Simulation-based Assessment of Hyperconnected Humanitarian Supply Chains Response Readiness

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Abstract

The escalating disasters and increasingly complex external environment are forcing humanitarian organizations to continually improve their operations to provide better humanitarian relief. Transformation towards hyperconnected humanitarian supply chains is one of the most promising paths and the Physical Internet could provide a paradigm for this evolution. However, the impact of this shift on the humanitarian supply chain's performance, particularly readiness, has been understudied. To address this issue, a simulation-based assessment of hyperconnected humanitarian supply chains' response readiness is conducted. Different combinations of multiple potentials of the Physical Internet are simulated, and the corresponding effects on relief operations are analyzed. The findings of this work provide greater insight into the transformation towards hyperconnectivity and thus are helpful for decision-makers to design appropriate evolutionary avenues for today's humanitarian supply chains.

Keywords: readiness, humanitarian supply chain, physical internet, hyperconnectivity, simulation

1. Introduction

In recent years, the frequency, intensity, and complexity of disasters have been escalating due to various factors such as COVID-19 epidemics, regional conflicts, and climate changes (Cozzolino, 2012; Grest et al., 2019). In the context of this trend, disasters have become one of the most severe challenges facing human society, which also indicates the necessity of better humanitarian operations (Beamon and Balcik, 2008; Salvadó et al., 2017). To mitigate the impacts of disasters, humanitarian organizations need to be prepared for potential hazards during normal times and to rapidly implement relief operations after being activated. However, the performance of humanitarian supply chains (HSCs) has been widely criticized, especially in terms of effectiveness and efficiency (Grest, Lauras, et al., 2020; Haavisto and Goentzel, 2015). Challenges such as scarce resources, disrupted environments, public scrutiny, and sustainability concerns are forcing HSCs to be more effective and efficient to better meet their objectives (Grest, Montreuil, et al., 2020; Kovács and Spens, 2007). And hyperconnectivity is one of the possible evolutionary directions that has attracted extensive attention in recent research, which can be seen as a state of the supply chain, with "*intense connection of components on multiple layers, ultimately anytime, anywhere*" (Montreuil, 2017).

Since about 80% of relief operations are logistics-related (Van Wassenhove, 2006), reorganization and innovation in logistics networks are essential to the transformation of HSCs towards hyperconnected ones, for which the Physical Internet could provide a paradigm. Consistent with the prospects of HSCs, the Physical Internet aims to establish a hyperconnected global logistics system that enables better efficiency and sustainability (Montreuil, 2017; Montreuil et al., 2013). While projecting the Physical Internet principles to the HSCs is attractive, the transformation towards hyperconnectivity should be a long-term step-by-step process that requires a significant investment (Grest, Inan, et al., 2021). Furthermore, the resulting hyperconnected state is also a challenge that humanitarian organizations need to handle. Therefore, it is important to quantitatively assess the impact of integrating the paradigm of the

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Physical Internet to humanitarian operations on the performance, which will also help decision-makers to design appropriate evolutionary avenues for today's HSCs.

The innovation that the Physical Internet brings to commercial supply chains has been extensively studied (Sternberg and Norrman, 2017), and some of the benefits and limitations have been demonstrated through the partial implementation of the Physical Internet principles in the real world (Treiblmaier et al., 2020). However, regarding the humanitarian context, such research remains limited. Most of the existing studies are confined to qualitative assessments (Abdoulkadre et al., 2014; Grest et al., 2019). The few quantitative studies are still limited to traditional metrics critical to commercial supply chains, such as agility, resilience, and sustainability, and do not adequately consider the specificity of HSCs (Grest, Inan, et al., 2021; Grest, Lauras, et al., 2021; Grest, Montreuil, et al., 2020).

From the disaster management perspective, HSCs need to meet certain preparedness requirements during the preparedness phase in order to achieve certain effectiveness and efficiency during the response phase (Coppola, 2006). Evaluating the performance of HSCs requires consideration of both preparedness activities during normal times and relief operations after a disaster (Beamon and Balcik, 2008). It is not sufficient to consider only the response phase and focus only on the traditional performance indicators. It is equally, if not more, important for HSCs to quantitatively evaluate the degree of being ready to respond to disasters before they occur. Therefore, this work starts from the concept of *readiness* and conducts a quantitative assessment of hyperconnected HSCs response readiness through a simulation experiment.

