety zone during the ammonia bunkering process refers to the designated area surrounding the bunkering operation, with restricted access and the implementation of the necessary safety measures. These observations indicate that the safety zone is not a static concept, rather, it may need to be adjusted based on changing circumstances or the ongoing risk assessments. Similarly, Ng et al. (2023) suggested no simultaneous operations such as inspection or maintenance while bunkering. This separation from time dimension blocks human access and other activities. The authors also suggested the bunkering heights would be lower than 5 meters, and should consider the wind direction to prevent a serious dispersion.

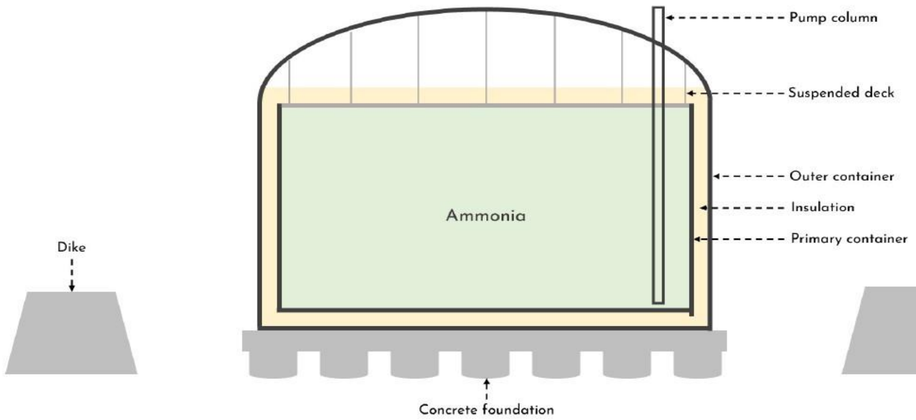

Figure 2: Double walled ammonia storage and safety zone surrounded by dike

As for the bunkering time, there is currently no revealed data yet regarding the real bunkering time duration, but it can be estimated based on similarities. Machaj et al. (2022) reviewed characteristic of ammonia and similarities, which led to a solution that LNG storage tanks and bunkering had great potential for ammonia storage. The simulation of Schotman (2023) also cited the LNG bunkering time duration from Park and Park (2019) and EMSA(2017).

The risks study should be used in the layout design of bunkering facilities, berth allocation and bunkering schedule planning. Certain safety measures can lead to higher construction cost (e.g., double wall storage tank and safety zone around), or higher operating cost (e.g., personnel training) or longer operating cost (e.g., no simultaneous operations, specific bunkering location). An inadequate guidance may compromise safety in construction and logistics operations, but an over-conservative safety measures could result in unnecessary higher costs and longer operating time. A balance between safety handling and efficient inter terminal logistics is vital for the ammonia transition.

2.3. Research gaps

The adoption of ammonia as a maritime fuel is challenging due to it hazard risks and safety concerns. The current applications are in the initial stages, and are predominantly led by the industry, primarily through pilot or demonstration scales at limited ports. There are several European commission projects are pushing the border of ammonia application, such as MAGPIE(Smart Green Port). The natural next steps are the upscaling of the usage volume or replication from one port to other ports. These technology solutions provide valuable insights, which necessitates case analysis, and requires summarizing the lessons learned.

Regarding the risks and safety operations, most data on risk analysis originate directly or secondarily from various sources. These include simulation results, international databases such as websites, regional standards by industry companies, and reports from ammonia or LNG-related organizations (DNV GL Group, the Port of Rotterdam, the Port of Singapore). This data leans towards the chemistry side instead of guidance to port authorities or terminal operators. Therefore, comprehensive interpretation is essential to ensure its understanding and application by port planners and operators. Beyond safety considerations, the port stakeholders also concern investment costs, operating cost, operating capacity and efficiency.

The ammonia transition at ports entails an involved cycle of interpretation, trial and calibration. Risk assessment can guide the ammonia storage site selection, and storage and bunkering infrastructures construction, material choices and others. This must be planned well in advance due to the construction lead time. Furthermore, risks assessment affect the operational processes, such as the berth allocation to those ammonia-powered ships, scheduling of ammonia bunkering activities, and other related tasks. Additionally, port authority should be full aware on the kind of accidents that can occur, in which part of the operations these may take place, understand it consequences in terms of related losses in subsequent stages. Last but not least, what effective actions can be undertaken to prevent or mitigate these risks. This demands a dynamic closed-loop assessment instead of a static approach. Based on these four interpretation requirements, we propose a risk assessment framework regarding the ammonia usage as a marine fuel, i.e., the storage and bunkering at the port.

3 Risk Assessment Methodology

The risk assessment and its methodology are not new, whose forming as a scientific field can be tracked back to 1970s (Aven , 2016). But content-wise it is to our knowledge not yet explored regarding the ammonia as a maritime fuel. The assessment methods have a big impact to the assessment results, the level of details to the decision support (Abbasi Kharajou et al. (2024)). The focus of this work is on overall framework construction and the choice of proper assessment methods therein, instead of developing new assessment method. In the following we briefly describe the chosen risk assessment in this work together with the choice reasons.

3.1. The assessment framework

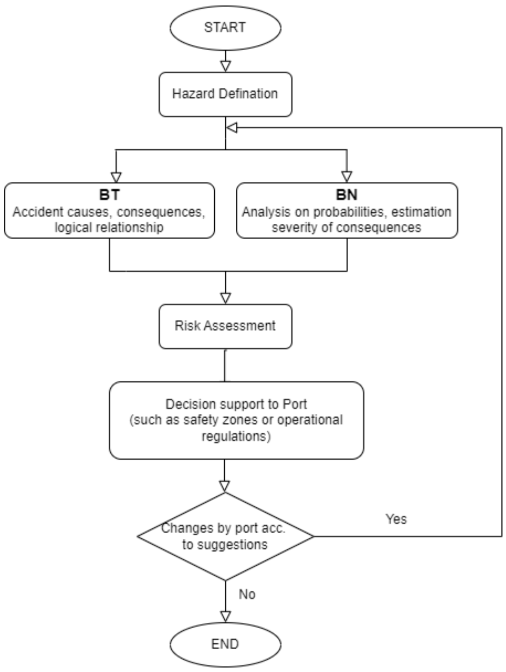

Figure 3 the proposed risk assessment framework, by authors

Based on the described gaps and the fundamental objectives in section 2, we build the risk assessment framework, as described in Figure 3. There are two approaches, qualitative and quantitative assessment. The qualitative approach usually concerns subjective evaluation to draw rough, but quick, conclusions. The quantitative assessment, on the other hand, resorts to numerical data and mathematical models to estimate probabilities and consequences. We choose the Bow Tie (BT) Diagram and Bayesian Network (BN) as the qualitative and quantitative assess tools, respectively.

To selection of the assessment tools lies in the assessment goal and methods themselves. The Bow Tie diagram offers a direct cause-effect visual expression that facilitates effective communication with the audience, whereas the Bayesian network provides a quantitative insight into the causality of the events. Moreover, Bayesian network allows for updating the event probabilities after the prevention or mitigation measures have been implemented. This is important for the cost benefit analysis of the prevention and mitigation. The BT and BN are described briefly in the following subsections.

3.2. Bow Tie diagram

BT is a graphical tool that illustrates an accident scenario, starting from accident causes and ending with its consequences (Khakzad et al. (2012)). Figure 4 presents the structure of the BT. It is centred around a critical event, which is connected by Fault tree on the left-hand side, and event tree on the right. The Fault Tree (FT) describes the top event influenced by risk factors. The Event Tree (ET) identifies its consequences. Safety Barriers in the FT act as the prevention mechanisms that reduce the probabilities of an accident. Furthermore, the Safety Barrier in the ET is the control process after the accident that aims to lower the impacts of the consequences of accidents (de Ruijter and Guldenmund (2016)).

3.3. Bayesian Network

Similar to BT, Bayesian Network (BN) method has been widely used in risk and safety analysis based on probabilistic and uncertain knowledge. BN is composed of two parts: graphical structure in the form of a Directed Acyclic Graph (DAG), and probabilistic structure in the form of conditional probability tables (CPT). Figure 5 shows a general DAG. The nodes represent the cause (node A and node H in Figure 5) and corresponding consequences (nodes D, F, G in Figure 5) of a chain event. Arcs between nodes signify direct causal relationships between the linked nodes, this is one important reason for choosing BN as the assessment tool.

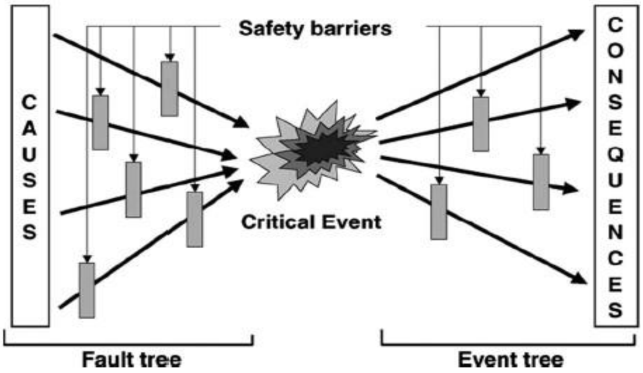

Figure 4: Generic example of a Bow Tie, taken from de Dianous and Fievez (2006).

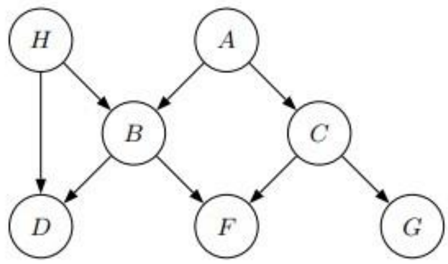

Figure 5: Generic example of a Directed Acyclic Graph by Bayesian Network, taken from Jensen and Nielsen (2007).

The quantitative contribution of BN originates from the probabilistic structure. It consists of two parts: (i) *prior probabilities* indicating the probability value of a certain basic node; and (ii) *conditional probabilities* predicting the probability value of one event based on the condition of another event. The prior probabilities can be obtained from historical accidents, failure records, or via an intensive literature collection. Furthermore, the conditional probabilistic can be calculated and expressed in *Conditional Probability Tables* (CPTs). This is the second reason for choosing BN is its advantages in checking the effectivity of preventing regularity or mitigating an event. This is referred to as the Roots to Bayes theorem. Given the information of prevention or mitigation information, BN re-evaluates from the original failure probabilistic (prior occurrence) to the reduced probabilistic or relieved accidents (posteriors).

3.3. BT and BN application to ammonia risk assessment

Using BT and BN, we describe the leakage or release of ammonia and the possible results during the bunkering process, see Figures 6 and 7. The consequence described in these Figures are based on the dispersion simulations of Ng et al. (2023).

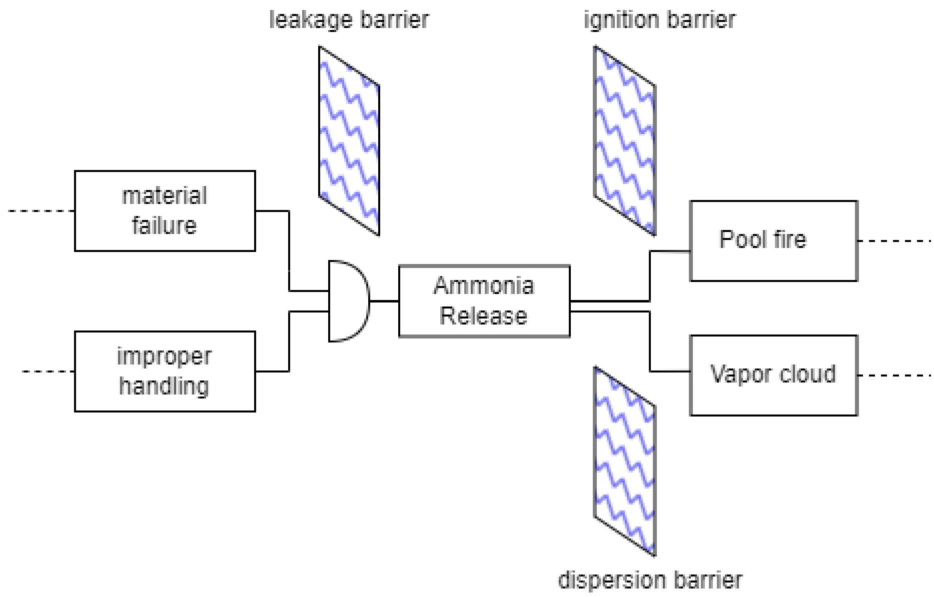

Figure 6: A bow tie description of ammonia leakage and possible results, resource: authors

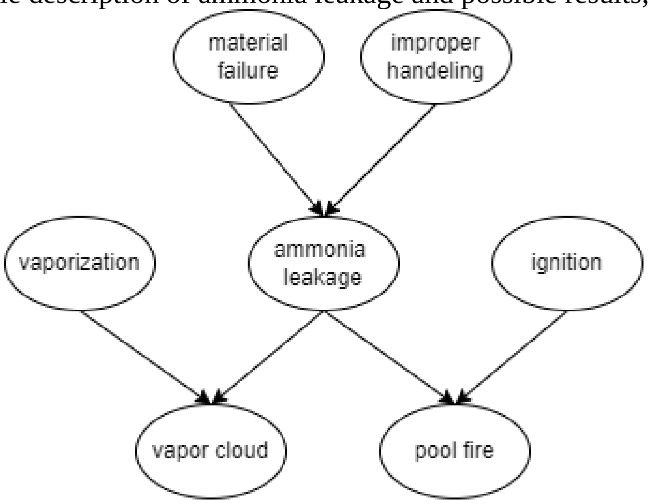

Figure 7: A Bayesian network description of ammonia leakage and possible results, the probabilistic information to be added from the next step, resource: authors

The next step is to design an interview or focus group in order to get input from chemical experts and Port of Rotterdam. Afterwards, the input (linguistic terms) will be converted to failure possibilities (numeric format). This can be achieving via methods such as linear opinion pool or max-min Delphi. On the other hand, the output, for example the suggested safety zones or regularities, will be validated with simulations, and calibrated by the port.

Hereby we answer the question regarding the safety consideration of site selection, which is mentioned at the end of section 2.1. The sites for storage tanks and bunkering berths can be firstly screened using the Bow Tie based on a set of safety requirements and expert opinions. Secondly, the sites will be evaluated by Bayesian Network to rank potential sites based on the probabilities together with the risk and mitigation costs. In the end, the port authorities and terminal operators will be aligned to verify the suitability of the sites.

4 Summary and outlook

The maritime industry is preparing itself to adopt new energy to realize its decarbonization goal. This work comprehensively reviews the ammonia storage and bunkering operations at the port, and provides a risk analysis of using ammonia as a fuel. Through this analysis, we identify research gaps that show the importance that the port should understand of ammonia risks, and should implement measures to prevent and mitigate possible risks in the infrastructure planning and daily operations.

Building on these findings, we propose a risk assessment framework aiming at interpreting the hazardous characteristics guided by safety protocols. The risk assessment consists of both a qualitative and quantitative assessment. Based on the assessment goal and available information, we select Bow Tie diagram and Bayesian network as assessment tools.

We note here, this is an ongoing work, the next step is to get input experts of both academic and industry. The experts opinion will be quantified and further used as input into the assess framework. The goal of this risk assessment framework aims to interoperate the risks into the regulations in port operations. The assessment output aims to provide the port authorities a clear overview of the different levels of risk, the corresponding probabilities the possible results and to what extend the regulations can avoid or mitigate the risk, together with the corresponding effects on the bunkering costs and time.

In the future, the proposed assessment will undergo calibration with the aid of industrial partners and chemical enterprises. The framework proposed in this study expands to other new sources of energy by examining the associated hazard characteristics.

Acknowledgements

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Dynamic Containerized Modular Capacity Planning and Resource Allocation in Hyperconnected Supply Chain Ecosystems

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Abstract: *With the growth of data-driven services and expansion of mobile application usage, traditional methods of capacity and resource planning methods may not be efficient and often fall short in meeting rapid changes in the business landscape. Motivated by modularity, containerization, and open sharing concepts from Physical Internet (PI), this paper proposes an effective approach to determine facility capacity and production schedule to meet current and future demands by dynamically allocating Mobile Production Containers (MPCs). In this work, we develop an iterative two-stage decision making model with dynamic rolling horizon approach. The first stage is capacity planning stage, where the model determines key decisions such as project selection, facility opening periods and project-facility assignment. The second stage is resource planning stage, where the MPC allocation and relocation schedule and weekly production schedule are decided. To validate the proposed model, we conduct a case study over a modular construction supply chain focusing on the southeast US region. The results demonstrate our model not only delivers a consistent production schedule with balanced workload but also enhances resource utilization, leading to cost effectiveness.*

Keywords: *Dynamic Facility Network Capacity Planning; Dynamic Resource Allocation and Relocation with Mobile Resources; Mobile Production Containers; Two-stage Decision Making; Physical Internet.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☒ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☒ PI Networks, ☐ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☒ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

Targeted Delivery Mode-s*: ☒ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation*

1 Introduction

According to a report from ABB Motion (2024), resource scarcity is a growing issue for 91% of industrial businesses, leading to increased costs for 37 percent of businesses, as well as supply chain disruption for 27 percent and slowdowns in production capacity for 25 percent. In addition, the COVID-19 pandemic has caused huge shortages in US labor market, which exacerbated the resource scarcity problem. The study by Ferguson (2024) indicates that the pandemic drove more than 3 million adults into early retirement as of October 2021. All of these facts highlight the urgent need to improve resource efficiency across industry, which also becomes key in achieving net zero targets.

[1] The authors contribute equally to this paper.

To address the problems, both industry and academia are exploring solutions to shift the conventional supply chain to a more efficient and sustainable one. In recent years, the sharing economy concept is explored to improve efficiency for modern enterprises by capitalizing on existing resources. Progress has been achieved through the implementation of this approach; however, it represents merely the initial phase, with additional research required to delve into deeper aspects. Under this global logistics challenge, Montreuil (2011) proposed the concept of Physical Internet (PI), aiming to provide an innovative way to facilitate the supply chain by utilizing modularity, containerization, and hyperconnectivity. One of the core ideas of PI is to employ the open cooperative sharing economy, emphasizing that PI infrastructure is accessible to multiple parties rather than exclusively dedicated to a single company or group of companies.

Inspired by modularity, containerization and sharing concepts from PI, we proposed an effective approach to facilitate the resource sharing of the entire supply chain ecosystem by using Mobile Production Containers (MPCs) (illustrated in Figure 1). MPC, a groundbreaking paradigm shift in containerization technology, can be considered as shipping containers with required equipment for facilities in the network, which serve as movable resources with flexibility, scalability, adaptability, and sustainability. By strategically relocating within the facility network and seamlessly integrating with potential production timelines, MPCs optimize resource utilization, facilitate agile response to evolving demands, enhance factory productivity cost-effectively, and dynamically mitigate production workload fluctuations. Additionally, their modular design and intelligent systems empower businesses to build and leverage hyperconnected supply chain ecosystems.

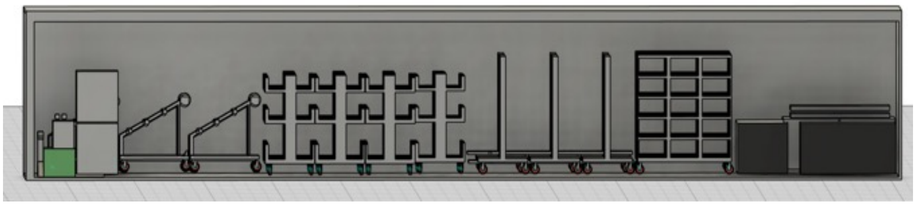


Figure 1: Schematic Diagram for Mobile Production Containers (MPCs)

The potential application scenarios of MPC are extensive. First, MPCs provide an agile solution for facilities facing sudden surges in demand. By swiftly relocate to these facilities, MPCs can seamlessly integrate into production lines, ensuring timely order fulfillment and optimizing resource usage. Additionally, they offer the flexibility to dynamically scale production capacity without requiring significant infrastructure investments. Second, in a globalized manufacturing scenario, MPCs offer multinational companies the ability to quickly adapt production to serve consumers worldwide. By easily deploying MPCs to small manufacturing hubs globally, transportation costs are minimized, carbon emissions decreased, and inventory management streamlined, enhancing overall efficiency. Third, in areas prone to natural disasters like hurricanes, investing in MPCs offers resilience against disruptions. By strategically deploying MPCs to nearby locations unaffected by the storm's path, production downtime is minimized. Moreover, the modular design of MPCs facilitates rapid relocation and setup, ensuring a swift response to disruptions while smoothly reintegrating original factory production processes once the storm passes.

An illustration of the relationship between capacity planning and resource deployment can be seen in Figure 2. With the input information including demand, supply, profit and cost, strategic capacity planning decisions set the maximum potential capacity of the system, while the effective and implemented capacity of the system necessary for valid production planning is determined by tactical decisions with resource deployments. By introducing the MPCs in the networks, capacity can be easily controlled dynamically by MPC allocations and relocations in facilities, taking production scheduling into consideration. This motivates the scope and focus of this research.

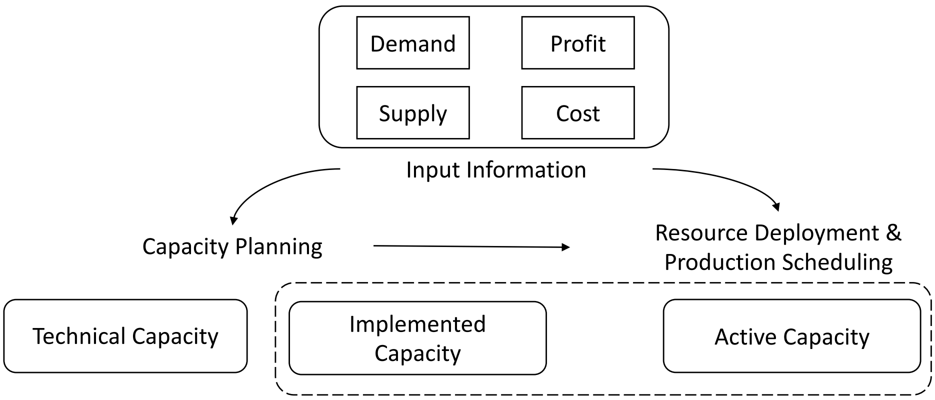


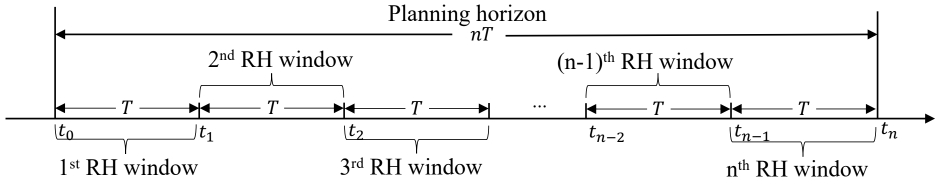
Figure 2: Capacity planning and resource deployment

2 Literature Review

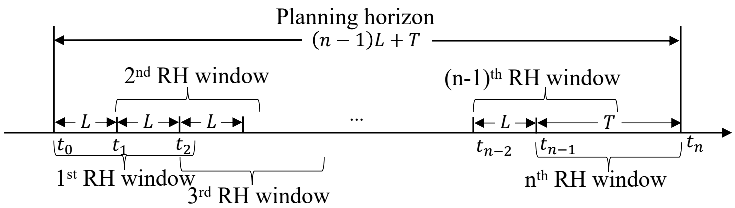
A few work has been done in developing capacity planning models in the field of PI. Faugère et al. (2018, 2022) considered a hyperconnected parcel logistics system where modular smart lockers can be dynamically deployed to PI access hubs for first-mile pickup and last-mile delivery. By using those dynamic access hubs as temporal storage locations, it enables to decrease the total capacity requirements and improve the resource utilization. Moreover, Oger et al. (2021) proposed a decision support system to facilitate the strategic capacity planning more dynamic and adaptable for hyperconnected and uncertain environment. On the other hand, Liu et al. (2023, 2024) studied a dynamic modular capacity planning of logistics hub in hyperconnected relay-based transportation under the uncertainty of demand and geographical disruptions. Inspired by key concepts of modularity and uncertainty from previous works in PI, this paper considers the strategic capacity planning in hyperconnected manufacturing and production industries. By smartly deploying mobile MPCs dynamically over the production network, we can control the production throughput rate and mitigate risks sourced from fluctuate demand and unpredictable disruptions.

Dynamic and customer-oriented resource allocation is steadily expending in the literature. The Physical Internet initiative, introduced in Montreuil (2011), aims to enhance global logistics efficiency and sustainability, provides an opportunity for resource allocations and relocations in hyperconnected networks. For example, Faugère et al. (2022) works on the operations of a two-echelon synchronization problem influenced by both modular capacity reallocation and a capacity pooling recourse mechanism in urban parcel networks. Also, Xu et al. (2022) propose a dynamic workforce deployment system in hyperconnected parcel logistic hubs to match predicted demand with shifts in real-time to respond quickly to demand changes and provide guidance for centralized workforce assignment. A few papers work on the integration of capacity planning and production scheduling at a tactical level. Yao et al. (2022) presents a capacity-based tactical planning model incorporating production decisions for a multiplant multiproduct manufacturing system.

