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:

$$R(X,T) = 1 - \frac{XT}{2T^*} \tag{2}$$

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:

$$R = Pr(A|i) = Pr(r_0 < r^* \; and \; t_1 < t^*) \tag{3}$$

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.

$$Z_A = \sum_i Pr(A|i) \times Pr(i) \tag{4}$$

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

$SC\ readiness\ measurement\ period\ \ defined\ by\ decision\ makers, T$

$SC\ readiness\ dimensions, A = \{TPL, TTR, MPL\}$

$Disruption\ scenarios,\ \ \Omega = \{\omega_1, \omega_2, \dots \omega_{|\Omega|}\}$

$s_\omega: Probability\ of\ occurrence\ for\ scenario\ \omega,\ \ \forall\omega \in \Omega$

$$\sum_{\omega \in \Omega} s_\omega = 1 \quad (5)$$

$TPL_\omega: Percentage\ of\ total\ performance\ lost\ by\ supply\ chain\ in\ scenario\ \omega,\ \ \forall\omega \in \Omega$

$TPL^*: Tolerable\ total\ performance\ loss\ level$

$MPL_\omega: Maximum\ performance\ deviation\ ratio\ in\ scenario\ \omega,\ \ \ \forall\omega \in \Omega$

$MPL^*: Tolerable\ minimum\ performance\ level$

$TTR_\omega: Percentage\ of\ the\ time\ period\ spent\ for\ recovery\ in\ scenario\ \omega,\ \ \ \forall\omega \in \Omega$

$TTR^*: Tolerable\ time\ to\ recover\ level$

$\Omega^*: Disruption\ scenarios\ that\ in\ which\ the\ SC\ performs\ within\ the\ tolerance\ levels\ at\ all\ dimensions$

$Re: SC\ readiness\ metric\ for\ given\ set\ of\ disruptions\ scenarios\ (\Omega)$

$$Re = \sum_{\omega \in \Omega^*} s_\omega \quad (8)$$

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.

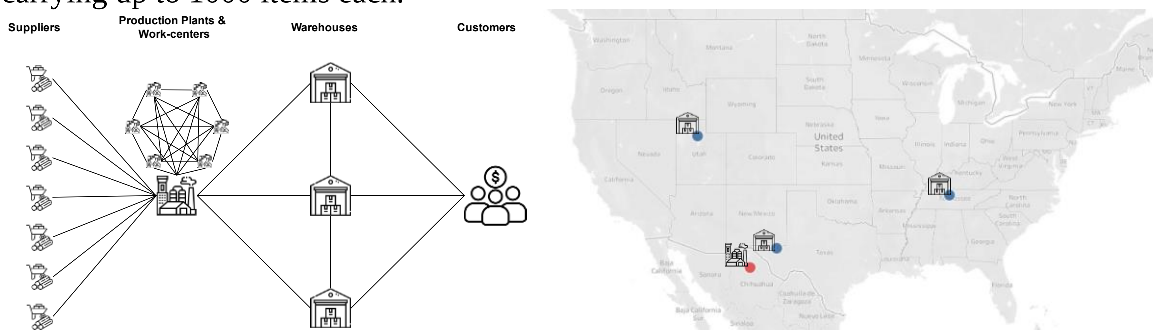

Figure 1 Supply Chain Network used in experimental analyses and real locations of the nodes

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	*Become unavailable*	30 days
				Medium		15 days
				Low		7 days
Production	Work center disruption	Work centers	Daily processing capacity	High	*Become unavailable*	30 days
				Medium		15 days
				Low		7 days
Logistics	Transportation disruption	SC nodes	Delayed deliveries (inbound) and shipments (outbound)	High	Delayed deliveries (inbound) and shipments (outbound)	21 days
				Medium		14 days
				Low		7 days
Supply	Supplier delivery delay	Production plants	Raw material replenishment orders	High	Delayed deliveries	80 days
				Medium		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.

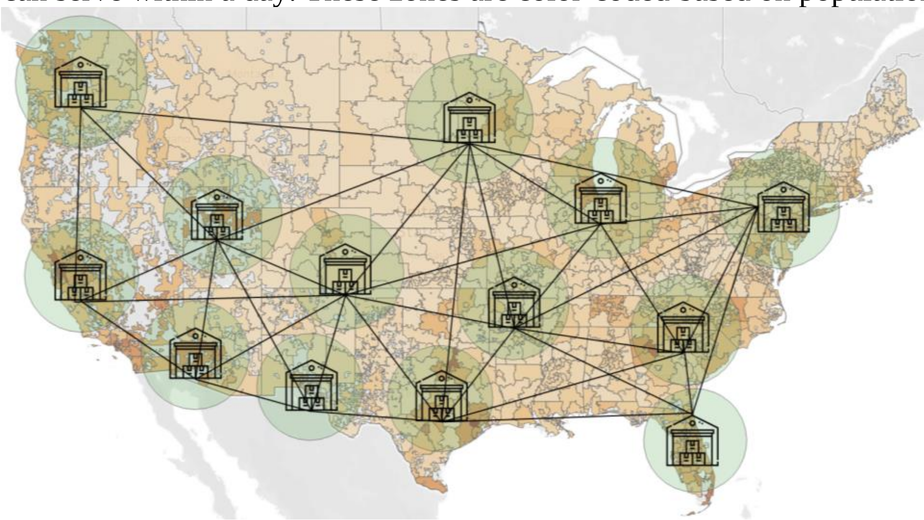

Figure 2 Open distribution network with OCSCs

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.