The article is organized as follows. Section 2 introduces the background of this work, namely the humanitarian response readiness and the potential of the Physical Internet to improve *readiness*. Section 3 describes the performance metrics and simulation system adopted in this work. Section 4 presents the details of the simulation experiment and the analysis of the results. Section 5 discusses the findings drawn from the analysis, as well as the limitations of this work. Section 6 summarizes the contributions and the potential perspectives for future research.

2. Background

In this section, the meaning of humanitarian response readiness is explained, as well as the difference between the concept of *readiness* in humanitarian and commercial supply chains. The Physical Internet potential for humanitarian sectors regarding the transformation towards hyperconnectivity is also presented.

2.1. Humanitarian response readiness

Readiness is defined by the Merriam-Webster Dictionary as "*the quality or state of being ready*" (Merriam-Webster, 2022). In the context of supply chain management, *readiness* can be interpreted as the degree of being prepared for meeting unexpected demands or responding to future disruptions (Ponomarov and Holcomb, 2009). For commercial supply chains, *readiness* is often seen as an important dimension for measuring supply chain resilience (Chowdhury and Quaddus, 2016; Hohenstein et al., 2015; Sheffi and Rice Jr, 2005). For HSCs, the operation patterns and objectives are quite different from those of commercial ones, and therefore the understanding of the term *readiness* should be adjusted accordingly.

Unlike commercial supply chains are expected to be resilient and have the adaptive capability for recovering from disruptions, the disruptive state is more like the norm for HSCs. Regarding the four phases of disaster management, humanitarian organizations are often absent in the *mitigation* and *recovery* phases due to a lack of funding (Kwon and Kim, 2018). Although preparedness activities such as pre-positioning have a significant impact on relief operations, HSCs remain almost inactive during the *preparedness* phase compared to the *response* phase. When a disaster strikes, the HSC is activated and needs to transport and distribute relief supplies to affected areas. Therefore, humanitarian logistics always operate in a disruptive environment, and HSCs need to be prepared to respond to disruptions in the *preparedness* phase.

What status can be considered as ready to respond for HSCs? In other words, how to measure humanitarian response readiness? The response coverage capability and the response speed capability are believed to be critical regarding this question (Acimovic and Goentzel, 2016; Beamon and Balcik, 2008; Chakravarty, 2021). The former represents the ability to provide enough relief supplies, while the latter represents the speed of distributing these supplies. A prepared HSC needs to have both the ability to respond quickly and to cover as many affected people as possible. Most of the existing studies focus only on one of these two capabilities or treat these two capabilities as independent factors when measuring HSCs' performance. However, these two capabilities are related to each other.

In one case, a HSC can provide enough relief supplies, but is unable to deliver within the required time; in the other case, a HSC can distribute items quickly but is unable to meet the full demand. Neither case can be considered successful. Therefore, the response coverage capability and the response speed capability should be measured together when evaluating humanitarian response readiness. To do this, a humanitarian response readiness metric firstly proposed in (Inan et al., 2020) was adopted for this study, which is described in detail in section 3.1.

It is worth noting that while both response speed and coverage are directly related to the performance during the response phase, the effectiveness of preparedness activities in the preparedness phase can also be reflected indirectly through these two indicators. This is because preparedness activities are aimed at improving these two capabilities and therefore *readiness*. For example, procurement in advance ensures that the HSC can provide adequate supplies after a disaster, while proper pre-positioning reduces the distance and increases the speed of distribution of supplies.

2.2. Physical Internet potential for hyperconnected humanitarian supply chains

To achieve their objectives in an increasingly complex and uncertain environment, HSCs need to continuously improve their effectiveness and efficiency and evolve towards hyperconnectivity (Grest, Montreuil, et al., 2020; Kovács and Spens, 2007). And this article suggests that projecting the Physical Internet paradigm to humanitarian operations could be one of the possible ways to realize this transformation. The Physical Internet was inspired by the digital internet and defined as "*an open global logistics system founded on physical, digital, and operational interconnectivity through encapsulation, interfaces, and protocols*" (Montreuil et al., 2013). The implementation of the Physical Internet will result in hyperconnected supply chain systems with densely connected actors and components (Grest, Lauras, et al., 2021). Guided by the principles of the Physical Internet, especially openness, interconnectivity, and accessibility, the hyperconnected HSC will revolutionize its logistics in terms of network design and operational management (Grest, Inan, et al., 2021; Montreuil, 2012). Seamless flow consolidation and assets sharing will be feasible, which will lead to faster information, physical, and financial flows of HSCs (Grest, Lauras, et al., 2021). The above predictable enhancements will reshape the way hyperconnected HSCs operate, and this work mainly considers the following four potentials: *sourcing*, *transport*, *distribution*, and *replenishment* (Grest et al., 2019; Grest, Montreuil, et al., 2020).