The rolling horizon (RH) approach is based on the idea that decomposing the planning horizon into several shorter, contiguous sub-periods is necessary as solving our problem over the entire horizon at once would be computationally intractable. The initial period or the first few periods for multiperiod problems are typically considered critically important since the forecasts further into the future is less reliable and more expensive, the computational burden also increase with extended planning horizons (S. Chand et al. (2002)). The global optimization model can be relaxed and broken down into multiple local optimal problems and the partial solutions in each sub-problems can be generated and assembled by utilizing this approach. Periodic RH scheduling strategy is illustrated in Figure 3(a), n rolling horizon (RH) windows, each with a planning length of T, are employed for a problem with a planning horizon of nT. The choice of the time window (T) impacts both computation efficiency and global performance. Smaller T reduces computation but sacrifices global information, potentially lowering performance (Yuan, P. et al (2018)). As illustrated in Figure 3(b), a planning horizon of $(n-1)L+T$ is decomposed into n RH windows with planning length of T and the rescheduling period L. The main difference between the two strategies is that there are overlaps between RH windows and decisions made within a RH window can be selected or be released for rescheduling in the following horizons with a certain frequency. The choice of how often to reschedule operations is important and depends on the arrival predictions and the computational costs.



(a). Periodic RH scheduling.



(b). Periodic RH rescheduling with selection-and-releasement.

Figure 3: An illustration of rolling horizon (RH) strategies.

3 Problem Description

In this paper, we focus on facility network capacity planning and resource allocation using MPCs. The goal of this work is to maximize the overall profit of the supply chain ecosystem by utilizing facility resources efficiently and building consistent weekly production schedules under stochastic demands. During the capacity planning stage, monthly strategic decisions involve selecting projects for each planning period, identifying new facility locations and their opening schedules, allocating accepted projects to specific facilities, and estimating the required number of MPCs to accommodate the progressive business growth. During the resource allocation stage, weekly tactical decisions involve establishing the MPC management schedule, which includes renting new MPCs, returning or relocating underutilized MPCs based on changing demand, and finalizing the production plan with smooth throughput rate.

Figure 4 illustrates the relationship between capacity planning stage and resource allocation stage. The capacity planning stage provides the information, including facility locations and status (e.g., open, close, reopen), facility-project assignment, and MPC number (i.e., capacities) at each facility, to resource allocation stage. Then, based on those provided information, the resource allocation stage will decide the weekly production schedule at each facility and update the MPC number and locations by considering relocation of MPC between multiple facilities. This approach can further reduce the MPC needed and improve the resource utilization. Finally, the unfinished demands at each facility locations and current MPC allocation are transferred back to the capacity planning stage, forming a complete loop structure.

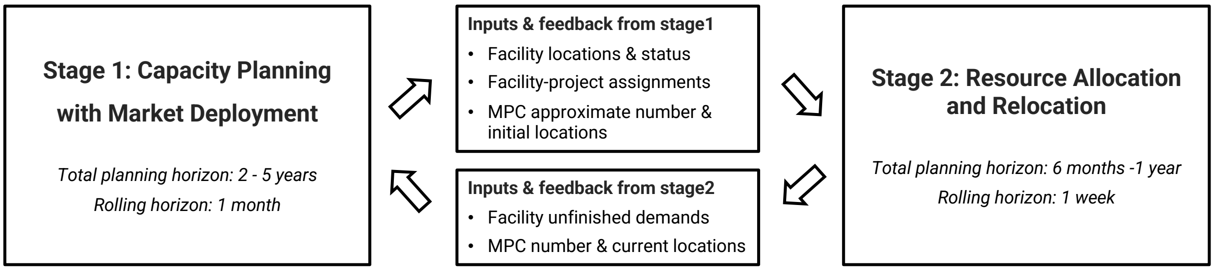


Figure 4: Relationship between Capacity Planning Stage and Resource Allocation Stage

The capacity and resource planning models are designed to operate seamlessly over time illustrated in Figure 5. At the start of each month, we conduct capacity planning with a planning horizon of 2 to 5 years. This enables us to leverage forecast demand to make long-term decisions such as negotiating project contracts, commissioning leased facilities, and preparing required resources. At the beginning of each week, we perform resource planning with a shorter planning horizon of 6 months to 1 year, which is based on the current facility network. The aim of this stage is to allocate and relocate resources, manage inventory storage, and produce weekly production. This iterative approach enables us to capture the evolving landscape of operations, facilitating agile adjustments and optimizations in response to emerging factors, including production disruptions and the emergence of new projects.

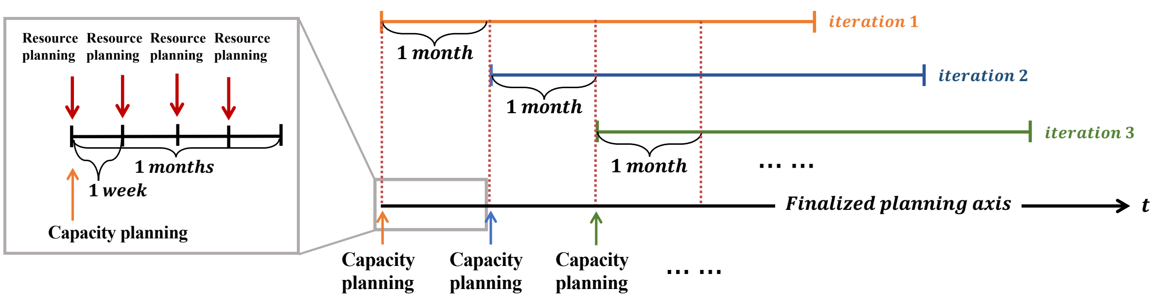


Figure 5: Timeline of the Dynamic Capacity Planning and Resource Allocation Model

4 Methodology

4.1 Capacity Planning

In this paper, we establish the following assumptions for capacity planning model. We remark that all assumptions are constructed based on realistic situations observed in a PI applied research project conducted with a real company.

- One facility can serve multiple projects.
- Each facility should be located within x miles of assigned erection sites (e.g., x=100). If a distance between facility and its assigned erection site is larger than x miles, then there will be a penalty cost based on the extra distance. The magnitude of this penalty serves as an input parameter. By tuning this parameter in line with the realistic factors of the studied case, the model can produce suitable strategies.

- Each facility has a 3-month commitment time. In other word, once a facility is opened, it should remain open for 3 months.
- Facilities can be closed after 3 months of opening based on the changing demand. In addition, each facility can be closed and reopened multiple times through the total planning horizon (i.e., 2-5 years).
- Facilities can expand or reduce its production rate by changing the number of MPCs. Specifically, each facility can lease new MPCs, return or relocate unuse MPCs during each planning period (i.e., 1 month).
- Each facility can have at most k fractals (maximum capacity limit) (e.g., k=8).
- Expand the facility capacity by one unit means leasing an additional fractal. Specifically, one additional fractal increases facility's maximal throughput rate by k (e.g., k = 2).
- One project can be assigned to multiple fractal facilities.
- Full truckload from facilities to erection sites and we do not consider detailed routing decisions in this study.
- The number of accepted projects, new facilities, and open facilities align with managers' strategies during each planning period (all of those can be controlled as input parameters).

Based on the provided assumptions, we develop a mixed-integer programming (MIP) model for the capacity planning stage. This model has four key decision areas: project selection, facility network planning (specifically, new facility acquisition and facility opening periods), project-facility assignment, and MPC leasing schedule. All these decisions are time dependent. The objective function aims to maximize profits within the hyperconnected supply chain ecosystem. The profits are computed as the total revenue from the accepted projects minus various costs, including new facility commissioning costs, open facility rental costs, resource commissioning and decommissioning costs, production costs, and transportation costs.

4.2 Resource Deployments

The dynamic containerized modular deployments in hyperconnected supply chain ecosystem are also modeled in this study. The key decisions involved include the allocation of MPCs to project activities, the scheduling of those activities, and the possible relocations of MPCs. The main assumptions for the problem are as follows:

- Decisions are made at the beginning of each week in the planning horizon.
- With the number of MPCs leased from capacity planning as an input parameter to the model, the addition or return of MPCs can be accomplished within a shorter timeframe with a detailed leasing plan.
- The initial locations of the MPCs are provided, which may either be their current positions or the most recent locations determined by the previous Resource Deployment model utilizing a rolling horizon approach.
- The relocation decisions are made at the beginning of each week.
- MPCs can only be relocated between facilities if the distance between them is within a specified distance limit.
- Transportation costs are calculated based on the shortest routing distance between facilities.
- The target start time, number of demand modules are given for each project.
- Constant erection rate, specified on a project basis, is provided as an input. One project can have one or multiple possible erection rates for consideration.
- According to current estimates, each MPC requires 2 trucks for shipment.
- Weekly production rate per MPC is assumed to remain constant.

The objective of this resource deployments model is to minimize total costs, encompassing module storage costs, production lateness costs, MPC transportation costs, MPC rental commissioning and decommissioning costs.

4.3 Rolling horizons

Faced with dynamic changes of demand, integrated capacity and resource planning is proposed to improve operational efficiency and flexibility utilizing a rolling horizon approach. Denote **CAP**(t, T^l) and **RES**(t, T^s) as two modules (or agents) for capacity planning and resource deployments at time t and with planning horizon T^l and T^s. Additionally, S^l and S^s denote the frequency for running capacity planning and resource deployments models, respectively. The rolling horizon procedure is detailed below in pseudocode format. To be specific, the inputs for the two proposed modules would be updated dynamically in this rolling horizon procedure.

```
ROLLING HORIZON PROCEDURE
/* Iterative process between capacity planning and resource deployments for dynamic
changes */
t = 0;
WHILE t < END THEN
        IF t MOD S^l = 0 THEN
                /* Capacity planning*/
                Run CAP(t, T^l);
                UPDATE Opened facilities and assigned projects;
                UPDATE Approximate number of MPCs;
        IF t MOD S^s = 0 THEN
                /*  Resource deployment */
                Run RES (t, T^s);
                UPDATE Produced number of modules for each open facility;
                UPDATE MPC allocations and relocations;
                IF t MOD 28 = 0 THEN
                        UPDATE Unfinished or produced-in-advance modules with
assigned projects;
                        UPDATE Number of leased or returned MPCs at facilities;
        t = t + 1;
RETURN Joint capacity and resource plans
```

5 Case study

5.1 Experimental settings

Inspired by a real-world scenario encountered within the construction industry, experiments are conducted to assess and analyze the performance of the proposed methodology. We aim to evaluate our models in a real-world scenario incorporating potential demand forecasts with rolling horizons. Given the real data of a large construction company in the US, we utilize their upcoming project forecast for capacity planning and resource deployments. The facility network and potential project locations are also assumed to be given from the company in this case study.

We set the overall planning horizon to be 20 months, the planning horizon for capacity planning to be 1 year and the planning horizon for resource deployments to be 3 months. Also, in the rolling horizon procedure, we set the frequently for running capacity planning and resource deployments models to be 1 month and 1 week, respectively.

5.2 Results

Figure 6 shows the required number of MPCs using three different approaches. The blue line is the baseline estimation without the proposed capacity and resource planning model, where the production rate remains fixed at 8 modules per day for each project, based on the value currently used by the company. The yellow line denotes the number of MPCs estimated through the capacity planning stage at the beginning of each month. Lastly, the green line is the required number of MPCs on a weekly basis determined by the resource allocation stage, where we consider MPC relocation and allow production date adjustments.

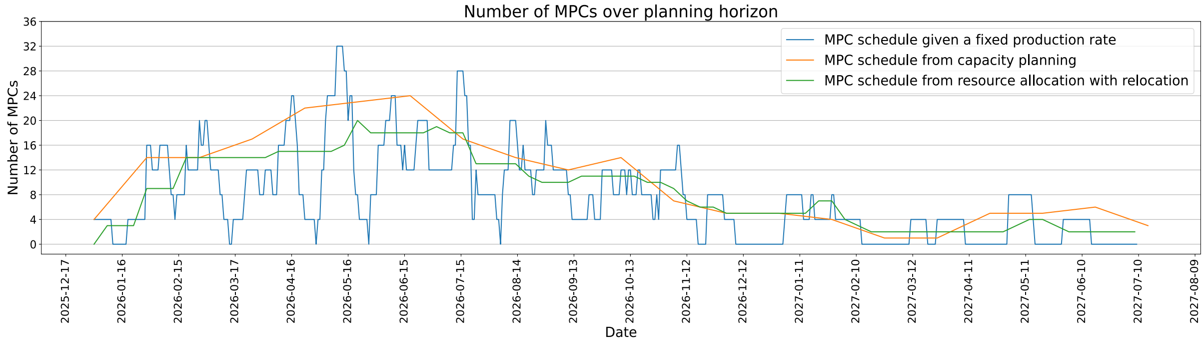


Figure 6: Results of the required number of MPCs estimated by the fixed production rate, capacity planning model, and resource planning model with relocation

As we can see from Figure 6, the yellow line given by the capacity planning model exhibits a smoother trend compared to the blue line from the fixed production rate scenario. This demonstrates that our model effectively balances the workload, enabling a more consistent production schedule. This is because the costs of frequently renting new fractals and returning used fractals is expensive. Since the objective of the capacity planning model is to minimize total expenses, the model will adjust the production throughput rate within each month to reduce the total number of fractals required and the frequency of changing the number of fractals. Additionally, it can be observed that the green line, representing the resource planning model with relocation, attains a lower average number of MPCs compared to the estimation derived from the capacity planning stage. This suggests that employing the relocation method can lead to further enhancements in resource utilization.

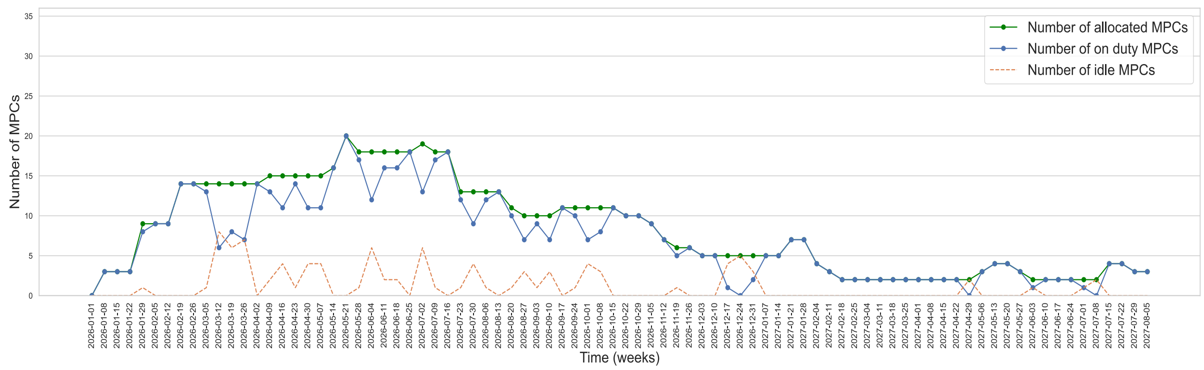


Figure 7: Timeline depicting the number of located, idle and on-duty MPCs

To offer a deeper insight of the MPC schedule given by the resource planning model, we present Figure 7. The green line corresponds to the same line plotted in Figure 6, which is the number of MPCs. Among them, some are on duty for module production while others are in idle, shown as blue and orange line accordingly. We can see that on duty MPC schedule from Figure 6 share the similar pattern with the blue line given a fixed production rate in Figure 7, and the number of leased MPCs has been smoothed utilizing the resource deployment model. Additionally, relocating MPCs incurs lower leasing costs for new fractals, ensuring optimal utilization of resources over time and enhancing cost efficiency within the operational framework.

6 Conclusion

In this paper, we present a novel rolling horizon procedure for integrated capacity planning and resource deployments in hyperconnected supply chain ecosystems. We seek to understand the value of the MPCs in capacity and resource deployments incorporating demand uncertainty and model performance under the rolling schedule procedure. By iteratively solving the proposed two models, we show that it is both computationally feasible and necessary to integrate capacity and resource deployments decisions. Dynamic changes of customer demand can be captured utilizing the integrated model with flexibility, offering management valuable insights into the optimal utilization of MPCs as demand fluctuates. For future research, stochastic programming approach considering different predictive scenarios for capacity planning under uncertainty is worth to be addressed. Additionally, distributed production planning and scheduling among multi-layer geographically separated production networks can be conducted, to determine optimal schedule of MPCs considering technical, logistical, and timing constraints.

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Assessing and Enhancing Readiness in Hyperconnected Supply Chains

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Abstract: *This paper investigates the resilience of supply chains (SCs) against a backdrop of escalating disruptions, developing a quantitative, performance-oriented metric to evaluate SC readiness and the efficacy of Physical Internet (PI) concepts in enhancing SC resilience. We employ the resilience triangle concept, traditionally used in infrastructure resilience assessments, to measure SC performance dynamics over time. Our findings reveal that PI concepts significantly improve SC resilience by improving the distribution and storage of goods across a network of Open Contracted Storage Centers (OCSCs). Sensitivity analysis further demonstrates the profitability of these strategies, even when the holding cost ratio in OCSCs is substantially higher than in traditional warehouses. This research contributes to the field by providing a framework for a priori SC resilience assessment, offering insights into the potential of PI concepts to create more adaptive, robust, and efficient SCs. Future research directions include applying these findings to various industrial sectors and exploring long-term impacts on global SC networks.*

Keywords: *Physical Internet, Supply Chain Resilience, Disruption Management, Disruption Preparation, Supply Chain Readiness, Hyperconnected Networks*

Physical Internet (PI) Roadmap Fitness*: ☒ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks*

Targeted Delivery Mode-s*: ☒ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation*

1 Introduction

The global supply chain (SC) landscape is increasingly susceptible to a range of disruptions, including natural disasters, geopolitical conflicts, abrupt shifts in consumer demand, and logistic constraints, which can significantly impact business continuity and profitability. Reactive approaches to SC management, characterized by decisions made in response to events as they occur, can lead to significant inefficiencies. These include increased operational costs, wasted resources, and missed opportunities for mitigation or prevention. The reliance on such strategies often results in a scramble to manage SC disruptions once they have already impacted operations, leading to rushed decisions that may not be cost-effective or sustainable in the long term. Instead, adopting proactive and dynamic approaches and strategies that enable SCs to anticipate and prepare for disruptions has become more prominent recently. Such approaches not only mitigate the impacts of disruptions but also strengthens the resilience and sustainability of SCs, ensuring they are well-prepared to navigate the uncertainties of today's dynamic economic environment. However, to take proactive actions, it is imperative to assess the current readiness level of SCs against potential future disruptions as it is not possible to improve any SC capability we cannot measure. Such an assessment directly corresponds to a priori

assessment of SC resilience. In this paper we are developing a performance-oriented readiness metric that represents the preparedness level of SCs for potential future disruptions quantitatively in a multi-dimensional fashion.
To enhance SC resilience, the literature offers diverse selection of approaches that try to tackle different SC problems at different levels. In this paper, we focus on the impact of Physical Internet (PI) concepts on SC resilience. We investigate the impact of having an open distribution network (ODN) that serves the needs for storing and distributing the finished goods. For the experiments, we developed a simulator that can simulate the SC operations in detail, disruption impacts, and consumer demand through time. By utilizing our readiness metric, the benefits of PI concepts are analyzed along with sensitivity analyses on various parameters.
The rest of this paper is structured as follows: Section 2 presents a review of the literature on SC resilience and PI concepts; Section 3 provides details on the SC readiness assessment; Section 4 illustrates the impact of PI concepts on SC readiness over a case study. The paper concludes with a summary of our findings and suggest directions for future research.

2 Literature Review

2.1 Supply Chain Resilience

SC resilience is increasingly garnering attention due to the rising frequency and impact of disruptions that supply chains face. Although there is a diverse selection of definitions and assessment approaches available in the literature (Hosseini et al., 2016; Heckman et al., 2015), focus varies significantly among researchers. Some emphasize recovery capabilities from disruptions, while others consider the capacity to respond by avoiding or mitigating their negative impacts (Ponomarov and Holcomb, 2009). Additionally, the capability of SCs to anticipate and prepare for disruptions has begun to attract attention as a key enabling capability of SC resilience (Hohenstein et al., 2015). Among the various definitions and frameworks for SC resilience, a common consensus is that it represents the supply chain's ability to anticipate, prepare for, respond to, and recover from disruptions.
SC resilience assessment approaches can be categorized into two main types: quantitative and qualitative. Qualitative approaches typically rely on expert surveys, questionnaires, and conceptual frameworks. However, this literature review focuses on quantitative approaches since our aim is to assess SC readiness via quantitative metrics. Studies that quantitatively assess SC resilience often focus on the performance of supply chains before, during, and after disruptions. These approaches can further be grouped as either deterministic or stochastic, depending on their capability to capture the stochastic nature of disruptions. Commonly, both types employ the well-known resilience triangle concept, introduced by Bruneau et al. (2008) for assessing the resilience of infrastructures. Due to its easily interpretable and flexible structure, this concept is extensively employed by both physical and social systems. The underlying idea in their formulation is to measure the SC's performance between the occurrence of a disruption and full recovery, comparing it with target performance levels. This paper develops a resilience loss (RL) metric with the formulation provided in Equation (1), where the disruption occurs at t_0 and the system recovers its pre-disruption performance at t_1. The functionality of the system at any time tt is represented by Q_t.

$$RL = \int_{t_0}^{t_1} \left(100 - Q(t)\right) dt \tag{1}$$

Zobel (2011) quantifies system resilience over a defined time period, T^*. In this model, resilience is calculated as the percentage of total potential functionality that is lost during T^*. The model utilizes two key parameters: the percentage of functionality loss, X, which ranges from 0 to 1, and the duration needed for complete recovery, T, which does not exceed T^*.

The resilience metric is formulated as shown in Equation-2, where R denotes the resilience index:

$$R(X,T) = 1 - \frac{XT}{2T^*} \quad (2)$$

The paper presents visualizations that depict the trade-offs between functionality loss (robustness) and recovery speed (rapidity) using hyperbolas. In addressing stochastic variability, it does not employ specific scenarios or probabilistic distributions. Instead, it considers all possible combinations of X and T values from the visualizations as potential scenarios, applying a deterministic approach to measure these. The assessment of the importance of recovery speed versus resilience, as well as determining the likelihood of each scenario's occurrence, is left to the discretion of decision-makers. Zobel and Khansa (2014) enhanced the resilience assessment approach by incorporating non-linear recovery models, including exponential, inverted exponential, and trigonometric recovery rates. Additionally, Zobel (2014) expanded the framework to address multi-event resilience, defining specific and partial resilience values for different types of events. These enhancements contribute to a more comprehensive understanding of resilience across various scenarios. Consistently, all related studies mentioned so far utilize a deterministic approach, maintaining a uniform methodology in evaluating and interpreting resilience.

Chang and Shinozuka (2004) enhanced the resilience triangle concept by incorporating predefined performance thresholds for robustness and rapid recovery. They defined resilience (R) as the probability that the initial impact of a disruption (r_0) does not exceed an acceptable loss level (r^*) and that recovery (t_1) occurs within a designated acceptable timeframe (t^*). This approach, articulated in Equation (3), conceptualizes resilience as a probabilistic function that satisfies specific performance criteria (A) for a given disruption scenario i:

$$R = Pr(A|i) = Pr(r_0 < r^* \text{ and } t_1 < t^*) \quad (3)$$

To evaluate overall system resilience (Z_A) in the face of various potential disruptions, Equation (4) combines the probabilities of achieving specified performance thresholds ($Pr(A|i)$) with the probability associated with each disruption scenario ($Pr(i)$). This integration facilitates a comprehensive assessment strategy, leveraging Monte Carlo simulations to accurately determine the likelihood of maintaining performance standards after disruptions occur. Such a methodical approach enables a thorough enhancement of resilience capabilities.

$$Z_A = \sum_i Pr(A|i) \times Pr(i) \quad (4)$$

2.2 Physical Internet

The Physical Internet (PI) embodies a revolutionary approach to logistics, characterized by its intricate network connections that facilitate the shared use of resources and capabilities. PI is defined as a "hyperconnected global logistics system that enables seamless open asset sharing and flow consolidation through standardized encapsulation, modularization, protocols, and interfaces," transforming traditional logistic frameworks (Ballot et al. 2008; Montreuil et al. 2013). The term 'hyperconnected' refers to the extensive and intensive links among network entities and physical components, integrating digital, physical, operational, business, legal, and personal layers (Montreuil 2011; Montreuil et al. 2013). This paper also explores ODNs within the PI framework. As delineated by Montreuil et al. (2013) and further illustrated by Montreuil (2011), ODNs, or distribution webs, represent dynamic networks of certified distribution centers. These centers efficiently deploy modular, standardized π-containers of goods across global markets, rapidly and reliably meeting demand.

In addition to hyperconnectivity, in this paper we also interested in the ODNs. As introduced in Montreuil et al. (2011) and illustrated in Montreuil (2013), the ODN or simply distribution web in PI context is a dynamic network of certified distribution centers that efficiently deploys modular, standardized π-containers of goods across global markets to meet demand rapidly and reliably.

The impact of Physical Internet (PI) concepts on supply chain (SC) resilience has been extensively explored in recent literature (Kulkarni et al. 2022; Pothen et al. 2023; Grest et al. 2021). Notably, Grest et al. (2021) highlighted how PI principles significantly enhance performance in humanitarian supply chains, which are among the most vulnerable to disruptions and operational challenges. Building on these foundational studies, this paper aims to extend these analyses further, exploring new dimensions of PI's influence on SC resilience and efficiency.

3 Assessing Supply Chain Readiness

Managing disruptions effectively within SCs requires a thorough understanding of their current readiness to handle potential disturbances. In this paper, we position SC readiness as an initial assessment of resilience, focusing on the capability to prepare for disruptions and providing a detailed, quantifiable understanding of this readiness. Our approach utilizes performance metrics that capture essential resilience aspects, such as total performance loss (TPL), time to recover (TTR), and minimum performance level (MPL). These metrics are informed by tolerance levels provided by decision-makers, allowing our models to accommodate various disruption scenarios, including those that are simultaneous or cascading, and are not limited to fixed performance outcomes. By adopting a performance-oriented perspective, we align these indicators with the strategic objectives of the supply chain, enabling a quantitative evaluation of how effectively these goals are met..

