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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.

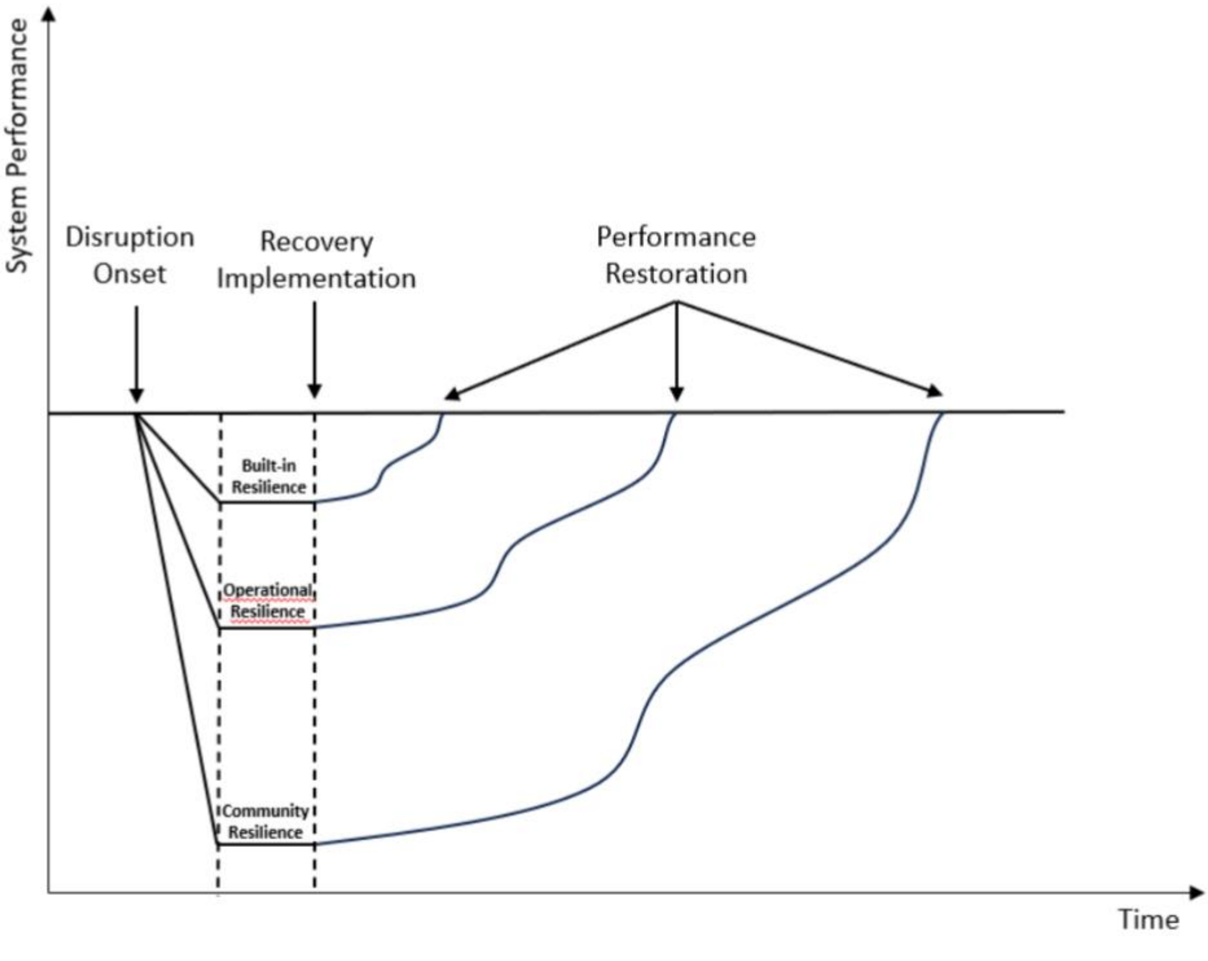

Figure 1 System performance over time during disruption and recovery.

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.

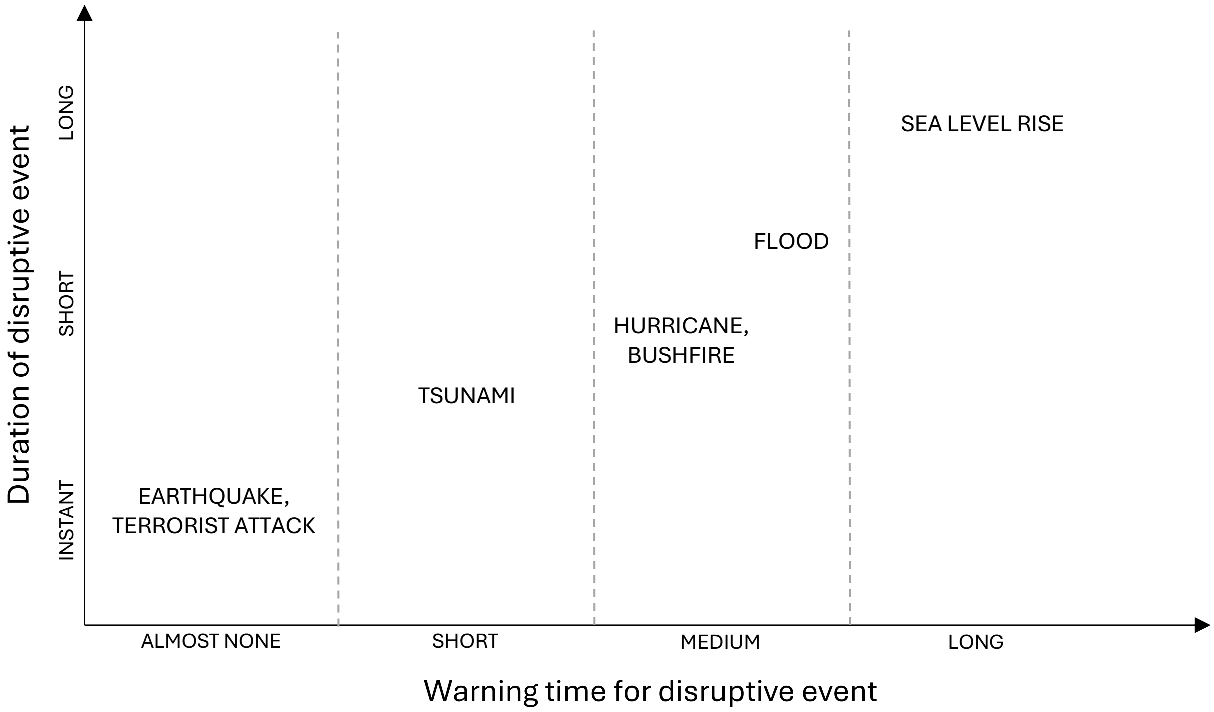

Figure 2 Classification of disruptive events according to duration and warning time, as discussed in Hasan & Foliente (2015)

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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