- ***Sourcing management***: *Hierarchical sourcing* vs. *matrix sourcing*. *Sourcing management* determines the strategy of sourcing an item in the supply chain (Spekman et al., 1999). The logistics networks of most typical HSCs are hierarchically structured and therefore follow a *hierarchical sourcing* strategy. In other words, relief supplies can only flow one single direction from higher levels to lower levels. The supplier of each node is pre-designated based on the position of the node in the hierarchical network. In contrast, thanks to the improved interconnectivity and information flow, the *matrix sourcing* strategy is possible for hyperconnected HSCs. Relief supplies can flow horizontally or even from lower levels to high levels. The supplier of each node could be dynamically determined by the pre-defined preferences. This more flexible sourcing strategy is expected to speed up the physical flow of the supply chain.
- ***Transport management***: *Dedicated deliveries* vs. *consolidated deliveries*. *Transport management* determines the operational mode of the transportation means in the supply chain. *Dedicated deliveries* are widely adopted by hierarchical logistics networks. However, the transport is often not fully loaded. To make matters worse, the relief supplies flow is one-way following the hierarchical sourcing strategy, so the transport is empty on the return trip. To address this issue, hyperconnected HSCs with the matrix sourcing strategy can achieve higher load rates through *consolidated deliveries* and thus improve the effectiveness of transportation (Sarraj et al., 2014).
- ***Replenishment management***: *Long response capabilities* vs. *short response capabilities*. *Replenishment management* determines the ability of the HSC to continuously respond to demand over relatively long time scales (Natarajan and Swaminathan, 2014). Due to the costs of maintaining inventory during normal times, it is common for HSCs to run out of stock and need to restock after disasters. With faster financial flow and better external connectivity, the hyperconnected HSC is expected to have *short response capability*, enabling faster replenishment compared with the current one.
- ***Distribution management***: *FIFO (first in, first*

out) vs. *equity*. *Distribution management* refers to the order fulfillment strategy in this study. Typical HSCs tend to follow the *FIFO* strategy. That is to say, the first order will be fulfilled first. However, the *FIFO* strategy is contrary to the principle of impartiality valued by most humanitarian organizations (Kwon and Kim, 2018). For hyperconnected HSCs, the *equity* strategy is possible thanks to the intense interconnectivity. In this situation, all orders will be at least partially fulfilled by splitting current and upcoming inventory.

To be noted, the potential of the Physical Internet paradigm for hyperconnected HSCs is not limited to the four aspects mentioned above, nor to the specific forms described above.

3. Simulation methodology

Since the hyperconnected HSC has not been fully realized yet, it is not feasible to collect real data and perform analysis. To quantitatively assess the impact of implementing the Physical Internet paradigm on the response readiness of hyperconnected HSCs, simulation-based research is conducted. This section illustrates the methodology used to perform the simulation experiment, mainly the quantitative metric for measuring humanitarian response readiness and the simulation system for modeling HSCs.

3.1. Humanitarian response readiness metric

As described in section 2.1, it is important to consider both the preparedness phase and the response phase when evaluating HSCs' performance. Combining the *response speed capability* and the *response coverage capability* with one metric is a better way for measuring humanitarian response readiness. Therefore, a comprehensive metric (namely the *humanitarian response readiness metric*) firstly proposed in (Inan et al., 2020) is used in this article.

As shown in Fig.1, the relative positions of the cumulative demand curve and the cumulative supply curve in a specific period after the disaster can comprehensively reflect the *response speed capability* and the *response coverage capability* of a HSC. The purpose of the preparedness activities implemented by humanitarian organizations during the preparedness phase can be seen as to minimize the gap between the two curves. Ideally, the cumulative supply curve of a prepared HSC during the response phase should overlap with the cumulative demand curve. This means the *response coverage capability* and the *response speed capability* of the HSC can fully meet the demands caused by the disaster.