Notation

$SC\ readiness\ measurement\ period\ \ defined\ by\ decision\ makers, T$

$SC\ readiness\ dimensions, A = \{TPL, TTR, MPL\}$

$Disruption\ scenarios,\ \ \Omega = \{\omega_1, \omega_2, \dots \omega_{|\Omega|}\}$

$s_\omega: Probability\ of\ occurrence\ for\ scenario\ \omega,\ \ \forall\omega \in \Omega$

$$\sum_{\omega\in\Omega} s_\omega = 1 \tag{5}$$

$TPL_\omega: Percentage\ of\ total\ performance\ lost\ by\ supply\ chain\ in\ scenario\ \omega,\ \ \forall\omega \in \Omega$

$TPL^*: Tolerable\ total\ performance\ loss\ level$

$MPL_\omega: Maximum\ performance\ deviation\ ratio\ in\ scenario\ \omega,\ \ \ \forall\omega \in \Omega$

$MPL^*: Tolerable\ minimum\ performance\ level$

$TTR_\omega: Percentage\ of\ the\ time\ period\ spent\ for\ recovery\ in\ scenario\ \omega,\ \ \ \forall\omega \in \Omega$

$TTR^*: Tolerable\ time\ to\ recover\ level$

$\Omega^*: Disruption\ scenarios\ that\ in\ which\ the\ SC\ performs\ within\ the\ tolerance\ levels\ at\ all\ dimensions$

$Re: SC\ readiness\ metric\ for\ given\ set\ of\ disruptions\ scenarios\ (\Omega)$

$$Re = \sum_{\omega\in\Omega^*} s_\omega \tag{8}$$

Our readiness metric quantifies the probability that a supply chain can respond to and recover from disruptions within acceptable performance thresholds. This metric is inspired by the methodologies of Chang and Shinozuka and is tailored to reflect the operational realities of different supply chain contexts, which may prioritize specific performance dimensions based on their unique needs. For instance, humanitarian supply chains often emphasize rapid response and recovery capabilities to ensure timely aid delivery, whereas commercial supply chains might focus more on minimizing overall performance loss or deviations to sustain profitability and market position. This method offers a precise and practical framework for assessing readiness, ensuring that supply chains are evaluated against the performance criteria most critical to their context. Supply chain performance is multifaceted, typically evaluated through various financial, operational, strategic, and service-related metrics. The model proposed here is adaptable, designed to assess readiness across these diverse performance dimensions. While this paper provides an overarching measure of readiness, a more granular analysis of performance is beyond its scope. Hence, our model assumes the availability of measurable indicators that reflect individual or combined performance aspects.

4 Experimental Case Study

To assess the SC readiness, performance projections of the SCs in case of given disruption scenarios is essential. The performance during disruption management phases is influenced by both the nature of the disruption and the resilience of the SC, introducing a level of stochasticity to the process. While some studies model disruption scenarios directly in terms of SC performance during response and recovery, these often oversimplify the complex dynamics of SC performance. A more effective approach involves simulating each scenario by detailing the modeling of the supply chain and its disruptions.

To better illustrate the readiness assessment process and impact of PI concepts on enhancing SC readiness, we developed an experimental case inspired by the network of our industry partner. By simulating the impact of disruptions on SC performance, this paper follows a stress testing approach for a priori measurement of SC performance over potential disruptions.

4.1 Experimental settings and assumptions

4.1.1 Supply Chain Network

Drawing from our industry partner's SC network, we designed a network for a production company extending from suppliers to customers. Our network includes one production plant in Juarez, Mexico, and three warehouses located in El Paso-Texas, Salt Lake City-Utah, and Nashville-Tennessee. It also involves local and global suppliers without specified locations and customers across the United States. The SC network and the physical locations of these facilities are depicted in Figure 1. For node transshipments, we only consider truck transportation, assuming a daily range of 660 miles at a cost of $0.00008 per item, with trucks carrying up to 1000 items each.

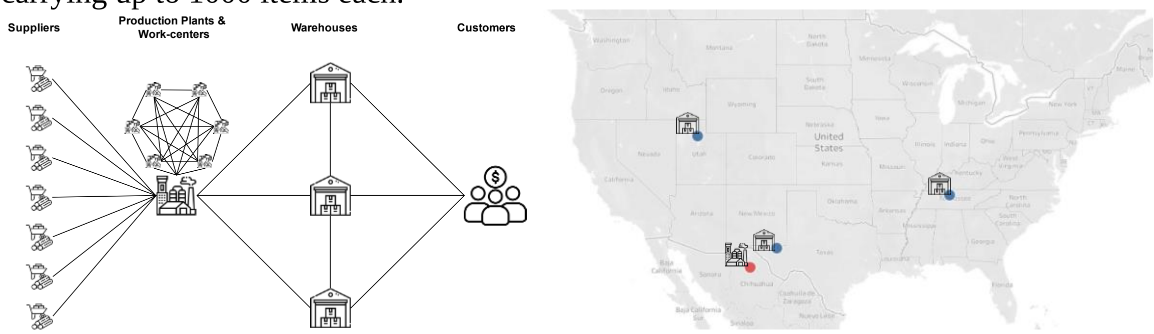

Figure 1 Supply Chain Network used in experimental analyses and real locations of the nodes

4.1.2 Supply, Production, and Storage

The manufacturing company produces 10 different products, utilizing 25 distinct raw materials and employing 10 unique production processes. Each product requires varied quantities of these materials, processed through specifically designed production flows that vary in process time. The production facility is equipped with individual work centers, each dedicated to a unique process, with their operational schedules set weekly based on incoming production orders. Finished products are stored at warehouses that also serve as distribution centers, providing ample storage capacity and functioning as fulfillment centers that ship customer orders via

third-party logistics providers (3PL). The assumption made here is that these warehouses possess sufficient storage capacity to handle the company's production volume without constraints. Inventory management at these sites is dynamically adjusted to align with the demand patterns from the nearest zones and to meet a targeted two-week supply autonomy.
The procurement strategy for raw materials involves three different suppliers for each material, differentiated by their unit price, supply capacity (maximum order quantity), and delivery lead times. In this competitive supplier landscape, no single supplier holds a predominant advantage over the others in terms of pricing or service delivery. The company's procurement policy prioritizes supplier capacity to ensure that production is not hindered by material shortages. When multiple suppliers meet the capacity requirements, the decision criteria shift to favor lower unit prices over shorter delivery times to optimize costs and efficiency in the supply chain.

4.1.3 Demand and Fulfillment

For customer demand, we utilize 5-digit zip codes to define 33,240 distinct demand zones. Our product portfolio is categorized into three groups based on demand volumes, with the characteristics of each demand zone for the product groups summarized in Table 1. Weekly demand for each product is generated and then randomly distributed across the days of the week for each product and demand zone pairing.

Table 1 Demand characteristics for differernt product groups and demand zones

Demand Zone Population	Product Group	Weekly Demand	Demand Zone Population	Product Group	Weekly Demand
<5000	High Demand	1	50000-100000	High Demand	5
	Medium Demand	0		Medium Demand	1
	Low Demand	0		Low Demand	0
5000-25000	High Demand	2	100000-150000	High Demand	7
	Medium Demand	0		Medium Demand	3
	Low Demand	0		Low Demand	1
25000-50000	High Demand	3	>150000	High Demand	9
	Medium Demand	0		Medium Demand	5
	Low Demand	0		Low Demand	3

To assess the impact of disruptions on supply chain performance clearly, we operate under the assumption that our demand is deterministic. This is particularly applicable as many orders originate from online subscriptions, resulting in recurrent but dynamically changing demand. This assumption allows us to overlook potential forecasting errors that could affect supply chain performance evaluations. Orders are fulfilled through third-party logistics providers (3PL) from the nearest warehouse, which helps reduce both costs and order-to-delivery times.
We categorize delivery lead times and costs into seven tiers based on the distance from the fulfilling warehouse to the demand zones, as detailed in Table 2. Orders within a 200-mile radius of a warehouse are delivered within a day at no additional cost, as the base shipment cost is covered by the customer. For greater distances, both the delivery lead times and additional shipping costs increase progressively. The pricing of products is aligned with the raw materials used and the time required for processing.

Table 2 Delivery lead times and shipping costs by distance

Distance Between Warehouse and Demand Zone	Delivery Lead Time	Extra Shipping Cost
<200 miles	1	0
200-400 miles	2	0.5
400-600 miles	3	1
600-800 miles	4	1.5
800-1000 miles	5	2
1000-1200 miles	6	2.5
>1200 miles	7	3

4.2 Readiness Assessment

SC readiness inherently demands pre-emptive measurement techniques capable of modeling disruptions and their management, incorporating the inherent stochastic nature of such events. In this paper, disruptions are viewed as outcomes of one or more trigger events that impact SC capabilities and actions over time. To properly account for these disruptions, we adopt a priori measurement using performance-based formulations. This approach enables us to define disruption scenarios that specify when disruptions occur and how they affect SC operations, effectively capturing the unpredictability of their occurrence and impact.

As we are using a stress testing approach, we are more interested in the consequences of disruptions, rather than the trigger events (Simchi-Levi et al. 2014). The disruption scenarios are crafted to provide insights into potential consequences that may arise from a variety of events. These scenarios encompass production, logistics, and supply disruptions, detailed in Table 3, and are characterized by type, magnitude, duration, and the elements of the SC they affect. We categorize each disruption into three severity levels—high, medium, and low—and assume equal probability of occurrence for each sub-type. Furthermore, given the occurrence of a specific disruption type, the probabilities of it being high, medium, or low severity are set at 0.2, 0.3, and 0.5, respectively.

Table 3 Summary of disruption scenarios

Type	Sub-type	Impacted SC elements	Impacted Parameters	Severity	Magnitude	Duration
Production	Plant disruption	Production plants	Daily production capacity	High		30 days
				Medium	*Become unavailable*	15 days
				Low		7 days
Production	Work center disruption	Work centers	Daily processing capacity	High		30 days
				Medium	*Become unavailable*	15 days
				Low		7 days
Logistics	Transportation disruption	SC nodes	Delayed deliveries (inbound) and shipments (outbound)	High		21 days
				Medium	Delayed deliveries (inbound) and shipments (outbound)	14 days
				Low		7 days
Supply	Supplier delivery delay	Production plants	Raw material replenishment orders	High		80 days
				Medium	Delayed deliveries	40 days
				Low		20 days

We use the profit of our company as the indicator of the overall SC performance. The daily profit is incorporating revenue, holding costs, and transportation costs (including transshipment

and additional 3PL costs), which highlights the efficiency of our fulfillment and the alignment between demand and supply. To evaluate SC readiness, we establish a baseline performance level—defined as the SC's performance in the absence of disruptions. This baseline helps us gauge the impact of disruptions by comparing the disrupted performance to the undisturbed state. The extent of recovery—whether the SC returns to, falls short of, or surpasses pre-disruption levels—depends on the SC's anti/fragility.
In this experimental framework, we set tolerance levels for the financial performance such that, following a disruption, the SC should not lose more than 5% of potential daily profit, 5% of total potential profit, and should recover to undisrupted profit levels within 7 days. The readiness score for these criteria stands at 0.70, indicating the probability of meeting these thresholds under disruption scenarios.

4.3 Leveraging ODN with Open Contracted Storage Centers

This section investigates the potential impact of implementing an ODN with multiple Open Contracted Storage Centers (OCSCs) strategically located across the United States.We consider 13 OCSCs located strategically to maximize the population coverage. In Figure 2 the locations of OCSCs are depicted, each marked with a 200-mile radius circle to illustrate the demand zones they can serve within a day. These zones are color-coded based on population.

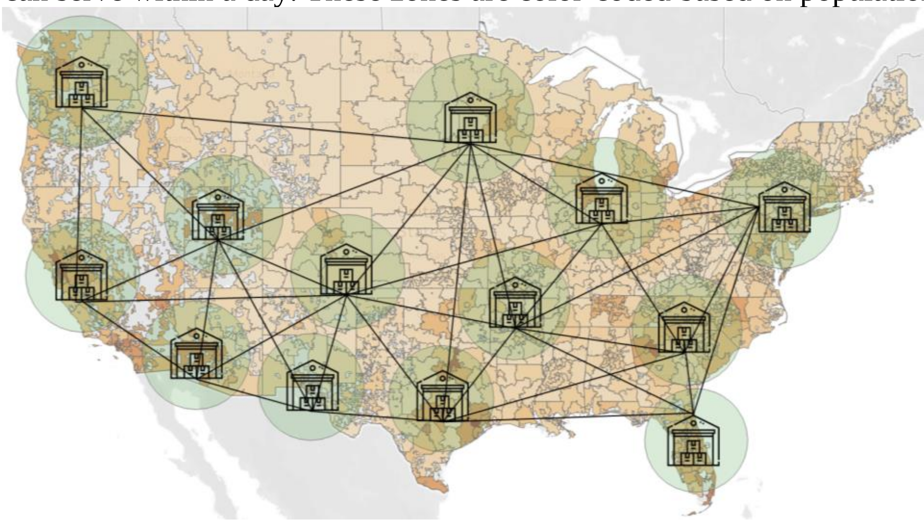

Figure 2 Open distribution network with OCSCs

For the capacity of OCSCs we assume that there is enough capacity to be reserved monthly based on our deterministic but dynamic demand. We aim to keep the same autonomy level target (2 weeks) and reserve capacity at each OCSCs based on demand from the zones that are closest to OCSCs. For the cost of reserving capacity, we assume that all potential costs are reflected on the unit holding cost for our products. Initially we assume that the unit holding cost and all other shipment and transshipment costs are the same as before.
With the availability of OCSCs SC readiness is increased to 0.78, marking 11% increase from the base case. To show the power of our metric on reflecting consequences of low SC performance and accurately assess the benefits of utilizing OCSCs, we compare the expected order-to-deliver times for two distinct setups under identical disruption scenarios previously analyzed. In the baseline scenario, the SC operates with only three private warehouses. In the enhanced scenario, it incorporates the ODN with strategically placed OCSCs. Figure 3 illustrates the expected average order-to-deliver times for orders from each demand zone in both scenarios, demonstrating the impact of the OCSCs under the same disruptive conditions. This figure vividly shows a significant reduction in order-to-deliver times across the United States, highlighting the efficiency of the ODN model.

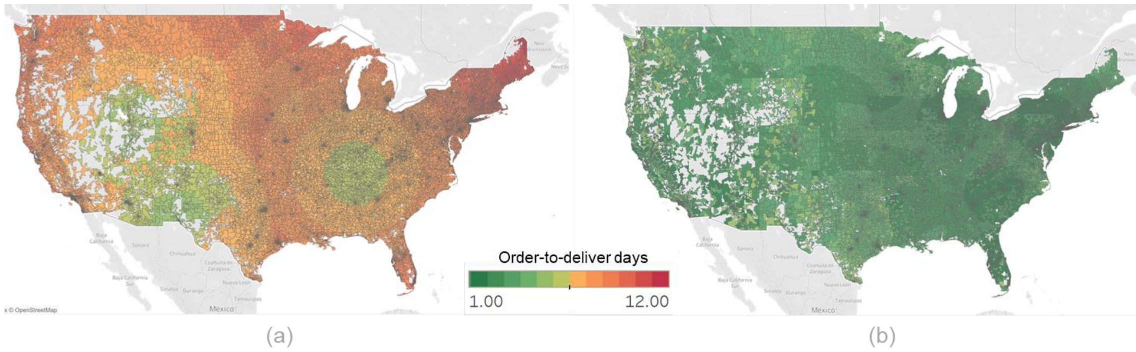

Figure 3 Expected order-to-deliver times for demand zones in base case (a) and open distribution network (b)

For a more detailed analysis, Figure 4 presents boxplots that depict the expected maximum delivery times for these demand zones, providing a comparative view of delivery efficiency across both scenarios. These boxplots show that maximum delivery times are consistently lower in the ODN scenario, demonstrating the network's effectiveness in improving supply chain resilience and customer satisfaction under disruptive conditions. This approach ensures that the performance improvements attributed to the OCSCs are evaluated in the context of consistent external challenges, allowing for a clear demonstration of their potential to enhance SC resilience and efficiency.

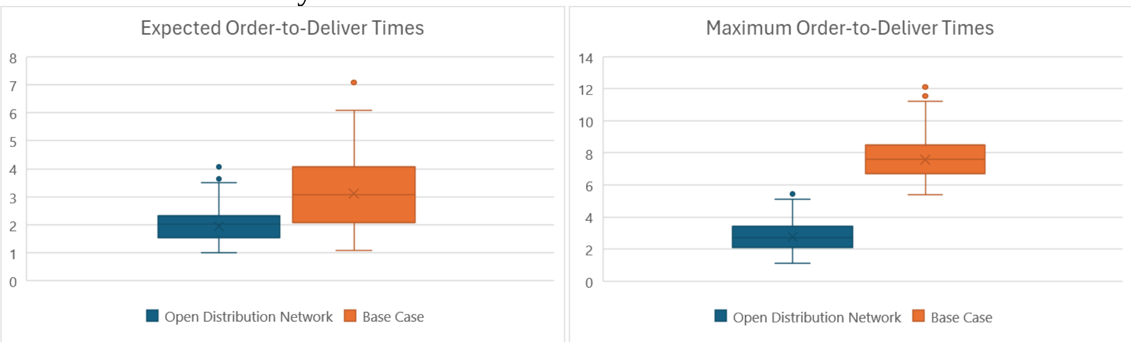

Figure 4 Box-plots showing expected average and maximum order-to-deliver times for demand zones

Next, we extend our analysis to the financial performance dimension by comparing profits under both scenarios. The evaluation of financial performance showcases the cost-effectiveness and profit potential of integrating OCSCs into our network. Figure 5-a presents a boxplot comparison of the expected total profits under the two scenarios. It is evident from the boxplot that the integration of OCSCs has significantly increased the upper quartile and median profit levels, despite a lower outlier, showcasing greater profit potential even under disrupted conditions. Figure 5-b illustrates the weekly profit ratio over a 20-week period, comparing performance under base conditions and with OCSCs, against an undisrupted baseline. The line graph reveals that the integration of OCSCs improves the SC performance even before the disruptions occur at the beginning of fifth week. After being disrupted, SC consistently maintains a closer performance ratio to the undisrupted base, indicating less fluctuation and enhanced stability in financial performance. With the help of OCSCs, our SC lost less performance (TPL), attained higher minimum performance levels (MPL), and jumped to its undisrupted performance level faster (TTR).

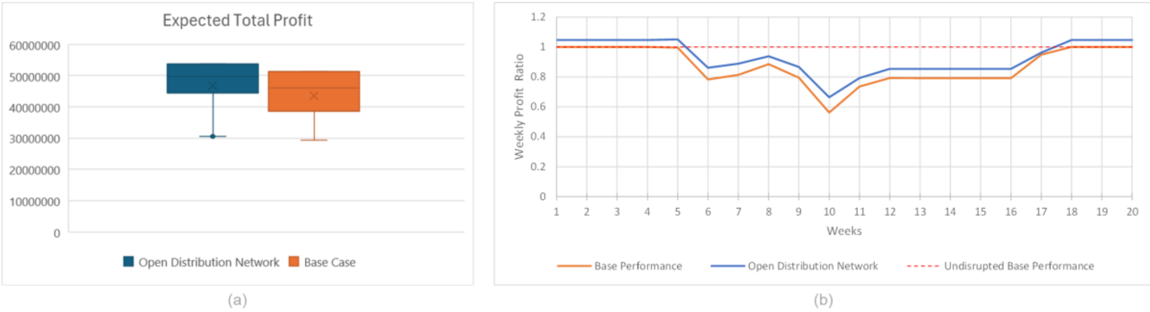

Figure 5 (a) Expected total profit values for disruption scenarios (b) Weekly profit ratio with undisrupted base case

4.4 Sensitivity Analysis

In our analysis, certain simplifications were necessary, particularly the assumption that the unit holding costs at OCSCs are equivalent to those at our private warehouses. This assumption was initially made to fully delineate the potential impact of the ODN. However, to assess the real-world viability of this model, a sensitivity analysis is crucial, particularly in understanding how profitability shifts with variable holding costs at OCSCs. Figure 6 visualizes the sensitivity of expected total profits by comparing the profit ratios of the ODN to the base case under varying unit holding cost ratios for OCSCs relative to private warehouses. The y-axis represents the ratio of expected total profit with ODN to that of the base case, considering different unit holding costs at OCSCs. As depicted, the break-even point is at a holding cost ratio of 10.8. This indicates that the ODN remains more profitable than the traditional model as long as the holding cost at OCSCs does not exceed 10.8 times that of private warehouses. This finding is significant as it underscores the operational flexibility and financial resilience of the ODN, even when facing increased costs. This analysis is essential not only in highlighting the cost-efficiency of the ODN under varying economic conditions but also in demonstrating its profitability advantage over traditional distribution models, especially in scenarios with disruptions. Despite the increased number of storage nodes in the ODN model, the system has shown to yield higher profits, reflecting its robustness against disruptive events and its capacity to leverage distributed storage effectively.

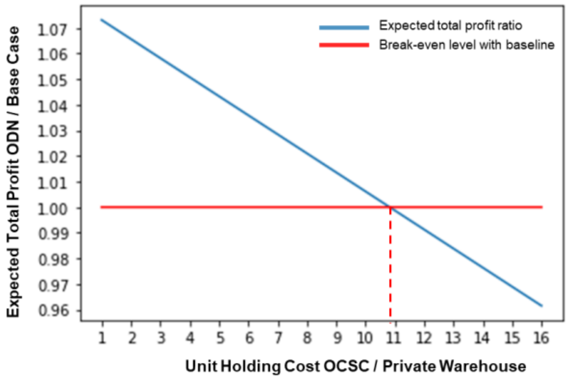

Figure 6 Expected total profit ratio of ODN and base case with increasing unit holding costs for OCSCs

5 Conclusion

This study has demonstrated that the implementation of PI concepts significantly enhances SC readiness, equipping it with robust capabilities to face and efficiently manage disruptions. Our analysis, grounded in the development and application of a performance-oriented readiness metric, reveals that SCs equipped with an ODN not only exhibit improved resilience but also maintain profitability even under heightened operational costs. Notably, the sensitivity analysis confirms that the benefits of PI implementation remain substantial even when the unit holding cost ratio in newly established OCSCs is almost up to 11 times higher than in current warehouses. The integration of PI concepts into SC operations facilitates a more agile and responsive framework, enabling businesses to respond to sudden changes and disruptions with greater flexibility. By distributing and storing products across a wide network of nodes, SCs can reduce the time and cost associated with last-mile delivery and improve service levels across diverse markets. Future research should focus on expanding the application of PI concepts to different industrial sectors and more complex SC configurations. Additionally, exploring the long-term impacts of PI on global SC networks could provide deeper insights into its transformative potential and sustainability benefits.

This study, while highlighting the substantial potential of Physical Internet (PI) concepts to enhance SC resilience, operates under certain assumptions and constraints that must be acknowledged. Firstly, the analysis assumes that there is sufficient capacity at the OCSCs to handle the logistics operations envisioned under the PI framework. This assumption may not hold in real-world scenarios where capacity constraints can affect the efficiency of supply chain operations. Additionally, the study does not account for the logistics complexities associated with full truckload (FTL) and less-than-truckload (LTL) transshipments. These considerations are critical in SC logistics as they impact cost, efficiency, and the environmental footprint of transportation. Despite these limitations, the study incorporates a comprehensive cost analysis from raw material replenishment to shipments involving third-party logistics (3PL) providers, which are sensitive to distance variations. The findings are promising, indicating that PI concepts can significantly improve supply chain resilience through enhanced efficiency and effectiveness.

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Efficient, Fast, and Fair Voting Through Dynamic Resource Allocation in a Secure Election Physical Intranet

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Abstract: *Resource allocations in an election system, often with hundreds of polling locations over a territory such as a county, with the aim that voters receive fair and efficient services, is a challenging problem, as election resources are limited and the number of expected voters can be highly volatile through the voting period. This paper develops two propositions to ensure efficiency, fairness, resilience, and security. The first is to leverage Physical Internet (PI) principles, notably setting up a "secure election physical intranet" (SEPI) based on open resource sharing and flow consolidation between election facilities in the territory. The second is to adopt a smart dynamic resource allocation methodology within the SEPI based on queueing networks and lexicographic optimization. A queueing model is developed to provide feasible combinations of resources and individual performances for each polling location by considering layout and utilization constraints. A two-stage lexicographic optimizer receives the queueing model's outputs and finds an optimal solution that is less expensive, fast, and fair. A scenario-based case study validates the proposed methodology based on data from the 2020 US Presidential Election in Fulton County, Georgia, USA.*

Keywords: *Physical Internet; Secure Elections; Physical Intranet; Resource Allocation; Optimization; Simulation; Efficiency; Election Queueing; Election Fairness*

Physical Internet (PI) Roadmap Fitness*: ☒ PI Networks, ☒ Access and Adoption*

Targeted Delivery Mode-s*: ☒ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation*

1 Introduction

Election is paramount to any democratic framework worldwide, yet long, uneven, and volatile waiting lines threaten this critical cornerstone. Within the United States, voters and election system administrators have noticed a rising waiting time in an increasing number of polling locations. During the U.S. in 2012, many polling locations in battleground states saw voters waiting for hours on election day (Famighetti et al., 2014). These long waiting lines can discourage people from voting and induce a huge national economic cost, as even a modest wait of 10-15 minutes from each voter can cost the U.S. approximately $500 million (Stewart III et al., 2013). Additionally, long waiting times disproportionately affect different polling locations, which can lead to unfairly treated voters' frustrations and potential impacts on election results. For example, during the U.S. Presidential Election of 2020, certain polling locations in Florida reported average waiting times of over 80 minutes, while other polling locations nearby had less than 10-minute waiting times (Barenji et al., 2023). Other studies also suggest that certain voter populations, such as racial minorities and lower-income communities, are more likely to experience long waiting times (Stewart III, 2013; Pettigrew, 2017). Addressing these concerns is imperative to safeguarding the democratic process and ensuring fair electoral participation for all citizens, and one pivotal solution is effective election resource allocations with fast and fair services.