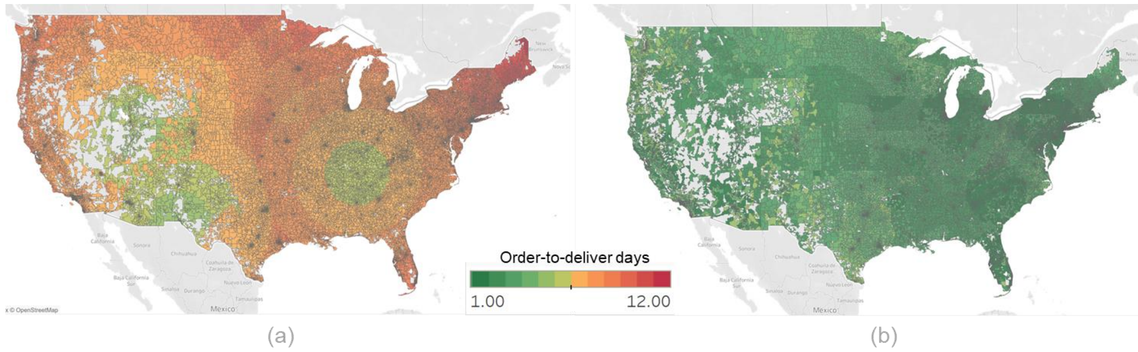

Figure 3 Expected order-to-deliver times for demand zones in base case (a) and open distribution network (b)

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.

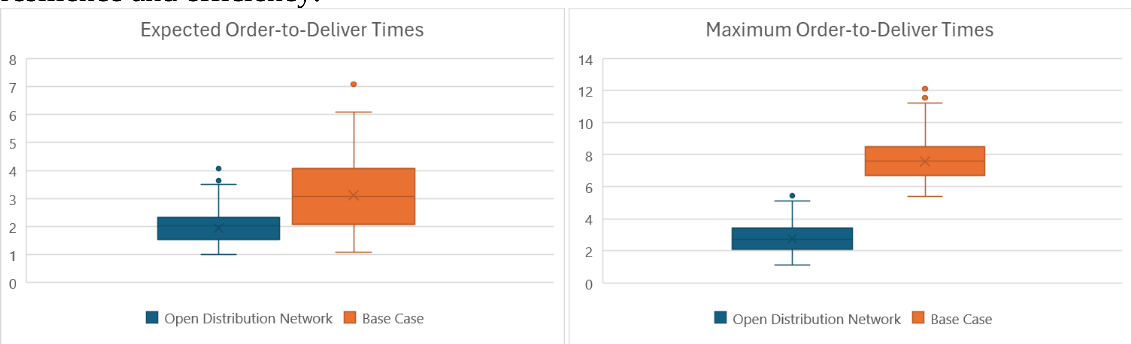

Figure 4 Box-plots showing expected average and maximum order-to-deliver times for demand zones

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).

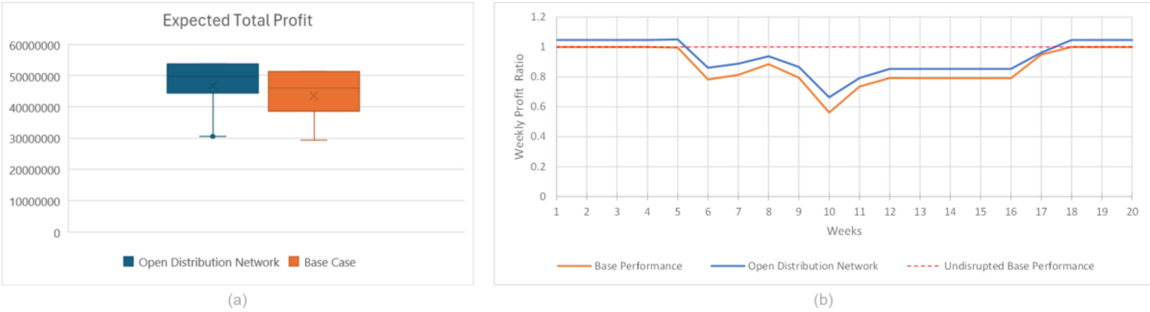

Figure 5 (a) Expected total profit values for disruption scenarios (b) Weekly profit ratio with undisrupted base case

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.

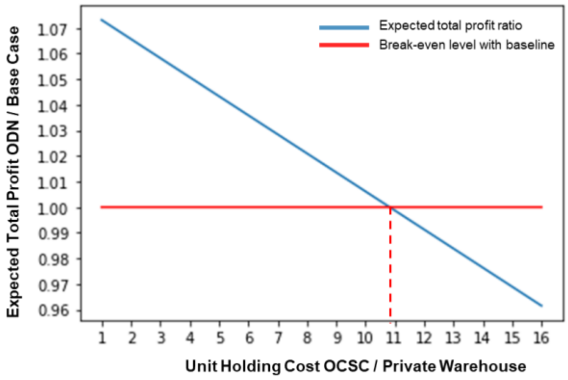

Figure 6 Expected total profit ratio of ODN and base case with increasing unit holding costs for OCSCs

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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