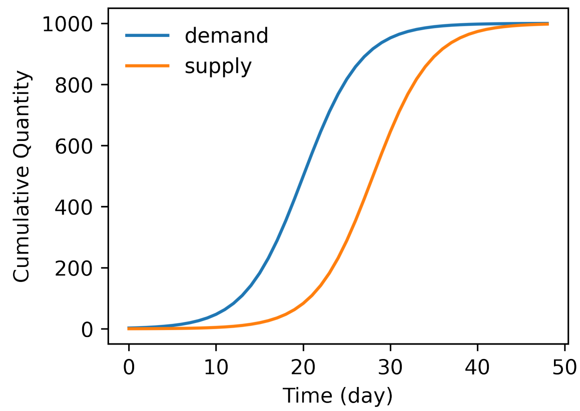

Figure 1. An illustrative chart of the cumulative demand curve and the cumulative supply curve.

Accordingly, the *humanitarian response readiness metric* is constructed by utilizing the two cumulative curves. Given a specific disaster d, the readiness r_d of the HSC is defined as follows (Inan et al., 2020):

$$r_d = \sum_{t \in T} \frac{1}{n} \frac{\min(Q_d, Q_s)}{Q_d} \qquad (1)$$

where $T = \{0, 1, 2, \cdots, n\}$ is the specific period considered after the disaster d strikes, Q_d is the expected cumulative quantity of the demand caused by the disaster d, and Q_s is the cumulative quantity of the supply that can be delivered regarding the disaster d.

Considering the complexity of disasters and the difficulty of prediction, it is of limited significance to measure only the readiness of HSCs for a particular disaster scenario. Thus, given a set of disasters $D = \{d_1, d_2, \cdots, d_m\}$ and the corresponding probabilities $P = \{p_1, p_2, \cdots, p_m\}$ ($\sum_{i=1}^{m} p_i = 1$), the definition of readiness R can be extended as follows (Inan et al., 2020):

$$R = \sum_{i=1}^{m} p_i r_{d_i} \qquad (2)$$

To be noted, the above definitions of the *humanitarian response readiness metric* consider only one type of product. When there are multiple types of products to be distributed, the overall readiness can be obtained by assigning weights to different products and then weighting the readiness for the single product calculated according to the above formulas.

3.2. Simulation system for humanitarian supply chains

To quantitatively assess the impact of implementing the Physical Internet paradigm on *humanitarian response readiness*, a simulation system for HSCs is needed. Considering the purpose of this study, the simulation system should have the ability to introduce disasters with different intensities at different times and locations, while allowing the simulation of different behaviors of the HSC regarding *sourcing*, *transport*, *replenishment*, and *distribution* management.

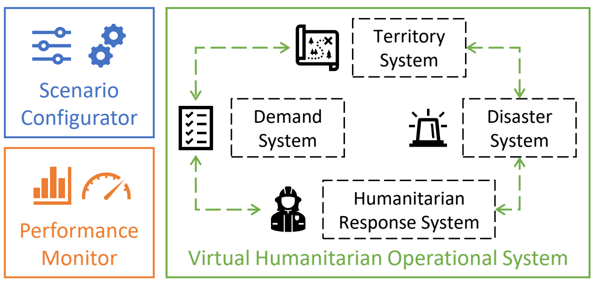

Figure 2. The HSC simulation system.

As shown in Fig.2, a prototypical agent-based and discrete-event-oriented simulator firstly proposed in (Grest, Inan, et al., 2021) is adopted as the simulation system in this work. The simulator is implemented using the AnyLogic software and consists of three parts: the *scenario configurator*, the *performance monitor*, and the *virtual humanitarian operational system*. The *scenario configurator* is used to determine the strategy for how the HSC will operate. By combining the different potentials of the Physical Internet, different scenarios are constructed through the *scenario configurator* before running the simulation. The *performance monitor* is used to calculate the key performance indicators of the HSC during the response phase under a particular scenario. The relief operations of the humanitarian organization will be recorded during the simulation, and the *readiness* metric will be calculated after the simulation through the *performance monitor*. As the core of the simulator, the *virtual humanitarian operational system* is composed of four sub-systems, i.e., the *territory*, *disaster*, *demand*, and *humanitarian response system* (Grest, Lauras, et al., 2021):

- ***Territory system***: The disaster-prone territory is characterized by the *territory system* through multiple overlapping layers. Administrative divisions, topography, transportation networks, and population are represented by each layer, as well as other features that may be relevant to relief operations.