Key resources to be allocated in an election system include poll pads, ballot marking devices (BMDs), and scanners. The allocation is often challenging due to voter turnout volatilities. Many factors can affect voter turnouts, drastically differing between county precincts and even between the same precinct's hours (Matsusaka et al., 1999). Resource limitations, location constraints, and governmental regulations also bound allocation plans. For instance, based on the Centers for Disease Control and Prevention's (CDC) recommendations, the social distancing regulation for COVID-19 greatly affected resource allocation during the U.S. Presidential Election of 2020 and led to many polling locations' shortness in providing efficient services (Sullivan, 2020). Past decision-making in polling resources mostly involved fixed population-based plans, in which all polling locations would receive unchanging amounts of various resources at the beginning of early elections, and the amounts usually relied on registered voter populations, historical plans, or the busiest anticipated day (Edelstein, 2006). However, fixed apportionment can lead to a waste of resources and cannot respond to a surprising uprising of voters. For instance, throughout the early-election period of the U.S. presidential election in 2020, many polling locations in Georgia experienced hours of waiting due to the number of early-election voters being higher than expected based on the 2016 turnout data.

In this paper, we develop two propositions to ensure efficiency, fairness, resilience, and security. First, we leverage Physical Internet (PI) principles (Montreuil, 2011), notably setting up a Secure Election Physical Intranet (SEPI) based on open resource sharing and flow consolidation between election facilities in the territory. The SEPI incorporates three considerations and ensures a secure and resilient allocation process. Second, we adopt a smart dynamic resource allocation methodology based on queueing network analysis and lexicographic optimization.

We assess the value of our propositions through comparisons with the fixed resource allocation plan derived from Barenji et al. (2023) for the 2020 US Presidential Election in Fulton County, Georgia, USA. Our approach outperforms the fixed official resource allocation plan regarding total resource and cost requirements, resource utilization, and voters' estimated robust wait time and fairness. We also identify critical polling locations that require policymakers' attention.

The full paper is organized as follows. Section 2 presents the related literature. Section 3 demonstrates the SEPI. Section 4 proposes the dynamic resource allocation framework. Section 5 analyzes the methodology's performance through a case study of three scenarios. Section 6 summarizes the contributions, limitations, and future work directions.

2 Related Literature

Researchers have conducted many related studies on election resource allocations and their assessments. Allen and Bernshteyn (2006) suggested using queueing network models in estimating and mitigating voter waiting times on election day. Its case study proved its effectiveness in reducing voters' average voting time. Allen et al. (2020) explored the application of indifference zones in determining whether a set of allocated resources can guarantee acceptable wait times in a polling location. A general binary search algorithm is also employed to improve the run time when seeking the optimal allocation combination. However, this set of procedures only yields limited options with high performances, and satisfying all these options for all polling locations from a managerial perspective can be challenging as election resources are often limited. Furthermore, Allend and Benshteyn's (2006) queueing network model and Allen et al.’s (2020) indifference-zone binary search approach only explored fixed resource allocation plans. They could not respond to demand fluctuations, especially when a polling location faces an unexpected demand rise.

Previous PI container studies have introduced and proven their specialty in improving security, efficiency, and reliabilities (Montreuil, 2011; Montreuil et al., 2016; Sallez et al., 2016). Their most fundamental pillar in protecting contained objects made them suitable for applying election systems, as election resources are extremely sensitive to the outside world’s contamination. PI containers’ modularity and traceability can also guarantee efficiency and reliability during resource transfers, which is critical in election systems, ensuring all resources are delivered quickly and correctly. Furthermore, PI containers’ specialties in sustainability can help alleviate economic and environmental stresses running the election system.

Another related topic in election resource allocations is voter turnout predictions. Two major categories of research are conducted in this field: individual-level analysis and population-level analysis. Individual-level analyses predict whether an individual voter will vote based on his/her utility cost function, of which positivity indicates whether a voter will vote (Lacy et al., 1999; Garcia-Rodriguez, 2020). Population-level analyses predict voter turnout rates of the entire population of a county, state, or nation (Huang, 2016; Turner, 2024). Specifically, Huang (2016) utilized Dynamic Learn Models (DLMs) to predict voter turnouts based on historical data.

3 Proposed Secure Election Physical Intranet

Security, ensuring all machines are functional and not tampered with, is critical to election resource allocations. While a piece of machine is transferred, it is exposed to more damage or interference from maleficent individuals or groups. Therefore, we aim to develop procedures to enhance machine security during and after transfers.

To protect resources from being damaged or touched during transfers, our methodology leverages Physical Internet concepts and principles to be implemented within a secured physical intranet for the election territory, with open resource sharing and flow consolidation among polling locations, election hubs, and warehouses (Figure 1). Resources are to be stored and moved in sealable PI containers with modular sizes and connectors such that transferred machines in compact and fitting sizes, greatly enhancing the security of the entire system (Montreuil et al., 2016). We also suggest only using localized machine transfers such that only polling locations of a certain managerial range, such as the commission district illustrated in Figure 1, can transfer resources to each other. By limiting the resource transfer range, machines’ travel distances are greatly reduced, reducing exposure to dangers and the chance of being interfered with. Moreover, polling locations within a managerial range will not have to cross administrative barriers to communicate with other election management, improving dynamic resource allocation’s speed and safety. After election resources are safely transferred to a new polling location, we encourage staff to examine the transferred machine fully. The examination protocols should be extensive and standardized so that no damaged machines would be put into actual use on the next day.

The above considerations are realized within our cost calculator model and the cost functions within the optimization models. The cost calculator model computes the cost matrix, in which polling locations from two different managerial ranges have a transfer cost of infinity that directly prevents optimization models from selecting such options. The optimization model’s cost function captures the costs of differently sized PI modules, transfers, and examinations.

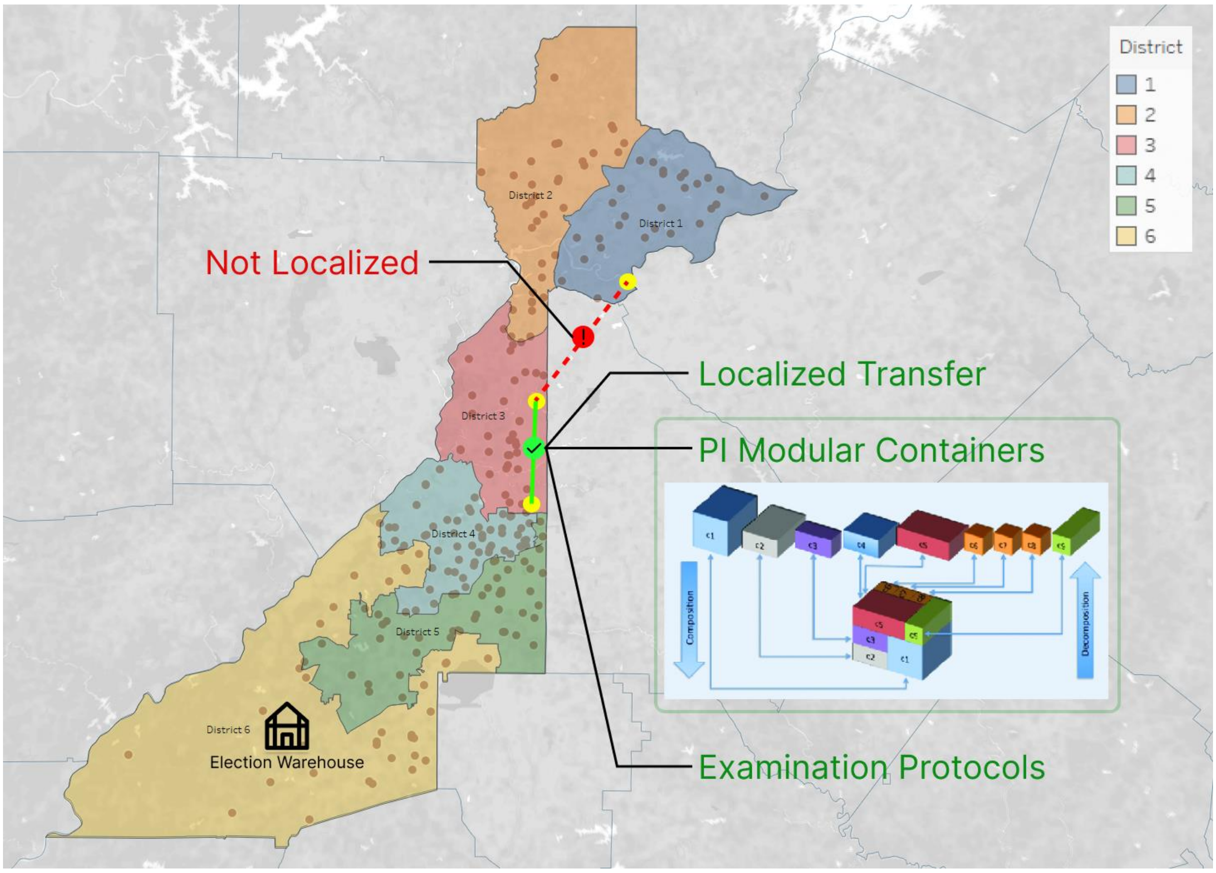

Figure 1: Illustrating the Proposed SEPI in Fulton County, GA (Montreuil et al., 2011)

In this context, the paper proposes a dynamic resource allocation methodology for supporting resource allocation and transfer of resources to polling locations across the SEPI territory, such as a county. For each polling location throughout the early voting period (e.g., 19 days in the U.S. in 2020), it monitors voter hourly turnout, predicts voter turnout in the upcoming election days, and seeks an optimal resource allocation and transfer plan involving all polling locations. Based on the transfer plan, each polling location, including the territory's election resource warehouse, transfers a designated amount of resources of each type to each other during nights when polling locations are closed to the public, abiding by election regulations.

4 Proposed Dynamic Resource Allocation Framework

Figure 2 illustrates the proposed dynamic resource allocation methodology's framework, which contains one major data pool and five computation models: the cost calculator, demand model, queueing network model, and a lexicographic optimization system composed of a first-stage optimizer and a second-stage optimizer. The cost calculator takes polling location latitude and longitude information as inputs and computes a cost matrix, of which each entry contains the transfer cost between two polling locations. The demand model intakes historical turnout and turnout data from previous early election days of the current election. It utilizes linear regression and statistical forecasting to predict hourly arrival for each polling location each day until the election ends. To improve the overall system's performance and consider the up-to-date demand fluctuation, our proposed demand model, queueing network model, and optimization models should be run at the end of every pre-election day for the most up-to-date plan. Throughout the early election period, the election officials are to direct the realization of optimized inter-location transfers with a designated amount of resources of each type during non-voting hours based on the latest refreshed plan.

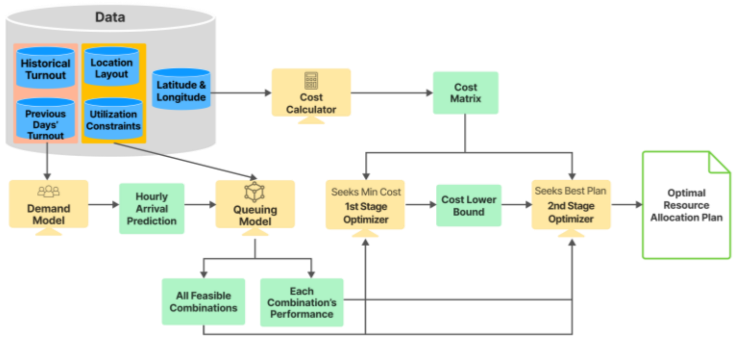

Figure 2: Illustrating the Proposed Dynamic Resource Allocation Framework

4.1 Queueing Network Analysis Model

The queueing network model takes the demand model's hourly arrival predictions, location layout constraints, and utilization rate constraints as inputs and computes all feasible resource combinations and each combination's performance for each polling location for all upcoming days until the election ends.

For each polling location on each day, we first select all feasible resource combinations that satisfy the location's layout constraint. Based on each feasible resource combination, the currently modeled queueing network considers three queues that simulate a full voting process: check-in at poll pads stations, casting votes at BMDs stations, and the scanner station, as displayed in Figure 3. A performance array is also initialized to record the performance values. The queueing network is then run for many iterations, such that results are stable and rigorous according to the Central Limit Theorem. Within each iteration, a voter-arrival array is built based on the hourly arrival prediction and used to compute and store the resource combination's performances, such as waiting time and each machine's utilization rate. Upon completing all iterations, we evaluate the current combination's utilization rates based on the stored performance values. If the utilization rates do not meet the utilization constraints, we will abandon the current combination. Otherwise, we continue to compute its robust waiting time and store it for future usage.

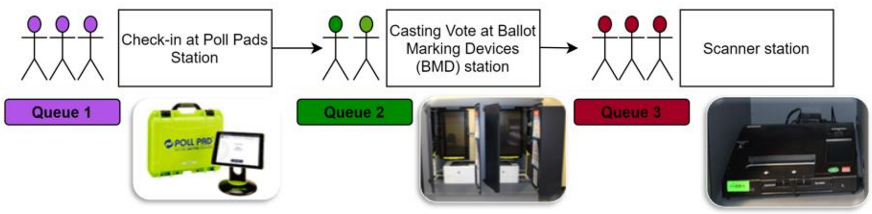

Figure 3: Demonstrating Queues within a Queueing Network

4.2 Allocation Optimization Model

The optimization model selects resource combinations from the queueing network model's computation results. The selected resource combinations are satisfied by utilizing a set of combination constraints, and the optimization model determines which location should transfer how many of which resources to other specific locations. A modified indifference-zone approach categorizes each resource combination's performance by translating its achieved robust waiting time (e.g., at 99.7%) into a performance score from 0 to 1, which does not need to exhibit a linear relationship and can be tuned as pertinent. This application results in a more effective resource allocation plan by preventing the optimization model from allocating more resources to polling locations that already satisfy most voters' expectations. For example, the

Presidential Commission on Election Administration (PCEA) suggests that most voters are willing to accept waiting times less than 30 minutes. As election resources are limited, in this illustrative situation, if a certain polling location's resource combination enables a 99.7% confidence waiting time of fewer than 30 minutes, an efficient resource allocation plan may not allocate more resources to this location by creating an indifference zone of all wait times below 30 minutes.

Our dynamic election resource allocation methodology aims to find less expensive, fast, and fair allocation plans, translating into three optimization objectives: minimize the total cost, maximize the total polling location performance score, and minimize the performance score gap. The third optimization goal would require searches for the best and the worst performances, resulting in a nonlinear optimization model that requires a long runtime. To resolve this challenge, we employ a pair of lower and higher performance score bounds within the optimization model, such that all selected resource combinations for all locations must have performance scores larger than the lower bound and smaller than the higher bound. By tightening the performance score bounds, we can create a set of fairness constraints to ensure a small performance gap between all polling locations on all days without nonlinear optimization models.

Cost minimization and performance score maximization conflict, as lowering the total allocated resources and limiting the number of transfers unavoidably result in certain polling locations not receiving enough resources for the best performance score. Therefore, our methodology employs lexicographic optimization in solving for the multi-objective system. Specifically, we rank cost minimization as the first objective and performance score maximization as the second and proceed according to the two-stage optimization methodology in Figure 4.

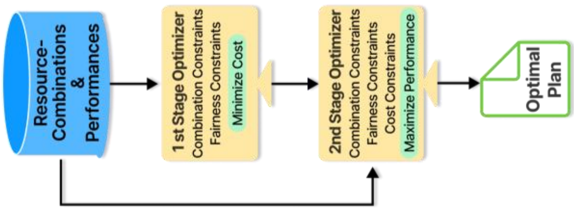

Figure 4: Showing the Optimization Model's Procedures

The stage-one optimizer takes the current resource allocation plan, combinations generated by the queuing model, and the cost matrix as inputs and finds the lowest possible total cost among all possible plans, satisfying the robust waiting time and fairness constraints. The stage-two optimizer utilizes all of the stage-one optimizer's inputs and constraints, and the relaxed cost lower bound produced by the stage-one optimizer as an additional constraint and finds the optimal plan that ensures low cost, low wait, and high fairness across all polling locations throughout the election.

5 Case Study

Fulton County, Georgia, is the state's most populous county, with a population of over 1 million, according to the U.S. Census Bureau in 2022. During the 2020 presidential election, Fulton County defined 238 polling locations, with 149 supporting early voting of 19 days. The turnout rate was approximately 65%, and around 60% of voters chose to vote during early elections. Based on Fulton County's 2020 presidential election, we construct two demand-fluctuation scenarios: a high early voting scenario and a low early voting scenario.

In both scenarios, we assume all polling locations each day exhibit the same hourly arrival percentage of their estimated voter turnouts as their counterparts on election day. The ratio between the daily voters of each polling location and the total voters of all polling locations on each day remains fixed. The total number of registered voters, the total turnout, and the number of absentee voters (voters by mail) are all consistent with Fulton County’s 2020 presidential election. We realize our previous applications of PI modules and examinations within the cost functions of optimization models. Furthermore, we assume each polling location only transfers resources to polling locations within the same commission district, corresponding to our localized transfer concern, and there are six commission districts.

The high early voting scenario assumes that 75% of the voters choose early voting. As the number of absentee voters remains unchanged, fewer voters vote on election day. Similarly, the low early voting scenario assumes 45% choose early voting, which results in more voters voting on election day. We made assumptions about these two scenarios based on the observed trend from the U.S. presidential election from 2016 to 2020. In 2016, approximately 45% of voters chose early voting, increasing to 60% in 2020. However, considering COVID-19’s impact and the CDC’s recommendations, it is unclear whether this trend will continue (Santana et al., 2020). Thus, we create two scenarios: the high early voting scenario corresponds to a continuation, and the low early voting scenario reflects a return.

We compare our allocation plan’s performance to the fixed allocation plan derived from Barenji et al., 2023. Although fixed, this allocation plan is developed through a multi-agent-based simulation platform and is superior to the official allocation (Barenji et al., 2023). We use a queueing network model separate from the one applied in the methodology to examine each polling location’s performances during the early voting period and election day. We split wait times into 6 ranges and utilize pie charts to demonstrate the percentage of polling locations within each range during early election and election day. Through the comparisons, polling locations that require more resources or expansion are identified.

Figure 5’s left side compares the fixed and dynamic allocation plans’ 99.7% rigorous wait times in the high early voting scenario. The fixed allocation plan allows all polling locations to wait less than 30 minutes throughout the early election. However, around 8% of polling locations saw voters waiting more than 30 minutes on the election day, within which most polling locations’ wait time lies in the 30-45 minutes range, and multiple polling locations’ voters are estimated to wait more than 150 minutes. Compared to the fixed plan, dynamic resource allocation enables all voters at all polling locations to vote after waiting for less than 30 minutes during early voting and election day, indicating a fairer waiting time distribution.

Figure 5’s right side compares the fixed and dynamic allocation plans in the low early voting scenario. The fixed allocation plan continues to provide efficient services throughout the early election. However, it results in more than 25% of polling locations with waiting lines of more than 150 minutes. During the early election, our dynamic plan allows most polling locations to have waiting times less than 30 minutes, and around 1% of polling locations will have waiting times above 30 minutes. On election day, the dynamic plan allows approximately 50% of voting locations’ voters to wait less than 30 minutes, more than 75% to wait less than 45 minutes, and 100% to wait less than 90 minutes. Due to fewer polling locations with long waiting times, the dynamic allocation is fairer than the fixed allocation.

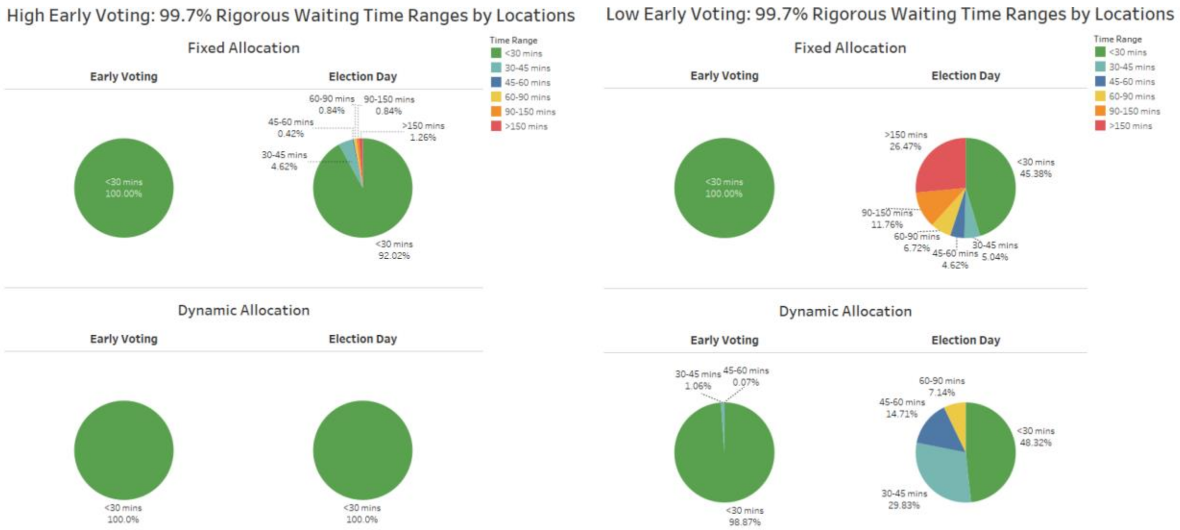

Figure 5: Comparing Fixed Allocation and Dynamic Allocation's Wait Times

In both scenarios, dynamic resource allocation requires fewer resources for early election and election day (Figure 6).

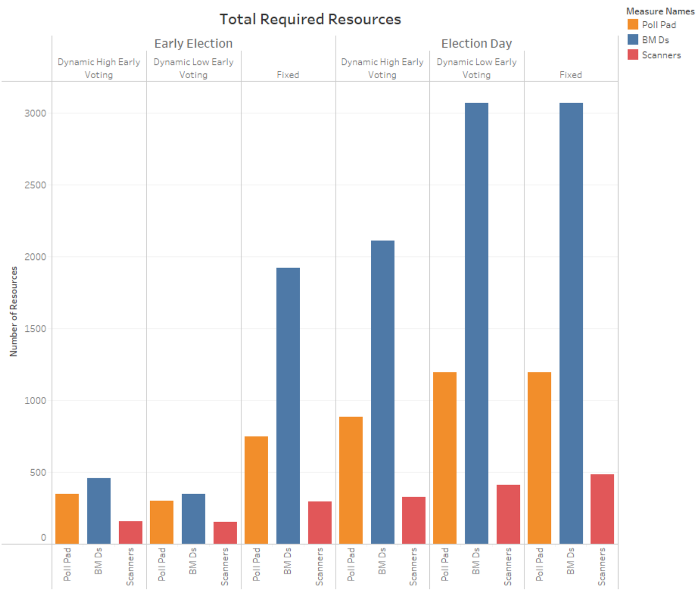

Figure 6: Comparing Fixed Allocation and Dynamic Allocation's Required Resources

Furthermore, dynamic resource allocation outperforms its fixed counterparts on average utilization rates of all three allocated resources in both scenarios (Table 1 and Table 2). This difference indicates that our dynamic methodology provides plans that exploit each piece of resource more scientifically, critically, and efficiently.

Table 1: Fixed Allocation and Dynamic Allocation's Average Utilization in High Early Voting

	Early Voting			*Election Day*		
	Poll Pads	*BMDs*	*Scanners*	*Poll Pads*	*BMDs*	*Scanners*
Fixed	10.2%	11.1%	6.5%	44.4%	47.6%	28.6%
Dynamic	24.8%	51.1%	12.7%	60.3%	68.2%	43.0%

Table 2: Fixed Allocation and Dynamic Allocation's Average Utilization in Low Early Voting

	Early Voting			*Election Day*		
	Poll Pads	*BMDs*	*Scanners*	*Poll Pads*	*BMDs*	*Scanners*
Fixed	6.4%	6.9%	4.1%	68.2%	73.0%	43.9%
Dynamic	16.3%	39.5%	8.0%	72.0%	75.2%	53.2%

We also want to point out that the fixed allocation considers social distancing, which puts a stronger location layout constraint on all polling locations (Barenji et al., 2023). Our model's allocation plan might require some polling locations to expand in practice. Policymakers should identify and improve such locations for better outcomes. Table 3 exemplifies a selected list of polling locations where our dynamic allocation improves performances and requires more resources than the fixed counterpart on election day in the low early voting scenario.

Table 3: Examples of Locations that Require More Resources on Election Day in Low Early Voting

	Fixed				*Dynamic*			
	Poll Pads	*BMDs*	*Scanners*	*Est. WT (mins)*	*Poll Pads*	*BMDs*	*Scanners*	*Est. WT (mins)*
Abernathy Arts Center	5	11	2	90-150	6	17	2	<30
Collier Park RC	3	6	1	45-60	3	9	1	<30
Johns Creek High School	5	14	2	60-90	6	16	3	<30
Morningside ES	6	18	3	60-90	9	19	4	<30

6 Conclusion

This paper leverages PI principles and proposes a SEPI and a smart dynamic resource allocation methodology to ensure efficiency, fairness, resilience, and security in election systems. Through a case study of two scenarios, the dynamic methodology outperforms the fixed allocation.

This study has four main contributions. First, it incorporates queueing network models and lexicographic optimizations to test and optimize resource combinations of each polling location on each day. Second, the proposed resource allocation methodology requires fewer input resources and performs better than a traditional plan. Countries or regions with constrained resources can exploit it to allocate resources efficiently and critically. Third, this study identifies critical polling locations requiring more resources or expansion for polling policymakers. Fourth, this study promotes a scientific procedure in political decision-making. By adopting and applying PI principles and ideologies, we can ensure a safer and more effective outcome that protects equality and democracy around the globe.