- ***Disaster system***: The *disaster system* is a discontinuous generator that introduces the disaster, which will have an impact on the susceptible territory. The injection of the disaster can be seen as the starting point of the simulation. The *disaster system* needs characteristics such as the type, duration, location, and intensity of the disaster as inputs.

- ***Demand system***: The *demand system* is used to generate demand that requires the HSC to respond. Throughout the response phase, the *demand system* dynamically creates demand for relief supplies based on the number of victims and the severity of damages in different areas.

- ***Humanitarian response system***: The *humanitarian response system* can be seen as a simulator of a supply chain for distributing relief supplies. The system elements include logistics operations and involved participants (warehouses, trucks, products, etc.). The information, physical and financial flow in the HSC are characterized, and the response activities are simulated with the *humanitarian response system*.

The logical relations between the four sub-systems of the *virtual humanitarian operational system* are as follows. The simulation starts with the introduction of a specific disaster by the *disaster system*, which hits the susceptible territory characterized by the *territory system*. To mitigate the negative impacts, such as victims and damages, the *demand system* generates demands for relief supplies and sends them to the *humanitarian response system*. The latter then implements a series of relief operations (mainly logistics-related) for response purposes. The simulation ends when all demands have been fulfilled and no new demands are created.

Based on the above-presented simulation system, a simulation-based quantitative assessment of hyperconnected HSCs' response readiness was conducted. A HSC belonging to the Indonesian Red Cross Society was modeled for the experiment. The context and design of the experiment are described in the next section, as well as the analysis of the results.

4. Experiment and results

For assessment purposes, a simulation-based experiment was designed and performed. Multiple performance indicators (mainly humanitarian response readiness) were simulated, and quantitative analysis was conducted based on the collected simulated dataset.

The details of the experiment are presented below, as well as the results of the simulation and analysis.

4.1. Experiment

The experiment in this study is based on the modeling of the current HSC of the Indonesian Red Cross Society. The context and details of the experiment are as follows.

4.1.1. Indonesian Red Cross Society modelling. Because of the dense population and the frequent disasters in Indonesia, the Indonesian Red Cross Society is one of the most representative and active humanitarian organizations today. As a member of the International Federation of Red Cross and Red Crescent Societies, the Indonesian Red Cross Society operates a HSC, distributing relief supplies to affected areas through its logistics network after disasters and receiving aid from national and international sources (Grest et al., 2019).

Through the HSC simulation system presented in section 3.2, a portion of the HSC was modeled based on data and information from a field survey conducted within the Indonesian Red Cross Society. The administrative division of Indonesia consists of four levels: province, regency, district, and village. Accordingly, the logistics network of the Indonesian Red Cross Society is organized as a hierarchical structure. Depending on the population distribution, almost every regency has district warehouses near major cities. Each district warehouse has a corresponding province warehouse as the supplier. Above that, regional warehouses are set up to supply multiple province warehouses. Each warehouse maintains a safety stock during normal times so that a rapid response can be achieved after being activated. As the end of the logistics network, "points of delivery" are dynamically set up in the affected areas after a disaster, responsible for receiving relief supplies transported from the warehouse and distributing them to the victims.

The Indonesian Red Cross Society operates this HSC in a fairly traditional way. For *sourcing management*, the *hierarchical sourcing* strategy is adopted and relief supplies can only flow from the regional warehouses to the "points of delivery". For *transport management*, local transporters with variant means of transportation are assigned to transport relief supplies. Limited by the insufficient information flow, only *dedicated deliveries* can be achieved. For *replenishment management*, the *response capabilities* often cannot meet the timeliness requirements of relief operations. It usually takes 15 days to complete the replenishment. And for *distribution management*, due to the inadequate overall situational awareness, only the *FIFO* strategy is implemented, which compromises the impartiality of relief operations.

As illustrated above, the HSC of the Indonesian Red Cross Society can be seen as a typical baseline. Different scenarios can be constructed by integrating different combinations of multiple potentials of the Physical Internet, thus enabling the assessment of impacts of evolving towards hyperconnectivity on humanitarian response readiness.

4.1.2. Experiment Design. The experiment is designed for simulating the relief operations implemented by part of the HSC of the Indonesian Red Cross Society under different scenarios. The simulated logistics network consists of one regional warehouse, one province warehouse, and 20 district warehouses. The "points of delivery" are deployed dynamically after the disaster strikes. The experiment considers the distribution of only one type of product.

Before the simulation starts, inventory allocation is needed to determine the number of stocks in each warehouse. The total inventory quantity for all warehouses is set to 3,000 and remains unchanged, while the pre-positioning plan varies for each simulation. The inventory is randomly assigned in the following steps:

(1) The total inventory quantity for all district warehouses is randomly determined through a uniform distribution $U[80, 800]$, and then randomly assigned to each district warehouse. The minimum number of stocks in the district warehouse is set to 1.

(2) The inventory quantity of the province warehouse is randomly determined through a uniform distribution $U[60, 600]$.

(3) The quantity of the remaining inventory is calculated and assigned to the regional warehouse.

After determining the inventory allocation, the simulation starts with the introduction of an earthquake as a disaster. The intensity of the earthquake is randomly generated following a normal distribution for each simulation, which affects the damage severity and number of victims and thus changed the number of relief supplies needed.

To assess the impacts of implementing the Physical Internet paradigm on humanitarian response readiness, twelve scenarios are constructed by combining different Physical Internet potentials (see Table 1). It is to be

Table 1. Combinations of different Physical Internet potentials of the twelve scenarios.

Scenario	Sourcing	Transport	Replenishment	Distribution
H.D.L.F.	Hierarchical sourcing	Dedicated deliveries	Long: 15 days	FIFO
H.D.L.E.	Hierarchical sourcing	Dedicated deliveries	Long: 15 days	Equity
H.D.S.F.	Hierarchical sourcing	Dedicated deliveries	Short: 3 days	FIFO
H.D.S.E.	Hierarchical sourcing	Dedicated deliveries	Short: 3 days	Equity
M.D.L.F.	Matrix sourcing	Dedicated deliveries	Long: 15 days	FIFO
M.D.L.E.	Matrix sourcing	Dedicated deliveries	Long: 15 days	Equity
M.D.S.F.	Matrix sourcing	Dedicated deliveries	Short: 3 days	FIFO
M.D.S.E.	Matrix sourcing	Dedicated deliveries	Short: 3 days	Equity
M.C.L.F.	Matrix sourcing	Consolidated deliveries	Long: 15 days	FIFO
M.C.L.E.	Matrix sourcing	Consolidated deliveries	Long: 15 days	Equity
M.C.S.F.	Matrix sourcing	Consolidated deliveries	Short: 3 days	FIFO
M.C.S.E.	Matrix sourcing	Consolidated deliveries	Short: 3 days	Equity

Table 2. Performance improvement from the shift towards the hyperconnected HSC.

Improvement regarding the average of performance indicator			
Implemented potentials	Readiness	Lead Time	Demand Coverage
Hierarchical Sourcing → Matrix Sourcing	↑ 29 %	↑ 29 %	↑ 10591 %
Dedicated Deliveries → Consolidated Deliveries	↓ 3 %	↓ 20 %	↓ 40 %
Long Replenishment → Short Replenishment	↑ 31 %	↑ 57 %	↓ 1 %
FIFO Distribution → Equity Distribution	↑ 9 %	↓ 4 %	↑ 109 %
Improvement regarding the standard deviation of performance indicator			
Implemented potentials	Readiness	Lead Time	Demand Coverage
Hierarchical Sourcing → Matrix Sourcing	↓ 314 %	↑ 18 %	↓ 896 %
Dedicated Deliveries → Consolidated Deliveries	↓ 353 %	↓ 1237 %	↓ 49 %
Long Replenishment → Short Replenishment	↑ 18 %	↑ 5 %	↓ 2 %
FIFO Distribution → Equity Distribution	↓ 232 %	↓ 363 %	↓ 20 %

↑ indicates improvement, while ↓ represents degradation.

noted that *consolidated deliveries* are only considered when a *matrix sourcing* strategy is adopted. This is because *consolidated deliveries* are limited by the vertical one-way flow of relief supplies when a *hierarchical sourcing* strategy is adopted.