This study also opens three future research avenues. The first is to effectively determine a limited number of polling locations with resource allocation plans, especially in regions with less compact populations. The second is to predict voter turnouts considering multiple factors, such as weather and media. The third is to allocate polling location workers during days.

This study finds dynamic resource allocations beneficial and critical for election systems in providing voters with satisfactory services. Policymakers and election practitioners are encouraged to utilize the proposed methodology.

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Dynamic Directional Routing for the Physical Internet: A Sector-Based Approach with Dynamic Adjustment

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Abstract: *This paper introduces an innovative directional routing protocol tailored for the Physical Internet (PI), utilizing a sector-based approach that dynamically adjusts to optimize logistics across multiple transportation network tiers. By dividing the network into distinct sectors and implementing a hierarchical tier system, this method enhances the efficiency, reliability, and responsiveness of routing decisions by integrating real-time data on traffic density, container locations, and network disruptions.*

Our methodology combines sector-based logic with dynamic routing tables and modular PI-container capabilities, which facilitates the consolidation of shipments and improves the adaptability of the logistics network. Through comprehensive simulations, we demonstrate how our approach significantly reduces total travel miles, increases truck fill rates, and avoids congested hubs, thereby minimizing idle time and enhancing overall operational efficiency.

The findings underscore the potential of sector-based dynamic routing in achieving a more sustainable and resilient logistics network, paving the way for future innovations in the Physical Internet. Future research will focus on integrating multimodal transport options, refining the dynamic adjustment mechanisms, and further optimizing the routing protocol to handle diverse and changing logistics demands efficiently.

Keywords: *Physical Internet, Hyperconnectivity, Mesh Network, Routing Protocols, Network Architecture, Multi-tier Network, Service Networks*

1. Introduction

The Physical Internet (PI) represents a groundbreaking shift in logistics, aiming to establish a globally interconnected network that boosts efficiency through the integration of digital, operational, and physical aspects, inspired by the evolution of the Digital Internet (DI) (Fahim et al., 2021; Montreuil, 2011). PI is characterized by its dynamism and reactivity, which allow it to adapt and respond quickly to changes and disruptions, a capability enhanced by the use of modular PI-containers that facilitate the consolidation of shipments (Pan et al., 2021). However, the complexity of managing the PI network necessitates the development of robust, consensual, and decentralized routing protocols to ensure the network's functionality, especially in the face of disruptions (Sallez et al., 2016). Research on PI routing protocols has been diverse, ranging from efforts to optimize vehicle routing problems with complex algorithms to the exploration of distributed and reactive routing protocols inspired by DI protocols, acknowledging the similarities and differences between the two networks (Sarraj et al., 2014). Despite these advancements, challenges persist in fully integrating vehicles and containers into the decision-making process, managing disturbances effectively, and optimizing the overall performance of this interconnected and dynamic system (Yang, Pan, and Ballot, 2017a, 2017b). Recent studies have proposed innovative solutions, such as auction-based protocols (Briand, Franklin, and

Lafkihi, 2022) and dynamic container routing, yet often overlook the collaborative principles of PI, the mechanisms for re-routing in case of disturbances, and the integration of local knowledge into routing decisions. This highlights an ongoing need for the development of routing protocols that are specifically tailored to the unique characteristics and challenges of the Physical Internet.

This paper introduces a directional routing protocol designed to navigate the PI's intricacies, leveraging sector-based divisions, hierarchical tiers, and the capabilities of smart containers. Smart packages within the PI have the ability to transmit data regarding their location, destination, and condition. This capability allows for a more responsive and adaptive routing mechanism, where packages can actively participate in the routing decisions that affect their journey through the network. This approach leverages the principles of dynamic routing and sector-based forwarding, ensuring that the Physical Internet can achieve its goals of efficiency, sustainability, and resilience in the face of changing demands and conditions in the global logistics landscape.

2. Methodology

Our methodology is structured to enhance routing efficiency in the Physical Internet by systematically addressing both the discovery of potential routing areas and the selection of nodes within those areas. The methodology is divided into two primary phases: Area Discovery and Node Selection.

- **Area Discovery Phase:** This phase is critical in establishing the geographic context for routing decisions. It utilizes two main approaches:
    - Cardinal Sector-Based: The network is divided into sectors determined by cardinal directions. This method simplifies the identification of potential hubs by grouping them into universally recognized directional sectors.
    - Density-Adjusted Dynamic Sector-Based: This more sophisticated approach adjusts sectors dynamically based on the density of traffic and container locations, allowing for a more responsive routing environment.

  Both approaches aim to define 'candidate hubs' (those within the potential routing path) and 'non-candidate hubs' (those outside the potential path)

- **Node Selection Phase**: Once the area has been defined and candidate hubs identified, this phase involves selecting the optimal routing nodes within the confined area based on a set of predefined protocols. These protocols are designed to evaluate factors such as network congestion, travel distance, operational costs, and environmental impact. The selection process is guided by dynamic programming techniques to ensure that decisions are both optimal and adaptable to changing network conditions.

3. Area Discovery Phase

When a PI container has data to transmit, it initiates the process by identifying the area of communication that includes potential next-hop candidates. The goal of this phase is to establish an active region between the container location (origin node) and the destination node (which could be another hub within the Physical Internet), wherein all nodes within this defined area are deemed potential candidates for routing. Consequently, during this phase, communication between the container and the destination node generates a virtual pie-shaped region, as depicted in Figure 1.

3.1 Cardinal Sector-Based Routing (CSBR)

We divide the PI network into hierarchical tiers and sectors to simplify navigation and routing decisions. Each tier, ranging from unit zones to continents, is further subdivided into eight sectors based on cardinal directions (North, Northeast, East, Southeast, South, Southwest, West, Northwest). This structure facilitates both localized and global routing strategies.

3.1.1 Defining Sectors and Tiers

The PI network is categorized into hierarchical tiers:

- Unit Zones (e.g., a city block)
- Local Cells (e.g., a city district)
- Areas (e.g., a metropolitan area)
- Regions (e.g., a state or province)
- Continents

Each tier is further subdivided into eight sectors, defined by their relative geographic orientation (N, NE, E, SE, S, SW, W, NW). Dividing each tier into eight sectors based on cardinal and intercardinal directions serves multiple purposes in the context of the Physical Internet:

1. Efficient Routing and Distribution: Goods can be directed through the most efficient routes within a sector, minimizing transportation times and costs, and reducing the environmental impact.
2. Scalability and Flexibility: As the demand for logistics services changes, the sectoral division allows for the flexible adjustment of storage and transportation capacities within and across different sectors.
3. Localized Operations: Each sector can focus on optimizing operations based on local demand, supply characteristics, and geographical constraints, enhancing the overall efficiency of the logistics network.
4. Disaster Recovery and Risk Management: The sectoral approach helps in isolating disruptions (e.g., natural disasters, strikes) to a specific sector, enabling more effective contingency planning and rapid response strategies to ensure continuity of operations.

For example, consider a shipment in a local cell, the sector-based approach determines the most efficient path by identifying the sector in which the destination lies relative to the origin, optimizing the routing process.

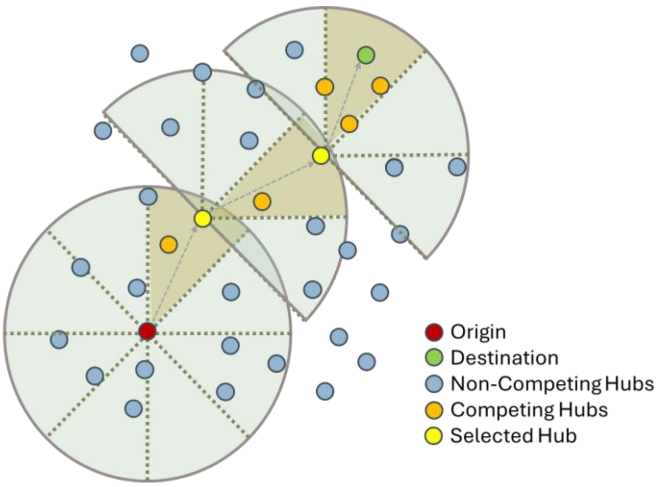

Figure 1: Example of a container path using CSBR Protocol in a single tier setting

3.2 Density-Adjusted Dynamic Sector Routing (DADSR)

This section introduces a refined approach to sector formation within the Physical Internet (PI) routing protocol, emphasizing dynamic adjustment based on the bearing from origin to destination and the density of the logistical network. This method, termed Density-Adjusted Dynamic Sector Routing (DADSR), enhances routing efficiency by tailoring sector boundaries to the specific geographic and logistical characteristics of each shipment path.

DADSR operates on the principle of creating sectors not solely based on fixed cardinal directions but by dynamically adjusting the sector's orientation and breadth based on the direct route from origin to destination and the density of available hubs within that trajectory. This approach ensures that each sector is optimized for both directness and logistical feasibility, addressing the key challenges of sparse network regions and ensuring robustness against network disruptions.

The key features of Density-Adjusted Dynamic Sector Routing (DADSR) are as follows:

- **Dynamic Sector Adjustment:** The base angle for sector creation is determined by the direct route from origin to destination. The sector then dynamically widens its angle to encompass a sufficient number of hubs, ensuring viable routing options.
- **Minimum Hub Inclusion Criterion**: A predefined minimum number of hubs within a sector ensures that each dynamically created sector has adequate routing infrastructure. If the initial sector does not meet this criterion, the sector's angle widens incrementally until the condition is satisfied.
- **Maximum Angle Constraint:** To prevent sectors from becoming impractically large, a maximum allowable angle or a maximum number of included hubs can be set. This ensures that while sectors adapt to include necessary infrastructure, they remain focused and efficient.
- **Network Density Awareness**: The approach inherently accounts for the varying density of the network across different regions, making it particularly suitable for large-scale, irregular networks like the Physical Internet.

3.2.1 Mathematical Model for DADSR

The mathematical model for Density-Adjusted Dynamic Sector Routing (DADSR) integrates geometric calculations for bearing determination with algorithms for dynamic sector adjustment based on the logistical network's density. The model consists of several key components:

- **Bearing Calculation:** Calculating the bearing (θ) from the origin (O) to the destination (D) using the formula involving latitudes and longitudes of the origin and destination and the difference in longitude between the destination and origin.
- **Dynamic Sector Formation:** Formation upon determining the bearing, the sector's initial angular width (ω) is set based on a predefined minimal criterion, which is then dynamically adjusted according to the density of the logistical network. The adjustment process follows:

  $$\omega = \omega_0 + \Delta\omega(n_{\min} - n)$$

  where:

  - ω_0: initial angular width,
  - $\Delta\omega$: incremental angle adjustment per hub deficiency,
  - n: actual number of hubs within the initial sector,

    - $n_{\min}$: minimum required number of hubs to ensure adequate routing infrastructure.

- **Minimum Hub Inclusion Criterion and Maximum Angle Constraint:** Ensuring practicality for routing purposes by maintaining a minimum number of hubs within the sector and a predefined maximum angular width. The dynamic adjustment continues until either the sector includes at least the minimum required number of hubs ($n \geq n_{\min}$), or the sector reaches a predefined maximum angular width ($\omega_{\max}$), ensuring the sector remains practical for routing purposes:

$$\omega \leq \omega_{\max}$$

- **Network Density Awareness:** The density of the logistical network (ρ) influences both the initial angular width (ω_0) and the incremental angle adjustment ($\Delta\omega$), with higher densities allowing for narrower initial sectors and smaller adjustments:

$$\Delta\omega = f(\rho),\ \omega_0 = g(\rho)$$

  where $f(\rho)$ and $g(\rho)$ are functions determining $\Delta\omega$ and ω_0 based on the network density ρ, respectively.

The central angle, α, is predetermined for all nodes within the network, and R represents the distance from the container to the edge of the network area, as shown in Figure 2. Nodes neighboring the origin node are categorized as competing or non-competing, based on their position and direction relative to the origin node. Nodes that fall within the active region of the container, denoted as x∈A, are considered competing, whereas those outside this area, indicated as x∉A, are deemed non-competing. It's important to highlight that the direct path from the container to the destination node forms the center of this active region.

3.3 Multi-tier Hierarchical Network

In the context of a multi-tier setting within the Physical Internet, the area discovery phase takes on additional complexity due to the hierarchical structure of the network, which includes Unit Zones, Local Cells, Areas, Regions, and Continents.

Upon a container's entry into the system, three critical elements are predefined: its origin (O), destination (D), and the required service level (S). According to Shaikh et al. (2021), the container routing algorithm efficiently navigates containers across the Physical Internet using a structured tiered hub system, which includes local hubs (Tier 2), gateway hubs (Tier 3), and regional hubs (Tier 4). The algorithm strategically determines the necessity to elevate a container to a higher-tier hub based on its current location within specific zones, cells, areas, or regions. For instance, if a container's journey spans different regions, the system escalates its routing through local hubs, gateway hubs, to inter-regional hubs, before traversing to the target region. Subsequently, it systematically de-escalates through gateway and local hubs, reaching its designated destination.

Building on the logic presented by Shaikh et al. (2021), we suggest refining the area discovery process to exclusively encompass candidate hubs within the specific tier relevant to the required escalations. In a multi-tier network when a PI container is ready to be moved, it not only creates a virtual pie-shaped region but also must consider which tier of nodes should be activated for potential routing. The central angle, α, and the radius, R, still define the scope of the active region, but the selection of potential next-hop candidates is stratified by the relevant tier. For instance, if the origin and destination nodes span different regions, the area discovery will focus on activating the corresponding tier's nodes that align with the container's path from origin to destination as shown in Figure 3. This tier-specific focus ensures that only nodes capable of efficiently forwarding the container towards its destination are activated, streamlining the route selection process. By concentrating on relevant tiers, the network efficiently manages the movement of containers, reducing unnecessary interactions and enhancing overall logistical efficiency.

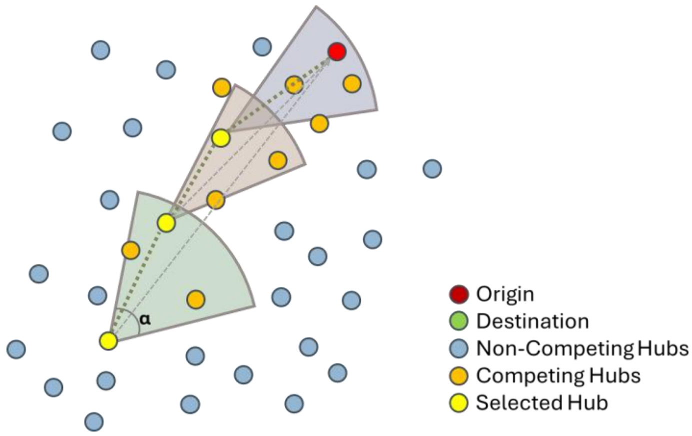

Figure 2: Example of a container path using DADSR Protocol in a single tier setting

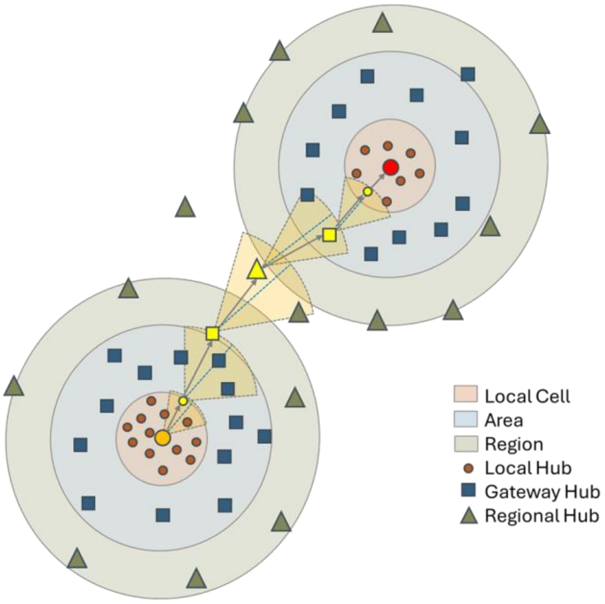

Figure 3: Example of a container path using the DADSR protocol in a hierarchical multi-tier network

4. Node Selection Phase

In this phase, nodes employ sophisticated dynamic routing tables that are continuously updated to reflect the real-time state of the network. These tables are integral to a decision-making framework that considers a wide array of metrics to guide the routing process. Each entry in a node's routing table captures critical information, including:

- Destination Sector: Identifies the target sector for the shipment.
- Estimated Transit Time: Predicts the time required to reach the next node.
- Waiting Time for Processing: Estimates waiting period for processing at the next node.
- Distance: Measures the physical distance to the next node.

- Cost: Estimates the monetary cost associated with routing through the next node.
- Environmental Impact: Assesses the carbon footprint of routing through the next node.

To address the diverse needs and priorities of PI users, the node selection phase has a flexible goal-weighting system. This system allows users or automated agents to assign varying degrees of importance to different routing goals, such as minimizing cost, reducing environmental impact, or optimizing for speed. The flexibility to prioritize goals can be achieved through the implementation of a weighted function.

5. Experimentation

The objective of this experimentation is to explore and demonstrate the efficacy of dynamic routing protocols, particularly focusing on directional routing and information sharing within the context of transportation networks. This research is structured to initially delineate an "area discovery" phase, followed by a "node selection" phase. While the area discovery process is designed to remain static, mirroring sector-based logic that does not vary with changes in node density, the study aims to delve into the implications of dynamic node selection in a single tier network. This is achieved through the application of directional routing, contrasting it with the traditional destinational (static) routing approach, which forms our baseline for comparison.

3.1 Model Assumptions

In the development of our PI network model, a series of foundational assumptions were made to streamline the complexity inherent in real-world transportation logistics, aiming to capture the essence of dynamic versus static routing protocols within a controlled simulation environment. Each truck is assigned to a parent node, adhering to the vision of the Physical Internet (PI) that emphasizes multi-segment transportation over traditional point-to-point deliveries.

Currently, the transport within the model is unimodal, exclusively focusing on truck-based delivery to isolate and examine time-based performance indicators without the complexities of multimodal trade-offs. This simplification, albeit a deviation from the PI's vision for integrated multimodal logistics, allows for a concentrated analysis on the efficiency of routing protocols within a singular mode of transport.

A uniform container size is adopted to streamline the simulation framework, sidestepping the complexities of cargo consolidation and optimization. While this simplification may not fully align with the diverse container sizes in real-world logistics, it ensures a consistent baseline for evaluating truck fill rates and the effectiveness of routing protocols across various scenarios.

The handling of trucks at nodes follows a First-In-First-Out (FIFO) queuing mechanism, simplifying agent interactions and reflecting a potentially realistic operational strategy employed by some logistics companies. Moreover, the arrival of new orders is modeled to follow a Poisson process, leveraging the 'memoryless' property of exponential distributions to simulate independent arrival events, a common approach in logistical simulations.

3.2 Baseline Static Routing Protocol

The baseline protocol is a static routing protocol where the containers take the shortest path from the origin to the destination, and do not change their routing decision during the simulation. This model presupposes a constant network topology and edge weights. Consequently, the shortest routes across the network only require computation once. Every node implements Dijkstra’s algorithm to construct a routing table. Due to the consistent routing of containers with identical source and destination through the same neighboring nodes, the static routing protocol organizes the node's inventory based on the subsequent destination.

The protocol, hereby called *FixedRoute*, employs four primary strategies to effectively manage the dispatch of trucks. The initial strategy is centered on the reassignment of idle trucks back to their original nodes. In cases where these trucks belong to different nodes and are transporting cargo in the same direction, priority is given to loading that cargo first. Furthermore, an element of 'patience' is introduced where trucks are allowed to wait at their destination briefly to accumulate more cargo, thereby optimizing their load capacity for each trip. Prior to dispatch, the protocol emphasizes the complete filling of trucks, particularly focusing on expediting urgent shipments to reduce potential delays. Finally, it adopts an urgency-driven approach to determine the sequence in which shipments are dispatched, ensuring that time-critical cargo reaches its intended destination in a timely manner. By integrating these strategies, our foundational protocol establishes a robust framework for comparison with more dynamic routing approaches.

3.3 Dynamic Routing Protocols

In this section, we explore the development and application of dynamic routing protocols within the framework of a directional routing concept. In this protocol, we no longer presume the edge weights in the routing table to be constant though we use the baseline edge weights and then adjust them to create the dynamic routing tables with updated weights. We achieve this in two ways. . The first protocol, hereby called the InformRoute, retrieves relevant information about neighboring nodes. It uses this information to make a more informed routing decision. This protocol assesses the anticipated waiting times for trucks at nodes by examining the arrival of incoming trucks, which includes the scheduled arrival times of trucks. The assessment process involves estimating the arrival time of a truck if dispatched immediately, followed by a simulation of inbound docks determine the minimum waiting time. This simulation incorporates the estimated arrival time into the queue and predicts the service sequence, taking into account the capacity of available inbound docks. When the queue goes beyond the capacity of the docks, the protocol establishes a minimum estimate for delays by calculating how long the docks will be occupied, affecting trucks that arrive later. The calculation of these unavailability periods, along with the earliest possible service time for trucks arriving later, allows for the adjustment of route selection to mitigate potential delays. Should the calculated earliest service time exceed the estimated arrival time, the protocol adjusts the routing decision by increasing the "weight" value associated with that edge. Note that we still take the shortest path in this protocol, but this time with the adjusted edge weights. This protocol tests the value of information in the network.

The second protocol, hereby called the *FlexRoute*, allows suboptimal paths, in the direction of the destination, to be taken if more containers can be transported that way. In our experimentation, we calculate the slack time of the container using the service level of the container and the shortest path from the current node to the destination. If the slack time is positive, then we can deviate from the shortest path, and we can see which are the candidate nodes such that the deviation does not cause a delay in service. This can be adjusted as per need, as sometimes the containers may inherently have some flexibility in their delivery date. If that's the case, the slack can be adjusted for that. In our current study, we assume that the delivery date is not flexible.

6. Results and Discussion

Our simulations evaluated the FixedRoute, InformRoute, and FlexRoute protocols within a single-tier network in the Southeast USA. Utilizing data from the Freight Analysis Framework (FAF) , we assigned inter-arrival times to origins and destinations in proportion to their flow magnitudes. To assess performance under diverse traffic conditions, we manipulated the load coefficients (0.6, 1, 1.4), representing low, medium, and high flow scenarios, respectively. Additionally, the hub network for our simulations was constructed based on the methodology outlined by Kulkarni et al. (2021). ensuring a robust and realistic testing environment.

Our analysis demonstrated that all protocols consistently achieved on-time delivery, with each protocol successfully delivering the containers within the specified service times. In Figure 4, we present the average truck utilization for all three protocols across various load coefficients. At lower load coefficients, the FixedRoute and InformRoute protocols perform similarly, as the InformRoute's advantage—its ability to adapt at bottlenecks—only activates under conditions of higher congestion, which are absent at these lower coefficients. As the load increases, InformRoute shows slightly better performance compared to FixedRoute reflecting InformRoute's adaptive capabilities as the network experiences more frequent bottlenecks.

For the FlexRoute protocol, it consistently outperforms both FixedRoute and InformRoute across all load coefficients. This superior performance can be attributed to its ability to dynamically alter its routing paths based on the potential for load consolidation, which enhances truck utilization more effectively than the other protocols, especially under higher load conditions.

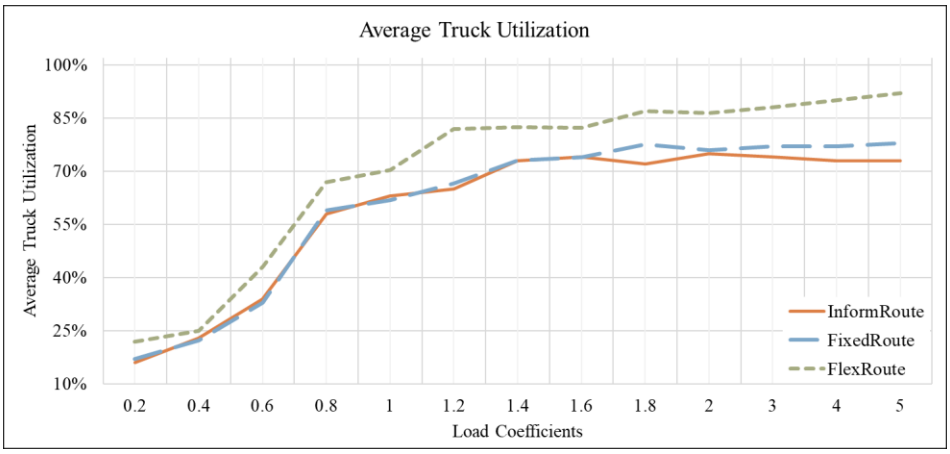

Figure 4: Average Truck Utilization across different protocols with increasing load coefficients

Figure 5 displays the traffic flow for FixedRoute, InformRoute and FlexRoute protocols under different load coefficients. This visualization highlights the distribution and volume of orders under each protocol, illustrating how FlexRoute adapts routing decisions based on increased order frequency.

Figure 6 offers a visual comparison of the routing paths selected by FixedRoute and FlexRoute for two distinct sets of origin-destination pairs. The first two maps on the left contrast the routes chosen under each protocol for one set of O-D pairs, showcasing the static versus dynamic nature of the routing decisions. The subsequent two maps on the right perform a similar analysis for another set of O-D pairs, providing further insights into how each protocol adapts to differing traffic conditions and routing challenges.

We observe that with the additional data utilized in the InformRoute, the total number of network edges engaged increased, indicating a more complex route selection process. Conversely, when allowing sub-optimal directional routing in FlexRoute, significant consolidation of routes was achieved. This adjustment suggests that FlexRoute is effective in optimizing the routing process by utilizing less direct paths that cumulatively reduce overall driving time and distance.

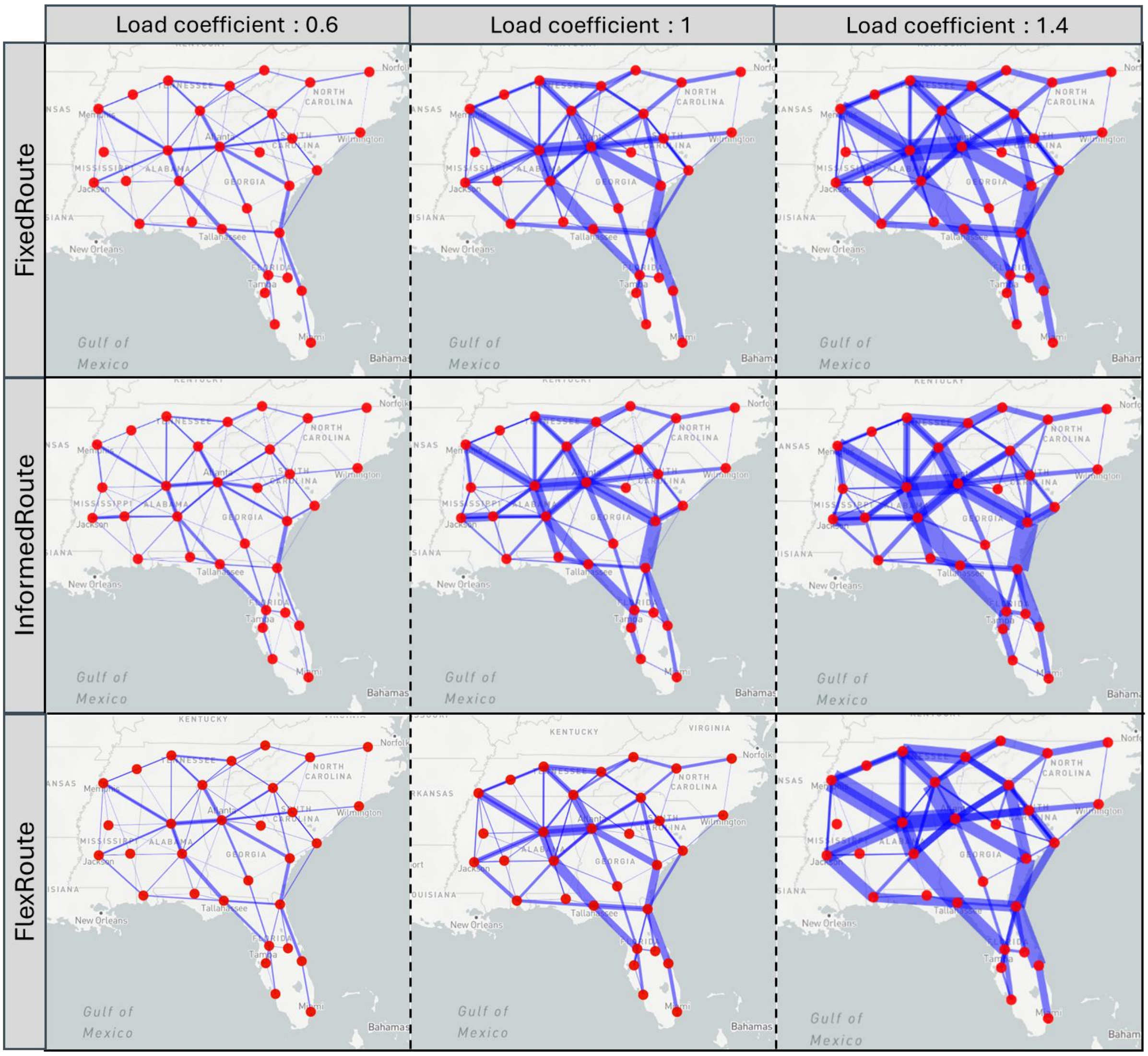

Figure 5: Comparative visualization of traffic flows under FixedRoute, InformRoute and FlexRoute protocols across varying load coefficients depicting the adaptation in routing strategies in response to changing densities

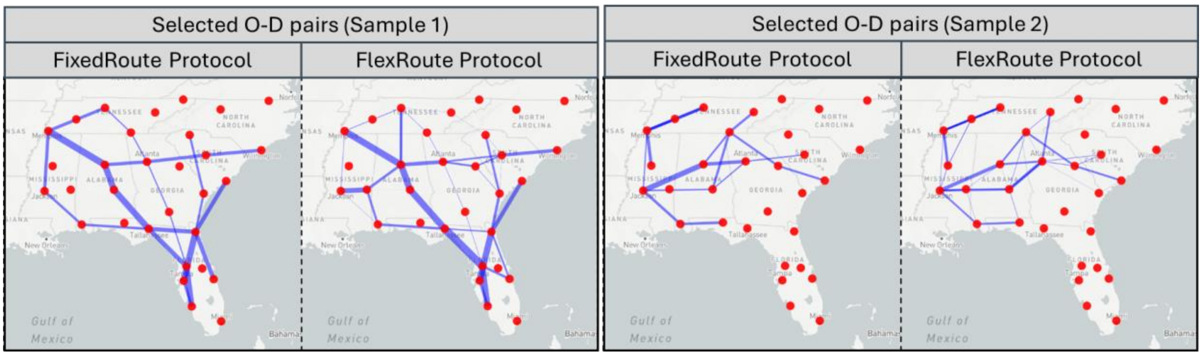

Figure 6: Route comparisons for two distinct sets of origin-destination pairs under FixedRoute and FlexRoute

We analyzed the driving distances for each protocol, as shown in Figure 7. This bar graph compares the driving time and distances between FixedRoute and FlexRoute across various load coefficients. Notably, FlexRoute achieves approximately a 6% reduction in driving time and distance at lower load coefficients, with even greater reductions at higher load coefficients. However, as the load coefficients increase beyond 1.4, the FixedRoute protocol consolidates more effectively than before, leading to a lesser reduction in driving distance.

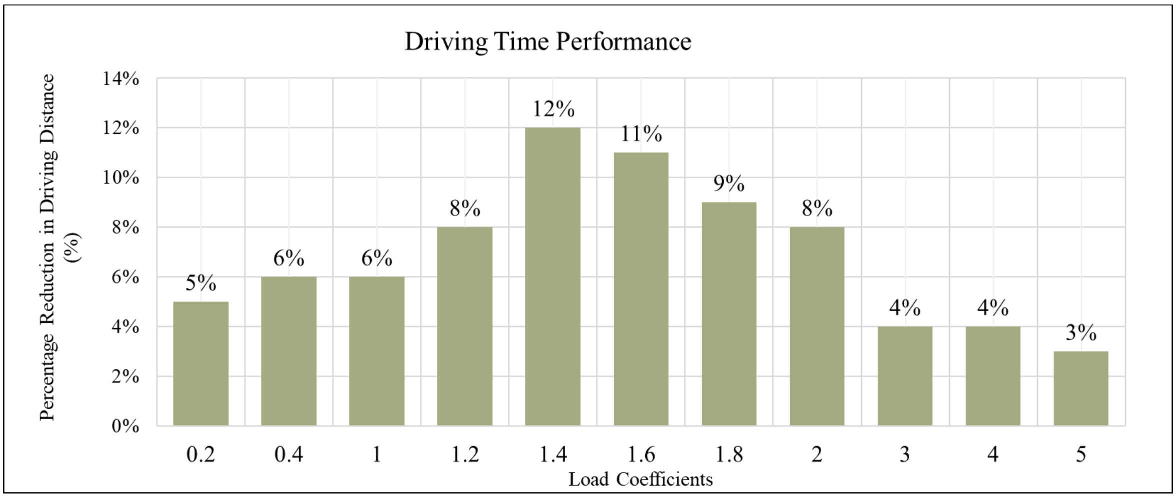

Figure 7: Comparative analysis of driving distances in FixedRoute versus FlexRoute protocols

7. Conclusion and Further Research

This study introduced a dynamic, sector-based directional routing protocol specifically tailored for the Physical Internet. By dividing the network into manageable sectors and dynamically adjusting routing decisions based on data from smart containers, we have laid the groundwork for a logistics system that balances efficiency, sustainability, resilience, and cost-effectiveness. Our results indicate that the proposed directional routing methodology enhances the ability to handle dynamic network conditions and disruptions effectively, thereby increasing the reliability and robustness of the Physical Internet. The flexibility of the model to adapt sector boundaries dynamically based on traffic density and shipment directions proves particularly beneficial in optimizing routing strategies and improving overall network performance.

In the future, the research will focus on several critical areas to enhance the capabilities and efficiency of the proposed routing protocol:

- Multimodality Integration: Future iterations of our model will include a more comprehensive integration of multimodal transport options. This will involve adapting our routing strategies to account for the unique characteristics and requirements of different modes of transportation, such as rail, air, and maritime, in addition to the existing road-based routes.
- Advanced DADSR Optimization: We plan to delve deeper into the parameters of Density-Adjusted Dynamic Sector Routing, optimizing its mathematical model and adjustment mechanisms. This will involve refining the criteria for sector adjustment, improving the accuracy of hub inclusion criteria, and fine-tuning the network density awareness functions. Advanced optimization techniques and machine learning algorithms will be utilized to dynamically adjust these parameters in real-time based on ongoing network performance data.

- Robust Testing and Validation: Comprehensive testing and validation of the enhanced model will be conducted across diverse scenarios and network conditions. This includes simulation-based testing as well as real-world pilot studies to evaluate the performance of the routing protocol under various logistical challenges and traffic densities.
- Parameter Sensitivity Analysis: A detailed sensitivity analysis will be carried out to understand the impact of different parameter settings on the performance of the routing protocol. This will help in identifying the most critical factors influencing routing decisions and network efficiency.

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PI-Service network design for fluvial cargo transportation.

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Abstract:

The use of rivers as transport corridors offers a cost-effective and environmentally sustainable alternative to road transport, facilitating the seamless movement of cargo from major maritime hubs to hinterland port cities. The objective of this research is to design an efficient transport service, inspired by the principles of the Physical Internet (PI), in a network that includes seaports and a set of river ports. This specific network is a missing link between local/regional road networks and deep-sea transportation lines. We consider the location of PI hubs as well as the determination of transportation routes, vessels and frequencies. We propose a mixed integer linear programming formulation of a service network design problem in the river network and explore the impact of a few business constraints inspired by the rules of the PI.

Keywords: *Physical Internet. Freight transport. Service Network design. Hub Location and Routing problem.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan:* ☒ *PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories),* ☐ *Transportation Equipment,* ☒ *PI Networks,* ☐ *System of Logistics Networks,* ☐ *Vertical Supply Consolidation,* ☐ *Horizontal Supply Chain Alignment,* ☐ *Logistics/Commercial Data Platform,* ☐ *Access and Adoption,* ☐ *Governance.*

Targeted Delivery Mode-s*:* ☒ *Paper,* ☐ *Poster,* ☐ *Flash Video,* ☒ *In-Person presentation*

1 Introduction

We address a Physical Internet Service Network Design (PI-SND) problem, immersed in a river network. The purpose of the network is to serve as an intermediate echelon between international maritime routes and hinterland ports and cities. The service will facilitate the trading of commodities through the main big maritime hubs, especially when they are located near waterways. Our goal is to contribute to the design of PI systems on this type of network.

Currently, a sustainable oriented design for logistic systems is on trend. River transportation systems are the most sustainable. Accordingly, PI-networks design on river networks are prone to be sustainable. An additional benefit for designing PI-Networks under sustainability principles is to reduce the transportation costs, because the river modal is the least expensive (Vilarinho et al., 2020).

The paper is organized as follows: Section 2 presents a brief literature review on service network design and its possible relationship with Physical Internet. In section 3 we present the problem settings and a mathematical model to tackle the PI-SND. Section 4 presents the results of computational experiments. Finally, we present the main conclusions of the research and future remarks.

2 Service network design and Physical Internet

In logistic networks, transportation service providers define services to transport commodities for stakeholders in a network. Therefore, to design them properly, the providers must define the frequencies, transportation modes, and routes to fulfil the demands of commodities (Wieberneit, 2008). A Physical Internet network is built from several segments and transportation modes, it is similar in terms of modularity and connectivity to backbone networks (Christiansen et al., 2020).

Krogsgaard et al. (2018) used a relaxed network, that is similar to a Physical Internet network in terms of segmentation and modularity of the transport. He used a PI-Networks as the basis to address a liner shipping network design problem. The design of the relaxed network is the first stage for a two-stage algorithm, an innovative approach to tackle efficiently liner shipping problem.

In our research we use Physical Internet Hubs (PI-Hubs). This kind of hubs are related to terminals on waterways and are useful for a rapid transit of freight (Pan, 2019). We use PI-Hubs on our service network designs to allow transshipments between routes.

Wang et al. (2023) addressed a liner shipping problem to include sustainability on vessel company processes. In a similar context Li et al. (2023), evaluated strategies to reduce CO_2 emissions produced by cargo transportation companies that operate on waterways. Accordingly, we can perceive an indirect relationship between the last two research and ours.

Interested readers on service network design can be referred to Brouer et al. (2017); Bu and Nachtmann. (2021); Christiansen et al. (2020); Monemi and Gelareh. (2017); we found those reviews relevant on theory and solution methods to address service network design problems, both on maritime and waterway/fluvial networks.

As far as we know, we could not find research directly related to ours. It is potentially a first attempt to address service network design problems on fluvial topologies, and that are also immersed on the PI context.

3 Problem settings and mathematical model for the PI-SND

In this section, we formally introduce the mathematical model for the PI-SND. The problem is based on a graph representation of the river network. Let G = (I, E), where the vertices $i \in I$ represent ports and the edges E represent segments of rivers between ports.

3.1 Data sets

The set of ports I includes a subset of candidate PI-hub, denoted $T \subset I.$ One main goal of the problem is to determine which candidate PI-hubs will be selected.

We consider a set K of commodities to be carried. each commodity $k \in K$ is represented by a triplet $\{o_k, d_k, q_k\}$, where o_k, is the origin port, d_k is the destination port and q_k the quantity to be carried.

Our formulation is based on a potentially large set of routes, denoted R. A route is a sequence of port calls. A route is operated by a given type of vessel, with a frequency that must be determined. The seamless interaction between routes is based on the utilization of PI-hubs where the goods can be efficiently transshipped from one vessel to another. However, the synchronization of route schedules at PI-hubs in order to reduce the commodities' delivery lead time is not considered in our mathematical model, which mainly concerns strategic decisions.

The liner network design literature considers several types of route patterns, including, for example, *circular*, *butterfly*, and *pendulum* (Christiansen et al., 2020). In this work, we consider circular non-elementary routes: the beginning and the end of each route take place at the same port, that is a candidate PI-hub. Given a route $r \in R,$ the predecessor and successor ports of port and a port i in route r (if they exist), are denoted $i-1$ and $i+1$, respectively.

We consider a heterogeneous set V of vessel types. Each vessel type $v \in V$ has a known capacity μ_v.

Note that in our proposed formulation, a route $r \in R$ corresponds to a unique trip executed once by a vessel type. Therefore, each repetition of the same "physical" itinerary results in a new copy of the route. A consequence is that a route can be identified in a unique way: it is associated with a vessel type, a schedule, and the commodities carried by the route.

A commodity $k \in K$ can be carried from its origin o_k to its destination d_k either directly by a single route, or by several interconnected routes. In the latter case, transshipments between routes are allowed only at PI-hubs. Transhipping a commodity requires both unloading it from a vessel and loading it on another vessel. These PI-hubs represent the highest investment costs in the whole network. Therefore, one important decision variable in the proposed mathematical model is the selection of the PI-hubs from a list of candidate locations.

3.2 Costs and other data

The fixed cost for locating a PI-hub at node $i \in T$ is denoted f_i. The cost of using a route with empty vessel is represented by C_r. The additional cost for every unit of commodity traveling on edge $(i,j) \in E$ is denoted $CT_{i,j}$. The cost of loading and unloading commodities at port i is denoted by P_i^+ and P_i^-, respectively. We consider a time horizon H fixed and t_{rv} is the time required to complete route r with vessel $v \in V$.

The flow indicator γ_{ir} is equal to 1 if port i is in route r, and 0 otherwise. The parameter $\propto_{ijr}$ indicates if route r visits ports i and j in a consecutive manner, in other words $\propto_{ijr} = 1$ if $\gamma_{ir} = 1 \wedge \gamma_{jr} = 1$, and 0 otherwise.

3.3 Decision variables

We define the following variables: binary variable Z_i takes value 1 if port i is selected as a PI-hub, and 0 otherwise. The location and the quantity of PI-hubs are not known in advance. The ports that are not selected as PI-hubs can be used only to load or unload commodities, not for transshipment.

The integer variables x_{rv} measure the number of times route r is performed by vessel type v. Binary variable x'_r is equal to 1 if route r is selected, 0 otherwise. Binary variable y_{kir}^+ is equal to 1 if commodity k is loaded on route r at port i and binary variable y_{kir}^- is equal to 1 if commodity k is unloaded on route r at port i. Binary variable u_{kir} is equal to 1 if commodity k is on route r departing from port i.

We define continuous variables L_{ri} to represent the total cargo traveling on route r departing from port i.

3.4 Mathematical formulation

With the above notations, we now give the mathematical formulation of the PI-SND problem:

$$Min\ Z = \sum_{i \in I} f_i z_i + \sum_{r \in R} c_r x_{rv} + \sum_{k \in K} q_k \sum_{r \in R} \sum_{i \in I} CT_{i,i+1} u_{kir} + \sum_{k \in K} \sum_{r \in R} \sum_{i \in I} (P_i^+ y_{kir}^+ + P_i^- y_{kir}^-) \quad (1)$$

s.t.

$$\sum_{r \in R} y_{ko_k r}^+ = 1 , \forall k \in K \quad (2)$$

$$\sum_{r \in R} y_{kd_k r}^- = 1 , \forall k \in K \quad (3)$$

$$\sum_{r \in R} y_{kir}^+ \leq z_i\ \forall k \in K , \forall i \neq o_k, \forall i \in T \quad (4)$$

$$\sum_{r \in R} y_{kir}^- \leq z_i\ \forall k \in K , \forall i \neq d_k, \forall i \in T \quad (5)$$

$$\sum_{r \in R} y_{kir}^- = \sum_{r \in R} y_{kir}^+ , \forall k \in K, \forall i \in I, i \neq o_k, i \neq d_k \quad (6)$$

$$\sum_{i \in I} y_{kir}^- = \sum_{i \in I} y_{kir}^+ , \forall k \in K, \forall r \in R \quad (7)$$

$$y_{kir}^+ \leq \gamma_{ir} x_r' , \forall r \in R, \forall i \in I, \forall k \in K \quad (8)$$

$$y_{kir}^- \leq \gamma_{ir} x_r' , \forall r \in R, \forall i \in I, \forall k \in K \quad (9)$$

$$u_{kir} \leq \gamma_{ir} x_r' , \forall r \in R, \forall i \in I, \forall k \in K \quad (10)$$

$$u_{k0_r r} = y_{k0_r r}^+ , \forall k \in K, \forall r \in R \quad (11)$$

$$u_{kd_k r} = 0\ \forall k \in K, \forall r \in R \quad (12)$$

$$u_{kir} \geq u_{k(i-1)r} - y_{kir}^- , \forall k \in K, \forall r \in R, \forall i \in I \quad (13)$$

$$u_{kir} \geq y_{kir}^+ - u_{k(i-1)r} , \forall k \in K, \forall r \in R, \forall i \in I \quad (14)$$

$$u_{kir} \leq 2 - u_{k(i-1)r} - y_{kir}^- , \forall k \in K, \forall r \in R, \forall i \in I \quad (15)$$

$$u_{kir} \leq u_{k(i-1)r} + y_{kir}^+ , \forall k \in K, \forall r \in R, \forall i \in I \quad (16)$$

$$L_{r0_r} = \sum_{k \in K} q_k y_{k0_r r}^+ , \forall r \in R \quad (17)$$

$$L_{ri} = \sum_{k \in K} q_k u_{kir} , \forall r \in R, \forall i \in I \quad (18)$$

$$L_{ri} \leq \sum_{v \in V} \mu_v x_{rv} , \forall r \in R, \forall i \in I \quad (19)$$

$$t_{rv} x_{rv} \leq H , \forall r \in R, \forall v \in V \quad (20)$$

$$x_{rv} \in \{Z^+\}, \forall\, r \in R \tag{21}$$

$$u_{kir}, y^+_{kir}, y^-_{kir}, x'_r \in \{0,1\},\ z_i \in \{0,1\}\ \forall\, k \in K, \forall\, r \in R, \forall\, i \in I \tag{22}$$

$$L_{ri} \geq 0\ \forall\, r \in R, \forall\, i \in I \tag{23}$$

Objective function (1) minimizes the total cost, including the cost to locate PI-hubs, the transportation costs and loading and unloading costs. Constraints (2)-(3) indicate that commodities k have to be loaded and unloaded at their corresponding origin and destination ports. Constraints (4)-(5) are used to locate the PI-hub at nodes in set T. The group of constraints (6)-(7) are used to establish the transshipment operations at PI-hubs.

Constraints (8)-(9) establish that a commodity can be loaded or unloaded at port i in route r, only if the route is selected and port i is in that route. Similarly, constraints (10) says that there can be only flows between port i and port $i+1$ if the respective route and ports are selected. Constraints (11) establish that commodity k is in route r at the first port of the route 0_r only if it is loaded in that port.

The set of constraints (13)-(16) define the scenarios when a commodity k is in route r or is not present at it.

Constraints (17) define the load at the starting port of a route is equal to the quantity of commodity loaded in that specific port and route. Group of constraint (18) are used to calculate the load of commodity that is leaving port i.

Constraints (19) establish an upper bound for the quantity of commodity that can be loaded at a vessel. Constraints (20) are used to establish the frequency of each route.

The group of constraints (21)-(23) define the nature of the variables used in this mathematical formulation.

3.5 Additional constraints

We also implemented two ideas that contribute to reduce the organizational complexity of the transportation network:

(i) Following the idea of relay-hub network in truckload transportation (Üster and Kewcharoenwong, 2011), PI-hubs are considered as relay points where different routes meet. Therefore, we assume that the selected routes will be adjacent to other routes only at PI-hubs.

(ii) To avoid overlapping of routes and favor efficient connection at PI-hubs, we assume that each segment of the river network between two PI-hubs is serviced by a single route. This *route-partitioning constraint* prevents routes overlapping and, therefore, clarifies the geographical areas and services offered by each carrier.

The group of constraints (24) avoid the overlapping of arcs between different routes. Constraints (25) define the maximal number of trips by each route, and constraints (26) reinforces it with a tighter bound.

$$\sum_{r \in R} \alpha_{ijr} x'_r \leq 1, \qquad \forall\, i \in I, \forall\, j \in I \tag{24}$$

$$x_{rv} \leq \left\lceil \frac{H}{t_{rv}} \right\rceil x'_r, \qquad \forall\, r \in R, \forall\, v \in V \tag{25}$$

$$x'_r \leq \sum_{v \in V} x_{rv}, \qquad \forall\, r \in R \tag{26}$$

4 Computational tests

We developed a case study based on the Lower Rhine region in the Netherlands, Belgium and Germany. This region includes 20 main ports. We considered actual traveling times between ports. The main data of our case study (commodities' features, transportation costs, fixed cost of PI-hubs, transshipment cost, traveling times etc.) were randomly generated according to values found in various professional sources and public reports.

Table 1 depicts the cardinality of the main data sets used to design 96 instances.

Table 1: Parameters for data generation

Sets	Symbol	Values
Ports	I	15, 20
Routes	R	25, 30, 35, 45
Origin-Destination pairs	o_k, d_k	50 to 160 (steps of 10)
Type of vessels	V	3

The mixed integer linear programming formulation was solved by the Gurobi solver (9.1.1) on an Intel Xeon 6230 CPU @2.1 GHz using 4 threads. The time budget to get optimal solutions was set to 2 hours. Figure 1 presents the results for CPU times for solving instances with 15 ports. All instances are optimally solved within 2 hours, except by two instances for which optimality gaps close to 4% can be observed.

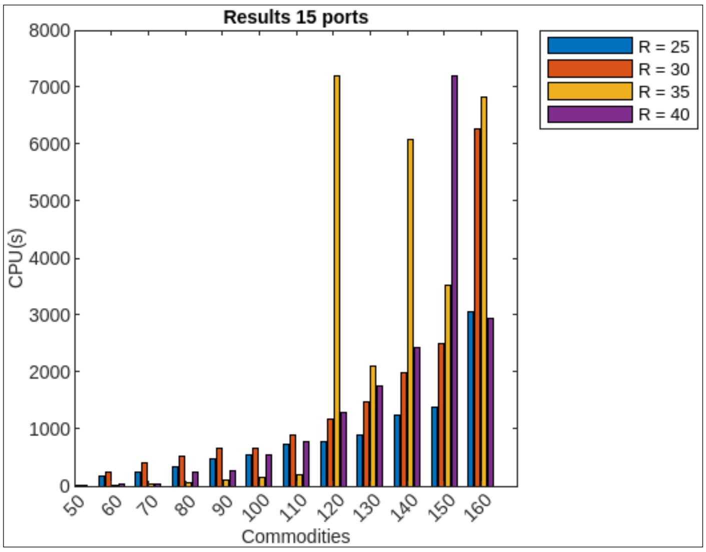

Figure 1. Results 15 ports

Figure 2 presents the results for CPU times for solving instances with 20 ports. Only 44% of these instances can be solved to optimality within the limit time of two hours.