For each scenario, the experiment was repeated 1,000 times for the simulation. The disaster intensity and inventory allocation for each simulation were randomly generated. The experiment finally yielded a simulated dataset consisting of 12,000 data, recording the post-disaster cumulative demand curve, cumulative supply curve, and humanitarian response readiness. In addition to this, two KPIs, lead time to serve total demand and demand coverage within one week, were collected to provide a deeper understanding of the *response speed capability* and *response coverage capability* of the hyperconnected HSC.

4.2. Results

The distributions of the simulated performance indicators of the HSC under different scenarios are presented in Fig.3. The transformation towards hyperconnectivity has significant impacts on the humanitarian response readiness, as well as the response speed capability and response coverage capability of the HSC. As explained above, the "H.D.L.F" scenario represents the traditional way how a typical humanitarian organization operates its supply chain and can be seen as a baseline. The other 11 scenarios represent different stages on the avenue toward hyperconnectivity. According to Fig.3, several patterns can be summarized as follows:

(1) The other 11 scenarios all achieved higher humanitarian response readiness compared to the baseline, indicating that the hyperconnected HSCs have better readiness than the existing traditional ones, even if the Physical Internet paradigm is only partially implemented.

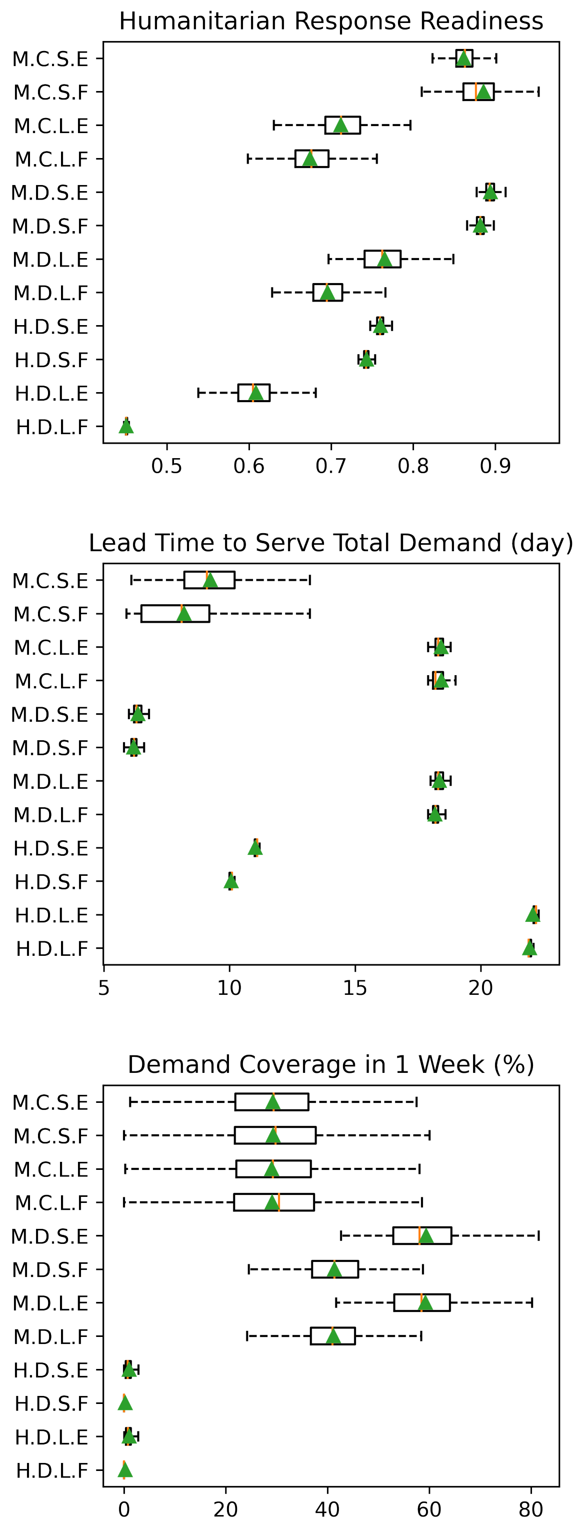

Figure 3. Box and whisker plots of the performance of the simulated HSC under different scenarios.

(2) For most scenarios, the shift to hyperconnectivity could shorten lead time and increase demand coverage. However, not all implemented potentials of the Physical Internet will yield better performance in both aspects.

(3) Improving the response speed capability and improving the response coverage capability is in some cases incompatible and need to be balanced to achieve better readiness.

For a deeper and finer perspective, Table 2 provides the relative rates of change in performance indicators resulting from the implementation of different Physical Internet potentials. A better average indicates better performance, while a lower standard deviation indicates better consistency facing uncertain disaster intensity and various inventory allocations. The following conclusions can be drawn from the analysis:

(1) Regarding *sourcing* management, switching from *hierarchical sourcing* to *matrix sourcing* will lead to better performance, especially the demand coverage within 1 week.

(2) Regarding *transport* management, switching from *dedicated deliveries* to *consolidated deliveries* will result in poorer performance. This is because consolidation has a time cost and therefore often has negative impacts on the response speed, coverage, and readiness. It is to be noted that *consolidated deliveries* can reduce transportation costs, but this is not taken into account when evaluating readiness.

(3) Regarding *replenishment* management, reducing the time required for completing replenishment can improve readiness and shorten lead time. The demand coverage during the waiting period for replenishment is essentially unchanged.

(4) Regarding *distribution* management, the implementation of *equity* distribution has a limited effect on improving readiness, which is mainly achieved by improving the demand coverage within 1 week.

(5) In most cases, the implementation of Physical Internet potentials leads to a larger standard deviation of performance indicators. This indicates that hyperconnected HSCs are more sensitive to uncertainties such as disaster intensity and preparedness activities such as pre-positioning.

5. Discussion

The hyperconnected state of HSCs is not only a solution for humanitarian organizations to achieve their objectives, but also a challenge for humanitarian sectors. This challenge can be understood in two ways, one being the need to design a rational avenue for transformation and the other being to deal with the unknown (or even negative) effects of the shift. From the analysis presented, several findings can be drawn that may be of value in addressing this challenge.

First, improved internal connectivity between logistics network nodes will lead to better response speed and coverage capabilities, and therefore better readiness. However, some of the Physical Internet potentials, such as *consolidated deliveries*, can help save costs and improve sustainability, but in the short term, these enhancements may conflict with the relief goals of humanitarian organizations. Regarding the ability to operate continuously, improved speed of replenishment often requires external connectivity for humanitarian organizations. A global hyperconnected supply chain suggested by the Physical Internet proposal may help. Given the specificity of humanitarian missions, some of the Physical Internet potentials, such as *equity* distribution, are more in line with the impartiality principle, but such improvements are not reflected in traditional performance indicators. This suggests the need to construct new metrics dedicated to characterizing different principles of interest to humanitarian sectors. Finally, smarter inventory allocation based on disaster forecasting is critical to maximizing the advantages of hyperconnected HSCs for response readiness.

This research also has limitations, mainly in terms of the simulation experiment and the readiness metric. Regarding the simulation experiment, the HSC of the Indonesian Red Cross Society was used as the context, which may compromise the generalizability of the conclusions drawn from the simulation results. In addition, the experiment only simulated the scenarios with a single product, single disaster, and single responder. The impact of these simplifications on the conclusions needs to be assessed by comparing the results of more complex and realistic simulations. Regarding the readiness metric, the current metric does not take into account factors such as cost, impartiality, and sustainability. In addition, the concept of readiness is particularly important in the face of uncertainty, and it would make more sense to introduce more uncertainty (e.g., multiple hazards, etc.) into the simulation and calculation of readiness.

6. Conclusion and perspectives

To better face challenges and achieve objectives, HSCs need to evolve towards hyperconnectivity. Understanding the impact of this transformation on HSCs' performance, particularly *readiness*, is critical to designing a sound shift avenue. To address this need, a simulation-based assessment of hyperconnected HSCs' response readiness was conducted. This work provides support for a deeper understanding of the shift to hyperconnectivity, as well as hints on how to achieve it.

Apart from that, some potential prospects for future research can also be expected. Considering the current progress, a solid validation of the simulation results is preferred. Since some simulated scenarios have not been implemented in the real world, new validation paths are needed. It is also worth exploring whether and how cost can be used as a factor in evaluating readiness. Given an extended vision, introducing artificial intelligence is promising for guiding the daily operations of HSCs and the transformation towards hyperconnectivity. The combination of simulation experiments and machine learning could be a potential approach to achieving this prospect. Since the data on which machine learning relies is difficult to obtain from the real hyperconnected system, simulation can provide simulated data as a substitute. Extending the research of this work from HSCs to commercial supply chains is also promising.

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