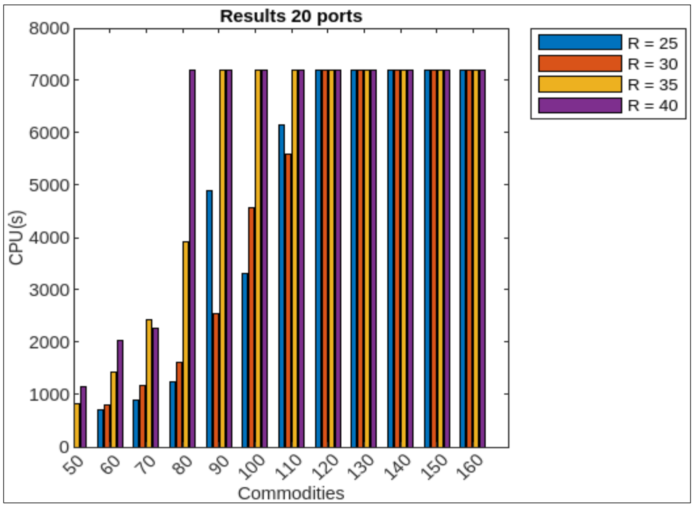

Figure 2. Results 20 ports.

Figure 3 presents the optimality gaps (in %) for instances with 20 ports. We can observe that the number of commodities and the number of routes are the main drivers of computational complexity. We do not present the optimality gap for instances with 15 ports, because 96% of the set of instances is solved to optimality.

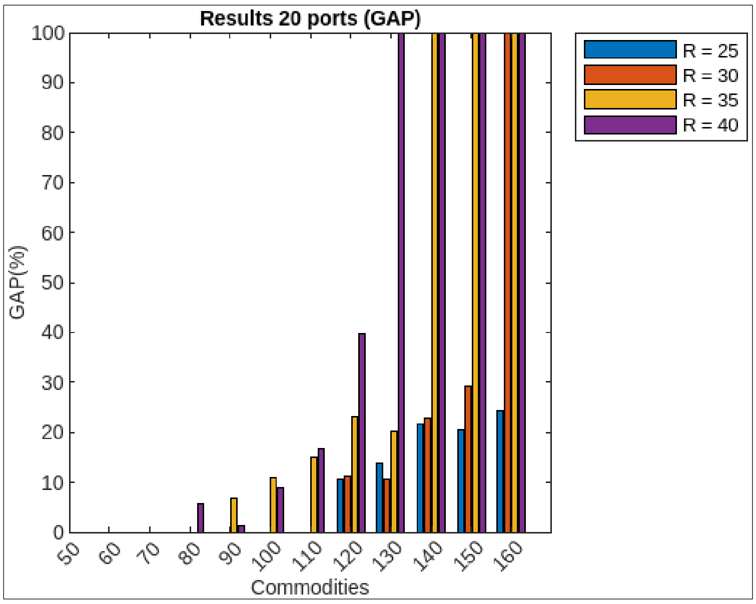

Figure 3. Results 20 ports (GAP)

Figure 4 and Figure 5 aim at identifying the effect of the route-partitioning constraint on the total transportation costs, on instance with 15 and 20 nodes, respectively. In each graphic, the horizontal axis represents the number of commodities and the vertical axis represents the total cost of the optimal solution or best-found solution (when the limit budget time is reached without finding an optimal solution).

In figure 5 we only present results for instances solved to optimality ($k = 50, 60, 70$), because it is the best method to do a fair comparison of the results. The blue lines correspond to the cost of solutions when route overlapping is allowed (the route partitioning constraints are deactivated). The red lines correspond to the cost of solutions when the route partitioning constraints are activated.

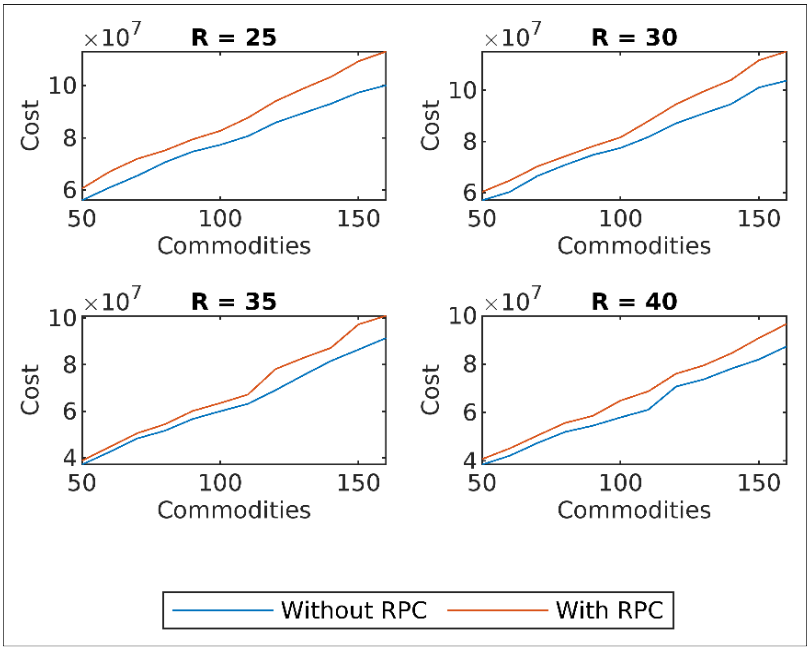

Figure 4: Comparison of transportation costs for instances with 15 ports, with and without route-partitioning constraint (RPC).

Transportation costs increase because of the activation of the route-partitioning constraint. For the set of instances with 15 ports, the total transportation cost increases on 8% on average, for the set of instances with 20 ports the total transportation costs increases on 36% on average. It must be noticed that the average percentage increase on total transportation for instances with 20 ports must be further analyzed; because in this section we are presenting results for instances solved to optimality.

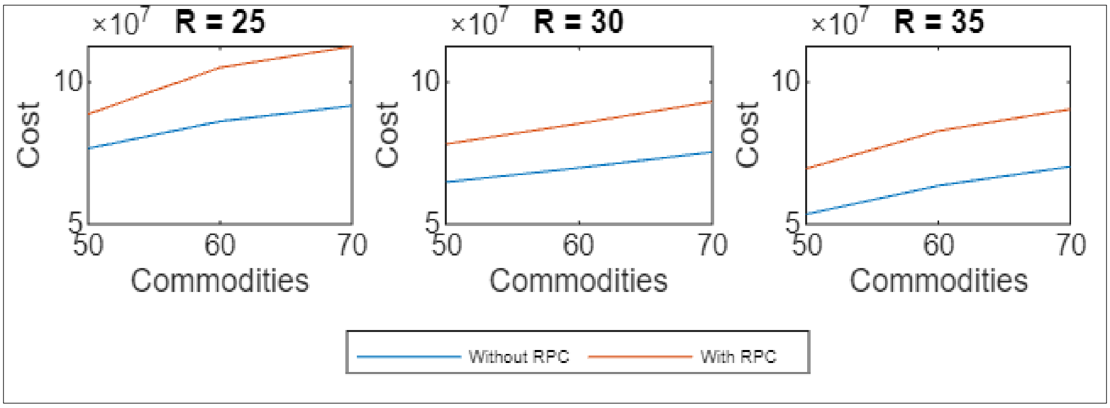

Figure 5. Comparison of transportation costs for instances with 20 ports, with or without the route-partitioning constraint (RPC).

5 Conclusion

In this paper we proposed a mathematical formulation of a service network design (SND) problem that can arise in the waterborne segment of Physical Internet networks. This works extends traditional SND models by considering practical considerations, the partition of a territory into independent routes that are connected only at PI-hubs.

Adding route-partitioning constraints increases the total cost by 22% on average. This cost increase is offset by a simplified network management. Comparing additional KPIs such as the GHGs emissions and service levels is among our further research objectives. The optimization of those KPIs could be determinant to confirm the benefits of using the route partitioning constraints.

The computational time necessary to solve our proposed model is mainly determined by the number of ports and commodities, then the number of routes. In particular, we plan to propose an alternative formulation based on the commodities' itinerary. This formulation would implicitly consider the transshipment, thus drastically reducing the number of decision variables.

One future remark is to include the resilience attribute to this kind of PI-service network design. The goal is to have PI-Hubs with resilience attributes, therefore, the services are more suitable to face disruptions in the overall network design. It would be interesting to appreciate the impact of the resilience attribute on the transportation costs, and it would be significant to validate the compatibility between more resilient services and the route partitioning constraints.

For future research is relevant to consider an itinerary based mathematical formulation for the PI-network design problem. This formulation will have immersed the location of PI-Hubs at it could be an initial step to solve larger instances on reasonable time.

Current formulation could be extended, aiming for a ramp-up for the trading process between the river network and ad-hoc cities to it. The sustainability of this multi-modal network could reduce greenhouse emissions, mainly from road trucks.

An interesting extension of the mathematical formulation in this work is to include constraints to design fluvial transportation services considering the draft of the heterogeneous fleet of vessels. The draft of the vessels will limit their access to clusters of ports located in specific regions of the waterway. Adding the draft constraints is useful to solve instances more related to real case scenarios. A similar extension for future research, would consider the impact of canals and similar infrastructures on service network designs.

Finally, working on larger networks and a larger number of commodities requires resorting to efficient decomposition algorithms or to heuristically solve the optimization problem.

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Stakeholder Cooperation for Network Feasibility in Electrified Freight Hyperconnected Logistics Networks

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Abstract: *For the implementation of electrified fleets, network feasibility is a large hurdle, simplified by battery swapping and charging technology. This paper identifies seven major stakeholders in the NetZero goal towards road-freight electrification, battery suppliers, energy and power distribution representatives, fleet carriers, hub operators, logistics operators, users of the system, and truck drivers. The argument of loose cooperation between stakeholders will enable a simplified and efficient integration of electric trucks into trucking systems following the Physical Internet methodology. Under the goal of hyperconnected logistic networks, the targets of cooperation, associated benefits, and overall outcomes are outlined. The paper seeks to demonstrate how guiding expectations from design to implementation can maximize environmental impact and build resiliency at every level of the network.*

Keywords: *Hyperconnected Logistics Network, Electrified Freight Systems, Physical Internet, Battery Swapping, Battery Charging*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan:☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories),☐ Transportation Equipment, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

Targeted Delivery Mode-s*: ☒ Paper, ☐ Poster, ☐ Flash Video, ☐ In-Person presentation*

1 Introduction

With increasing consumer demand comes increasing transportation costs, costs measured by dollars, miles traveled, and CO2 emitted. The EPA reported that in 2021 Medium and HeavyDuty trucks emitted about 407.8 million metric tons of just CO2 [US EPA (2023)] in the United States. To combat such environmentally detrimental outputs, clean energy can replace gas or diesel fuel sources in freight systems. With equally demanding customer bases for rapid deliveries, transportation and commerce networks are being revolutionized. To keep up with innovation and implement clean energy sources, solutions must incorporate modular techniques to prevent additional costs to networks.

In the Physical Internet (PI) template for freight supply chains, electrification limits trucks to be serviced at hubs of optimal route-flow and of electrically feasible charging bays. This combination requirement under battery reenergizing significantly filters capable hubs in the network when constructing charging bays. Doing so at all the facilities in a network pose financial investment challenges. These additional locations may lack electric grid capabilities as well, leading to the route-optimal structure already existing under the Physical Internet infeasible. Since battery charging also requires the electric trucks to be charged at bays in the determined feasible set of hubs, the charging time will often be far greater than estimated dwell time for the facility [Bernard et al. (2022)]. Factors like driver motivation and incurred costs from lag-time minimize the profit achievable through electrification.

An alternative technology, battery swapping eliminates the need for trucks to be charged during hub stops, alleviating long wait times. Known to average around five minutes per swap [Zhu et al. (2023)], the function can be built into existing dwell times for vehicles in the optimized route. However, relying solely on battery swapping poses additional complexity in physical battery inventory management, algorithms on battery swapping optimization policy, and the direct costs of purchasing batteries. Eventually every battery in the system must be reenergized, requiring charging stations like battery charging with different specifications. Without fully charged batteries for every time cycle of transportation, the flow will halt.

The combination of two related technologies, battery charging (BC) and battery swapping (BS) can generate more implementable solutions under the Physical Internet framework. The electrification of hyperconnected logistic networks (HLN) will propose less barriers to entry and maximize the marginal utility of electrification. Hyperconnected logistic networks offer resiliency and sequential decision making [Crainic, Gendreau (2020)] by taking in modular container routing to provide optimized policies on which fuel method should be assigned to each arrival [Grover et al. (2023)].

2 Research Objective

Taking into account combined advantages of implementing networks fitted with both battery swapping and battery charging technologies, we explore the steps needed to develop capable electric freight systems. Drawing from literature, an outline of expectations from associated stakeholders will be introduced for efficient integration of the electrification of freight vehicles. In this paper, we seek to highlight the cooperation of major stakeholders to implement hyperconnected logistic networks and a framework for collaborative innovation to reach NetZero goals across industries and maximize environmental impact.

3 Literature Review

Electric vehicles and associated research have exponential grown in the past five years to match market interest. Much research has focused on optimization models for battery charging logistics systems, integration of battery swapping at DCs, solving the logistic challenges of this solution, and electric grid capabilities and technology. Exploring modeling techniques, some define swapping stations with arrivals following distributions, other model for unpredictable arrivals, and others to minimize operating costs. Models also vary in constraints, where some focus on quantifying nodes in the network, batteries in inventory, or both. Few projects focus on the integration of related industries, all essential to the implementation of electric fleets. A few studies are presented to capture the overall theme and focus of modeling work.

Management of battery inventory and charging are critical operations to implement electrified fleets at a level of commercial advantage. The mathematical model for battery swapping stations developed by Mahoor et al. (2019) minimizes daily operating costs and found that charging schedules minimize costs and can track degradation of batteries with random customer requests. Similarly, Raeesi and Zografos propose a route planning model for electric commercial vehicle

battery swapping for freight logistics in 2020. Inventory management for battery swapping will be crucial to embedding electric vehicles in freight systems. Other models like Raessi and Zografos in 2022 propose increasing driving range through a BS algorithm that swaps batteries en-route. Two studies based in China focus on heavy duty trucks. By studying the operating cost of electric trucks, Wu depicts how the growth of battery swapping stations can be quantified in terms of environmental contribution. Wang models a bi-objective model for battery swapping in Beijing based on trajectory data analysis.
More recent literature incorporates multiple layers in battery swapping modeling. Deng et al. (2023) focus on battery degradation to propose an optimal design for swapping policy.

Literature shows the capabilities of technology. Now, the integration and partnership amongst stakeholders across technologies is needed to have an efficient transition to electric fleets. The work presented by Revankar & Kalkhambkar (2021), Zhang et al. (2020), Bernard et al. (2022), and Çabukoglu et al. (2021) are some of the few which have studied the implementation of these technologies within a freight fleet. Their conclusions that while Battery Swapping and Battery Charging are more cost effective [Revankar, Kalkhambkar (2021)] to logistic networks, their combination with advanced energy sources are necessary for full transition to electrified fleets [Zhang et al. (2020)]. Currently, the technologies are available but have large barriers to entry such as weight constraints, requiring hyperconnected networks [Grover et al. (2023)], and high energy consumption levels across networks [Çabukoglu et al. (2021)]. However, through more strategic partnership and policy, electrified fleets can be integrated into networks in the near future [Bernard et al. (2022)].

4 Barriers to Implementation

The 2023 Transportation Research Board Annual Meeting's fleet electrification workshop identified five key challenges, transit knowledge, high demand charges, charging infrastructure, electric grid capabilities and permits, and high initial investment [Zazir et al. (2023)] to the integrated electrified fleets. In the lens of hyperconnected logistic networks, the first three barriers to implementation are weight constraints due to battery technology, integrated hub networks for freight systems necessary to "refuel" trucks, battery swapping and charging, and high energy needs within networks. In this study, the associated challenges specifically for network feasibility are explored, and how a few general working assumptions can greatly mitigate them.

In a given network, the switch to electric vehicles, or trucks, pose large upfront investments for conversion. While large carriers are known to upgrade around 10% of their fleet every year, having this percentage converted to electric vehicles would be naïve without broader preparation and analysis. A larger factor into initial investments arise around the physical attributes of facilitating an electrified fleet: costs from vehicles, batteries, swapping stations, and charging stations. The specifications of vehicles and batteries greatly impact flow due to their proportionately greater weight and limited range. Another major incentive to fit electrification with both battery swapping and charging technologies, efficient refueling policy can remove the barrier increased weight imposes to flow transit. Despite these costs, battery swapping models show the profitability of electrified fleets due to the significantly lower daily operational costs [Zhu et al. (2023)].

One step further, the construction of swapping stations requires government authorization, energy availability & consumption analysis, and strategic placement in a network. Without this, the stations would not provide an able and more importantly quick service to vehicles during their routes. The relationship between swapping batteries off vehicles and recharging the depleted capsules would need to be timed to satisfy arrivals across the entire network.

In terms of the transshipment organization, the network will need to track batteries, vehicle power levels, and available batteries along transportation paths to ensure the vehicle can safely leave a destination and arrive at the necessary hub. In the scheduling of flow of goods, the routes must fit the relay formatting enabling trucks to "refuel" without increased lag times at facilities. This would require detailed planning, operations, and network communication, further highlighting the impact of a hyperconnected logistic network. At individual hubs in the network, a system is needed to recommend swapping policies, or charging directions for a given arrival. This requires connectivity to the larger network, adjacent hub operations, and the overall context of power supply in the given technology. While the full-scale implementation will take time, these immediate challenges delay the integration of electrified fleets and prevent electric ground transport from satisfying consumer demand while decreasing greenhouse gas emissions.

5 Stakeholder Definitions

Like any initiative, the NetZero goals for ground transportation have barriers to implementation, but key stakeholders can minimize these challenges by innovating under some general expectations. The seven main stakeholders focused on in this review, battery providers, energy representatives, drivers, fleet carriers, facility/hub operators, logistic operators, and corporate teams representing the system users, have direct links to the electrification goal.

Battery Suppliers and Producers: Technology representatives have control over battery design, specification, price, licensing, and connectivity with vehicles. It is assumed that a finished good, the battery, is supplied, and associated maintenance and operational knowledge is shared with other stakeholders.

Energy and Power Distribution (including government entities): The consumers (other stakeholders) are required to consult the energy and power distribution representatives to build charging and swapping stations. This stakeholder will provide context on the feasibility of energy distribution to a particular location, the cost, and the required safety for additional energy consumption.

Fleet Carriers: This category represents the various parties in truck-fleet operations, including private companies, trucking companies, and owner-operators. While there is a large overlap between fleet carriers and truck drivers, the distinction allows truck drivers to focus on dayto-day vehicle operations, while the fleet carriers are more interested in route planning, management, overall operations of goods' transportation in association with hubs.

Facility/Hub Operators: To simplify, hubs, distribution centers, and warehouses are all treated as facilities. At each location, managers and staff control the individual operations and work of the center. These stakeholders prioritize efficiency and make decisions based on constraints, with the overall context of the broader network, due to the Physical Internet framework for a hyperconnected logistics network. The hubs implement the swapping policy specified by the logistics operators.

Logistics Operators: These stakeholders handle the routing problem in the network. By understanding the grid capabilities, facility locations, constraints from carriers, and demand

from users, they bring the system together. They also control the guiding policy for swapping policy for hubs, while being responsible for the overall charging policy for battery inventory. Company and Investors: The group represents the main party using the electrified road-freight network. The group is assumed to bring large investments due to their public commitments in reducing greenhouse gas emissions. The corporate representatives are also assumed to provide forecasting data on necessary vehicles, shipments, and destinations. In this review, these stakeholders are treated as users of the electrified network.
Truck Drivers and Unions: This body of stakeholders have a more niche control on vehicles in the electrification goals. It is assumed that the truck drives either own their electric vehicles or drive other stakeholder-owned vehicles. This distinction is not considered in this review.

While direct partnerships may cause delays and large organizational hurdles, innovating under guiding principles targeting standardization and multi-tier resiliency will enable seamless connectivity during implementation, self-solving network feasibility, regardless of stakeholder.

6 Cooperation Between Stakeholders

To reach a stage of reality in the electrification goals, stakeholders need to solve network feasibility. While certain alignments pose more value, the general cooperation gives way to progress in NetZero efforts. Under the hyperconnected logistic network model, the foundation of transition can be built into transportation system through policy, operations, and investments. Figure 1 depicts the convergence of interests between the stakeholders. The top half contains areas to work through to prepare for optimized electrification of fleets. While many other stakeholders exist the seven specified highlight the largest interest groups. Each stakeholder has control over different components of electrification.

	Battery Suppliers	Energy	Fleet Carriers	Facility Operators	Logistic Operators	Users	Truck Drivers
Battery Suppliers	**Innovation & Battery Standardization**	Battery specifications Energy consumption Standardization	Battery usage Charging/Swapping stations	*Swapping and charging standardization*	Inventory size Charging capabilities Weight limitations Range limitations		*Safety*
Energy and Power Distribution	Grid level resiliency Increased safety	**Overall Grid Resiliency**	*Charging locations*	Energy consumption Alternative energy technology	Locations feasible with energy demands		
Fleet Carriers	Decrease swapping / "refueling" time	*Grid Resiliency*	**Overall Trucking Optimization**	Facility operations standardization Scheduled operations Swapping operations	Route planning		Operations
Facility Operators	*Decrease swapping / "refueling" delay*	Facility level resiliency Grid level resiliency	Decrease dwell time Efficient refueling delegation	**Overall Facility Resiliency**	Standardization Battery swapping policy Unexpected arrivals		Refueling operations
Logistic Operator	Battery transshipment Optimized route planning	Network framework Optimized charging delegation Hub level resiliency	Efficient route planning Route level resiliency	Decrease dwell time Decrease lead time Network resiliency	**Overall Network Optimization**	Demand Flow of goods Schedule and lead times	
Users					Decrease lead time Decrease transportation costs	**Clean Energy Commitments**	
Truck Drivers	*Increase productivity* *Prevent high-risk events*		Decrease lead time	Decrease dwell time Increase time on the road Vehicle level resiliency			**Morale, Health, & Safety**

Figure 1: Areas of Cooperation, Targeted Assumptions

Starting from the battery suppliers and producers, they can exchange expectations with energy stakeholders, fleet carriers, and logistic operators. When the three groups develop internal strategies motivated by standardization, battery design, vehicle designs, specifications, and energy needs can be consistent throughout the system. Working towards an optimal network, the battery quantity can be predicted for a hyperconnected logistics network to function with battery swapping and charging technology. Standardization in design, maintenance, and charging infrastructure is necessary for a system created under the Physical Internet framework.

When logistics operators consider limitations from batteries, more accurate needs for inventory size can be estimated. In parallel, battery suppliers have a clear understanding of preferred characteristics expected from each battery, fueling design and innovation.

Similarly, energy distribution and power representatives working under aligned strategies with fleet carriers and hub operators, in addition to battery suppliers can prevent high-risk events during transportation operations. Rather than a rigid partnership, priority of resiliency at the grid level, will explore intermediary power storage and supply technologies, solving the power challenge in network feasibility. Exploring alternatives while innovating for greater efficiency, will enable connectivity between battery charging and consecutively swapping onto trucks operated by carriers, at hubs. The expectation for balance in the grid can lead to network feasibility. Literature in energy management highlights the necessity of capacity for optimized network feasibility [Revankar & Kalkambhar (2021)] [Zhang et al. (2021)].

Fleet carriers play a key role, being at the center of network feasibility in the implementation of electrification in supply chains. Beyond operational goals, charging infrastructure, battery weight limitations, and range limitations expectations directed towards battery suppliers can cause range anxiety. A Swiss case study found that while battery swapping is not feasible today, broad expansion in a network driven by carriers enables electrification to become a reality [Çabukoglu et al. (2021)]. The carriers can also structure their operations with flexibility, enabling resiliency in route planning and vehicle resiliency. The associated operational costs can be minimized through guiding assumptions shared with hub operators.

Parallel to carriers, facility operators and representatives are crucial to the implementation of an electrified freight system enabled by battery swapping and charging. Connecting a seamless in-bound and out-bound process under the PI system fitted with swapping refueling operations. Since the relay network is fundamental to the battery swapping mechanism to work, hubs, DC's, and charging hubs will be at the forefront at these stops. Zhang et al. (2021) propose a model to deploy battery swapping stations and supercharging networks, assuming this theory at hub locations, the system can achieve resiliency at a hub level. Working under consistent assumptions that trucks and batteries are standard, the swapping time can be minimized. Under this, energy consumption is optimized and feasible for the location, charging and swapping delays can be minimized. The development of operational centers with considerations of electric truck flow will enable seamless stops for electric trucks promoting the hyperconnected logistics networks. Moreover, the guiding disciple for refueling strategies can be optimized.

Most optimization models for battery swapping treat the transshipment of batteries to flow through a network parallel to vehicles. Hubs will be responsible for battery inventory collection. While the charging challenge might be broken up by seeking charging services off location or rely on other parties for the physical transport and recharging of the batteries, all these operations come together at the hub at the very first and very last step of the battery inventory system, batteries are swapping onto and off of a vehicle.

Companies play a leading role in motivation for the electrification of freight systems. Due to commitments for reducing emissions, corporations with large ground transport operations in their supply chains are greatly interested in battery powered electric trucks. Also not to be forgotten, truck drivers can build resiliency by working under the assumption of optimized routes and battery limitations. By understanding the logistics of navigating BS and BC fitted hubs, they can minimize dwell time and prioritize safety. When logistics operators work under principles prioritizing driver preferences and conditions, they can promote safety and health.

7 Benefits of Stakeholder Cooperation

The impact of collaboration has many effects. Stemming from battery cooperation, standardization, safety, innovation in range, and resiliency at an energy level are achieved. The impact of costs from battery variability and the limitations caused by weight are decreased in the overall network.

Energy regulators enable risk mitigation at the energy level by analyzing grids in context of location, energy consumption schedules, and alternative storage technologies. This gives way to decreased costs for power, decreases the number of vehicles and batteries needed, and develops resiliency at the energy level. For example, if batteries at a specific location were unable to charge or be delivered, for periods of time, alternative charging locations can take overflow, swapping can occur at alternate locations without compromising the integrity of the grid.

The benefits enhanced by fleet carriers focus on vehicle and network resiliency. embracing morale and safety by working under the same expectations as drivers, the health impact of traditional trucking is minimized. Through route planning and operations, vehicle maintenance standardization, and efficient flow through facilities, lead times can be stabilized and drive operating costs down. Electrification may even give way to new carriers, promoting competition and investment in the industry due to the opportunity in volume of freight transport.

Similarly, facility operators add to the standardization of operations at hubs. The minimization of wait time, in parallel with decreasing operation costs build resiliency at the hub level. These factors play a role in a hub being able to accept urgent or unscheduled arrivals. If we treat each node as a collection of containers, data from each tier can make decisions on swapping and charging policies. With the context of the entire network, optimality can be reached from the smallest level of modularity up to the largest being regional hubs and charging facilities. The communication of information between hubs on battery degradation and power consumption are at the foundations of the hyperconnected logistics model, enabling for better battery refueling policy. The inputs of one decision are taken from the outputs of another, reinforcing resiliency at facility and network tiers.

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Users					**Decrease lead time Decrease transportation costs**	**Clean Energy Commitments**	
Truck Drivers	*Increase productivity Prevent high-risk events*		**Decrease lead time**	**Decrease dwell time Increase time on the road Vehicle level resiliency**			**Morale, Health, & Safety**

Figure 2: Potential Impacts of Cooperation at the Stakeholder level

Figure 2 illustrates how this methodology overlaid by the Physical Internet structure brings the network to resiliency and sustainability. The reflection of expectations innovating under (blue shaded region) depicts the benefit provided to the stakeholder convergence (lilac shaded region).

At each tier, companies gain in decreasing costs and increasing the flow of goods through electric trucks while staying true to their commitments on emissions. Electric fleets have been proven to be more cost effective over the long run [Zhu et al. (2023)], especially in a hyperconnected logistics framework. Similarly truck drivers and unions gain in health, safety, and driver morale as trips, routes, and duration can be personalized and fair.

8 Network Impact

Working under consistent expectations causes additional effort from each stakeholder. While this may cause delays in innovation and implementation, the resultant network connectivity brings uncapped potential. The benefit of vehicle resiliency may protect a truck driver, but combined with resiliency at a distribution center, carrier may be able to shuffle schedules to accommodate emergencies caused by weather. If there are additional constraints in sectors of the grid network, alternative charging facilities can assume overflow and protect productivity against disruptions. While each stakeholder innovates independently in preparation of largescale freight electrification, the confluency of different key players gives way to a strong optimized network. At the root of connectivity, battery standardization leads to vehicle flexibility, a large component to how hubs respond to unexpected events. While this may cause a strain on the energy distribution, built-in technologies, and alternatives from innovating under consistent assumptions, ease the burden. The communication of battery levels, usage, and power supply across nodes enables efficient policy leading to overall facility resiliency, moving hand in hand towards overall network optimality. The intersection of assumptions and individual benefits provides the overall impact of stakeholder cooperation.

	Battery Suppliers	Energy	Fleet Carriers	Facility Operators	Logistic Operators	Users	Truck Drivers
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Figure 4: Network Impact from Stakeholder Cooperation at the combination of assumptions and individual benefit

Beyond optimization, the environmental impact of electrification is still at the forefront of the initiative under a hyperconnected logistic network. Electrification of freight fleets has been identified in part as a solution to reducing carbon footprints. Current freight systems detrimentally harm the world, and trucks have found to be the most polluting [Hecht, Andrew (1997)]. Effecting air, water, noise pollutions drastically, reducing emissions is a key motivation for the electrification of trucks. However in this pursuit, the stakeholders across industries must work together to ensure other environmental harm from increased mining, necessary to meet material demands for battery inventories, and energy production are not caused. Additional power generated through non-clean sources, powering batteries does not achieve carbon reduction goals, rather displaces the location of pollution.

9 Conclusion

Further research on electric grid capabilities, distribution, and integration of electrified freight fleets is necessary to reach the NetZero goal [Revankar, Kalkhambkar (2021)]. Beyond the governmental interests in electrified fleets, large industries have incentives to adopt more clean energy technologies. Innovation policy must provide an incentive for standardized swapping technologies and charging stations to reduce costs to promote seamless integration into Hyperconnected Logistic Networks.The modularity and interconnectivity of battery management in a electrified fleet following the Physical Internet methedology has the ability to change the network organization of road-freight systems. Through strategic cooperations between battery suppliers, energy and power distribution representatives, fleet carriers, hub operators, logistics operators, users of the system, and truck driver stakeholders, network feasibility can be achieved, allowing electrified fleets to become reality on a larger scale.

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Physical Internet in passenger air transport to decrease emissions – a concept

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Overall Summary

This study proposes implementing the Physical Internet (PI) concept in EU passenger air transport to enhance energy efficiency and reduce CO2 emissions. It aims to increase Load Factor (LF) from the 2019 level of 85% to 95%, potentially reducing total emissions by 9.3 Mt (13.5%) compared to 2019. The concept leverages IoT and real-time data analytics for dynamic route and schedule optimization, transforming air travel into a more efficient, reliable, and sustainable system.

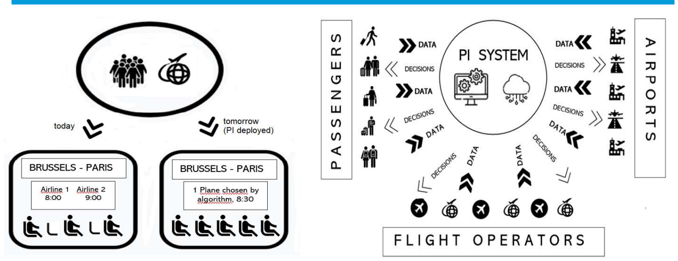
Boundary Conditions for Implementation of PI

The implementation of the Physical Internet (PI) in passenger air transport can be managed in three ways according to the European Commission:

1. Bottom-up Approach: Logistic nodes, networks, and systems develop independently.
2. Top-down Approach:
   a. Public Lead: Central unit plans and organizes PI under government supervision. This requires public sector action to enforce standards and ensure fair market competition.
   b. b. Industry Lead: Large corporations create and open solid logistic networks to other parties, including end consumers. The bottom-up approach is preferred for organic growth, ensuring gradual, business-oriented development.

Mixed forms of management might emerge, and the network should operate transparently and fairly, guided by European Commission frameworks. Strategic, tactical, and operational collaboration is essential for sharing high-capacity aircraft, potentially extending service to the last miles.

Simplified draft of the concept



Feasibility and potential of the concept

Stakeholders' decision to join the Physical Internet network involves weighing various factors and trade-offs specific to their circumstances. Mandatory participation, enforced by regulatory bodies, could expedite infrastructure and standards development, fostering widespread network adoption. However, it might also introduce substantial costs and resistance. In a voluntary context, stakeholders must assess the benefits against costs and potential penalties for non-compliance.

Deploying the Physical Internet in passenger air transport could notably impact passengers by enhancing flexibility, efficiency, and reducing emissions.

Calculations

Assumption: each passenger participates equally in the emissions of a single aircraft (1.1)

$$PE_t = \frac{AE_t}{AC_t * LF_t}$$

Where:
PE – average passenger emissions
AE – average aircraft emissions (annual journeys)
AC – average aircraft capacity (annual journeys)
LF – average aircraft load factor
t – period subscript

Load factors: $LF_{t=1} = 0.85$

$LF_{t=2} = 0.95$

We can also calculate emissions based on eq.1.1. and the numer of passengers (1.2.)

$$TE_t = PE_t * P$$

Average aircraft capacity is proportional to the space required to carry passengers in the premium and economy classes multiplied by their respective weights (1.3.)

$$AC_t = \frac{TS}{SP * PS_t + SE * (1 - PS_t)}$$

Where:
TS – passenger space on average aircraft (times the number of annual journeys) – constant
SP – space needed for a premium seat – constant
SE – space needed for an economy seat – constant
PS – share of premium seats on average aircraft

Based on the mentioned considerations, we can assumet that premiem seat takes 2.7 of the economy seat and the share of premium seat is 2%. Then we assumet that this will drop to 0% after introducing PI

$$SP = 2.7 * SE$$

$$PS_{t=1} = 0.02$$

$$PS_{t=2} = 0$$

On this basis, an airplane with 100 seats can accommodate a 5.4 economy passenger in the current seats occupied by two premium passengers, which is 3.4 percentage points increase in capacity. (1.4. and 1.5.)

$$AC_{t=1} = \frac{TS}{1.034 * SE}$$

$$AC_{t=2} = \frac{TS}{SE}$$

So, this assumption together with the assumption that LF will increase from 85% to 95% we can calculate total emissions reduction (eq.1.6.;1.7.;1.8)

$$PE_{t=1} = \frac{AE_t}{\frac{TS}{1.034*SE} * 0,85} = \frac{AE_t * 1.034 * SE}{TS * 0.85}$$

$$PE_{t=2} = \frac{AE_t}{\frac{TS}{SE} * 0.95} = \frac{AE_t * SE}{TS * 0.95}$$

$$\frac{PE_{t=2}}{PE_{t=1}} = \frac{AE_t * SE}{TS * 0.95} * \frac{TS * 0,85}{AE_t * 1.034 * SE} = \frac{0,85}{0.95 * 1.034} = 0,865$$

Therefore, under eq.1.2. and the assumption of constant numer of passengers:

$$TE_{t=2} = 0.865 * TE_{t=1}$$

If 69Mt is base emissions, we conclude that the total emissions reduction would amount to **9.3 Mt (ca.13.5%).**

Limitations and further research

- Assumptions and simplifications were necessary for the analysis, which might introduce biases.
- The complexity of the air transport sector, with many stakeholders and variables, limits the study's scope.
- The focus was mainly on economic efficiency, environmental impacts, market response, and policy conditions, not addressing social or marketing impacts.

Future research is suggested in areas such as efficiency, cost, and convenience benefits of PI, challenges in network implementation, and strategic implications using game theory.

Conclusions

Implementing PI in passenger air transport can optimize traffic flow, reducing air traffic congestion and improving aircraft and airport capacity utilization. It enhances predictability in flight scheduling, leading to a more reliable and punctual service. Overall, PI leads to significant efficiency improvements, cost savings, lower emissions, and an enhanced passenger experience.

Physical Internet has the potential to revolutionize passenger air transport by improving efficiency, reliability, and sustainability. It offers a pragmatic approach to addressing climate change concerns in the aviation sector and could be a critical step towards achieving net-zero emissions in the foreseeable future.

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A Four-Dimensional Spatiotemporal Bin-packing Problem in the Cyber-Physical Internet: A Deep Reinforcement Learning

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Introduction

Bin-packing problem is a combinatorial optimization problem of loading smaller items into larger bins that have to satisfy geometric constraints. It is categorized into three dimensions: One-Dimensional(1D), Two-Dimensional(2D) and Three-Dimensional(3D). In the field of logistics, the 3D bin-packing problem is also commonly referred to as the Container Loading Problem(CLP). With the establishment of Physical Internet (PI), goods are packaged in smart containers of modular dimensions that are reusable or recyclable, i.e., PI(Π) containers. It standardizes containers and promotes the research on weakly heterogeneous 3D loading problems.

Monitoring through PI identifiers facilitates tracking and tracing, akin to internet data packets, thereby digitizing the physical bin packing process. The emergence of Cyber Physical Internet (CPI) provides real-time information to the network layer, propelling the transition from 3D spatial packing problems to four-dimensional spatiotemporal packing problems. In contrast to PI, CPI further demands rapid alignment between freight demand and logistics resources, necessitating real-time decision-making within large-scale PI network. Rather than planning for the future, decisions are made at the moment of data acquisition. However, when dealing with extensive datasets, executing pre-forecasted packing scenarios according to a predetermined plan becomes challenging, leading to resource wastage and reduced network efficiency.

Methodology

CPI Network Interface Card Framework

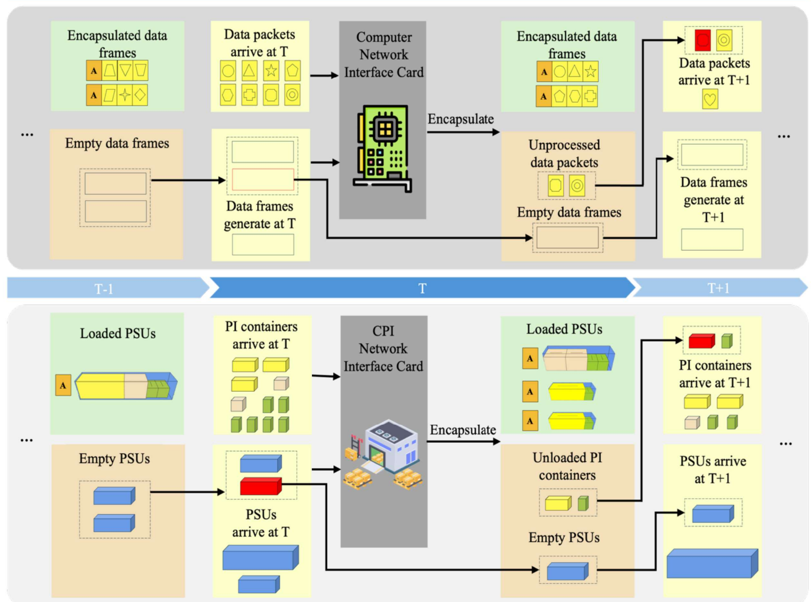

Figure 1 CPI Network Interface Card Framework

In this paper, the four-dimensional Spatiotemporal bin-packing problem is split into two phases: box-splitting and bin-packing. The box-splitting stage deals with the problem in the time dimension, and bin-packing solves the problem in the three-dimensional space.

Objectives

This paper employs the out of order execution approach to address the impact of uncertainty on loading problems. Based on four-dimensional spatiotemporal data, we construct a packing model to tackle spatial filling under the time dimension. The optimization objectives are twofold: minimizing the overall packing cost for goods destined to various locations and maximizing the space utilization within each container. However, these two objectives are not always positively correlated.

$$max \sum_{j=1}^{N} \sum_{i=1}^{Q} e_i \cdot f_i \cdot g_i \cdot D_{ij}$$

$$min \sum_{j=1}^{N} C_j$$

$$\Downarrow$$

$$min\ \alpha \sum_{d=1}^{\theta} \sum_{i=1}^{I} \sum_{c=1}^{m_j} \sum_{j=1}^{J} C_c\, O_{di} \cdot (1 - D_{dicj}) + \beta \sum_{c=1}^{m_j} \sum_{j=1}^{J} C_c \cdot n_{jc}$$

Conclusion

We employ deep reinforcement learning (DRL) to obtain an optimal loading scheme, enabling real-time matching of large-scale freight vehicle resources with customer order demands under dynamic and stochastic conditions. Furthermore, we investigate the computational advantages of different solution methods across varying time windows. In comparison to existing heuristic algorithms such as Hybrid Adaptive Large Neighborhood Search (HALNS), Genetic Algorithm (GA) combined with Differential Evolution (DE) and Best-Match-First (BMF), DE + BMF, and Particle Swarm Optimization (PSO) combined with Deepest-Bottom-Left Fill (DBLF), DRL demonstrates faster solution times and greater "real-time" capability.

Future Work

The experimental data presented in this paper are specific to three different sizes of PI containers and three different sizes of trucks. Further research should be conducted using actual data from logistics sites. Sensitivity analysis has demonstrated that the proposed model in this paper exhibits a certain level of stability. However, further exploration of the model's generalisation capabilities is required. In the future, we plan to introduce additional constraints to enhance the suitability of the Deep Reinforcement Learning model for CPI scenarios.

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Towards Cyber-Physical Internet

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Introduction

The concept and practice of PI are global and require worldwide cooperation to achieve more efficient, sustainable and intelligent logistics and supply chain networks, relying heavily on advanced information and communication technologies (ICT). Cyber-physical systems(CPS), with powerful computing, communication and control capabilities, is one of the key technologies to support dynamic decision-making based on real-time information. CPS shows great potential for implementing PI. Despite current studies have made preliminary exploration of empowering PI with digitalization capacity from CPS, it is still challenging to conduct a seamless combination of CPS with PI due to their unclear integration boundary.

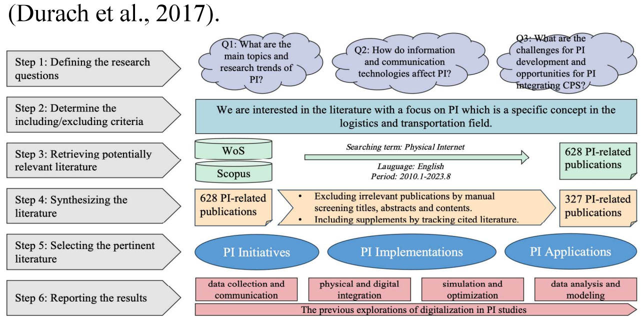
Objectives

This study aims to demonstrate the potential for CPS integrated with PI by addressing the following research questions:

- What are the necessities, rationales and opportunities to enhance PI's cyber digitalization capacity toward a Cyber-Physical Internet (CPI)?
- What is the fundamental framework of CPI to innovate the next evolution of logistics system as simple as sending emails?
- What are the building blocks of CPI that must be further explored, designed and discussed to enable the application prospects for typical logistics scenarios?

Methodology

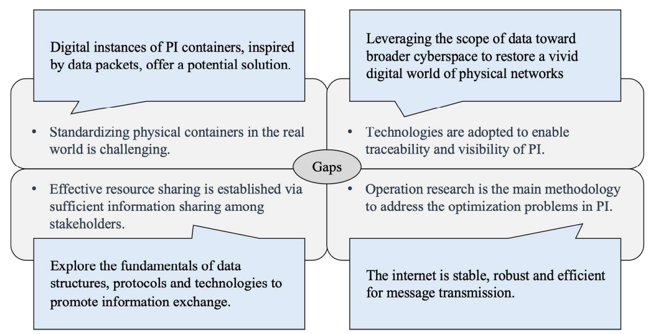
- To respond to above reseach questions, this study first conducts a systematic literature review (SLR) on PI to extract and reveal the research trends and remaining gaps, which is a well-established review method in the field of management sciences (Durach et al., 2017).



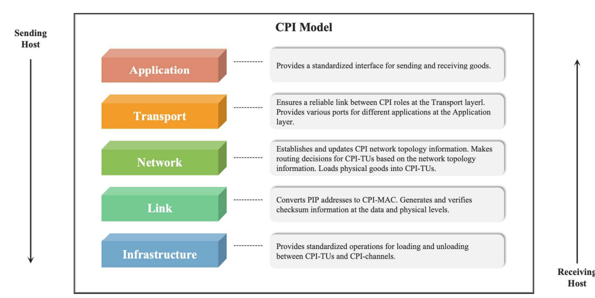
- Based on the key findings, and to extend the research focus of PI, a five-layer model, which works as the OSI model for computer networks, is proposed as the fundamental framework to define CPI at the abstract level.
- Finally, based on this proposed model, further research directions are summarized in terms of CPI digitalization, network configuration and operation.

Results

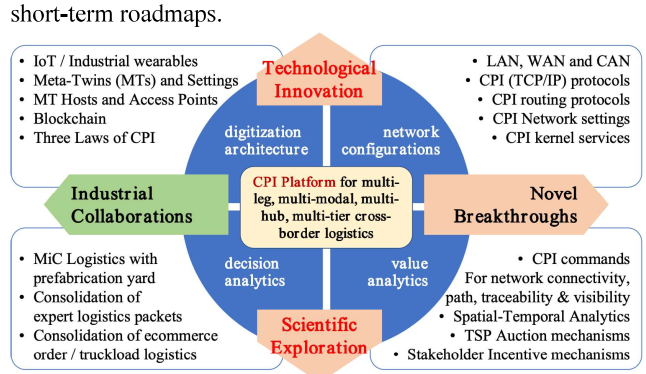
- First, our review has revealed that insufficient digitization in the PI has generated limitations at the physical, digital, and operational levels, which motivates the emergence of CPI.



- Second, the CPI five-layer model is designed as a fundamental framework to maintain the separation of responsibilities so that protocols, mechanisms, and standards can be loosely coupled to suit different logistics scenarios.



- Third, some future research directions on CPI have been systematically summarized, providing a clear depiction of CPI short-term roadmaps.



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DT-PoseFormer: A Digital Twin-enabled Transformer Network for Precise Pose Estimation and Trajectory Prediction of MiC Modules

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ABSTRACT

Modular integrated construction (MiC) is a game-changing disruptively-innovative approach, which improves quality, simplifies management and reduces construction time due to its off-site production and on-site installation characteristics. However, as one of the most sophisticated processes of MiC, on-site assembly still faces: 1).insufficient interoperability; 2). low-efficient module alignment; 3). highly susceptible safety incidents. To address these challenges, our contributions are:

- A digital twin (DT)-based real-time module tracking framework for real-time monitoring and control of MiC assembly to fulfill sufficient interoperability.
- A transformer-enabled (DT-PosFormer) network for real-time spatial-temporal module data analysis to automatic pose estimation.
- A trajectory prediction of MiC assembly alignment to prevent potential structural collision and misaligned stacking.

INTRODUCTION

The workflow of MiC mainly consists of three stages: production, logistics, and on-site installation, as shown in Fig. 1. In the production stage, modules are manufactured in the factory based on lean manufacturing principles, advanced manufacturing technologies and automated equipment to ensure quality, precision, and standardization of the modules. Effective collaboration and communication among different departments within the factory, as well as with suppliers and clients, are conducted to provide timely feedback on production status and coordinate logistics and delivery plans. In module logistics stage. dynamic transport planning are conducted based on real-time traffic condition, on-site assembly progress, and module arrival times to reduce storage space requirements and facilitate assembly sequence planning. Finally, modules in the installation queue are stacked by the crane to the target position. The complexity and uncertainty of the hoisting process seriously affects the smoothness and accuracy of the stacking.

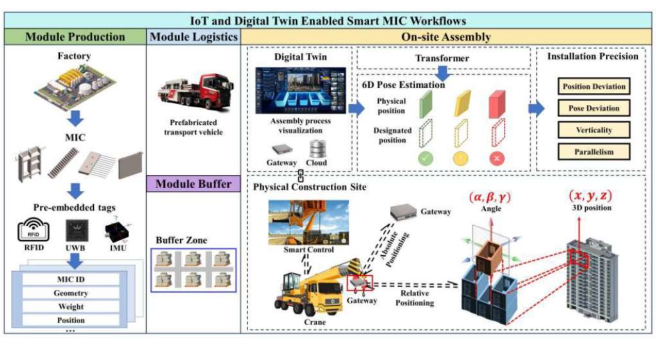

Fig. 1: The workflow of the MiC.

METHODOLOGY

The framework illustrates the overall structure of the DT-based pose estimation and trajectory prediction system, which includes physical layer, digital layer and service layer, as shown in Fig. 2.

- Physical Layer

Dynamic construction assets including on-site workers, crane and modules.IoT devices (UWB, IMU) for data collection, transmission.

- Virtual Layer

DT for visualization and data analysis.Static modeling includes terrain modeling, fixed facility modeling, and asset intrinsic feature modeling.

Dynamic modeling includes dynamic environment modeling, asset dynamic sensing, interaction and emergency response.

- Service Layer

Pose estimation uses UWB for 3D position and IMU for 3D attitude of modules. Trajectory prediction is based on transformer for real-time data processing and feature extraction.

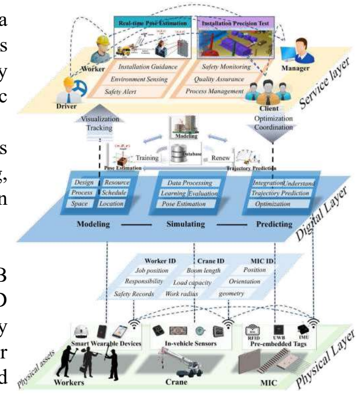

Fig. 2: The framework of DT-Poseformer.

EXPERIMENTS

a. Quantitative experiment

$$FDE = \frac{1}{n}\sum_{i=1}^{n}\left|p_{i_p}^{t_f} - p_{i_{GT}}^{t_f}\right|$$

$$ADE = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{t_f}\sum_{t=1}^{t_f}\left|p_{i_p}^{t} - p_{i_{GT}}^{t}\right|$$

TABLE I. COMPARISONS ON EVALUATION METRICS AND LOSS

Model	Smooth L1 loss	ADE	FDE
MLP	0.07129	57.32236	316.55729
GRU	0.1141	26.19518	137.12731
GRU-Attention	0.07162	26.17367	138.24061
LSTM	**0.004935**	26.30367	139.94350
BiLSTM	0.052	26.01963	139.14750
BiLSTM-Attention	0.05083	26.02726	139.12281
LSTM-Attention	0.01908	26.01323	138.46538
Ours(PoseFormer)	**0.00661**	**23.58859**	**136.27763**

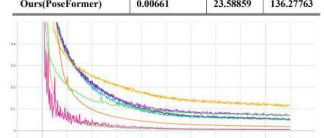

Fig. 3: The loss of different models.

b. Visualization experiment

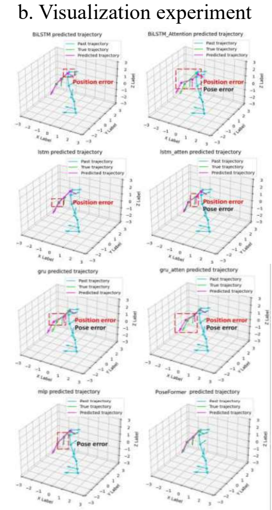

Fig. 4: The predicted trajectory.

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CONCLUSION

We propose a framework for module installation process services based on digital twin and IoT. On one hand, real-time pose estimation information of modules is obtained through UWB and IMU sensors. On the other hand, a deep neural network based on transformer, named DT-PosFormer, is employed for trajectory prediction during the module installation process.