Design of a Simulation-Based Experiment for Assessing the Relevance of the Physical Internet Concept for Humanitarian Supply Chains

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Abstract: *The challenges faced in delivering relief items to victims of natural disasters and the growing external pressures urge humanitarian supply chain organizations to initiate some change. In this regard, the physical internet concept can offer a paradigm shift in relief organization and resource mobilization. To convince humanitarian actors to embrace this path, we propose a rigorous methodology leveraging a prototypical agent-oriented discrete-events simulator built within the AnyLogic platform, to conduct scientific experiments enabling to investigate the suitability and relevance of PI concepts for HSCs by systematically quantifying their benefits and drawbacks on HSC performance, sustainability, and resilience. We provide preliminary experimental results contrasting the baseline shaped by the current HSC structures, behaviors and practices, notably relative to sourcing, transporting, and warehousing, with those of hyperconnected HSCs in line with the Physical Internet at distinct degrees of maturity. In the experiment, we study past disaster scenarios that occurred in Indonesia and response efforts under different behaviors simulated with this platform. Initial results show that PI concepts are smoothly fitted to HSCs and the performance of hyperconnected HSCs is better than the current baseline.*

Conference Topic(s): *PI Modelling and Simulation*

Keywords: *Physical Internet, Humanitarian Supply Chains, Disaster Relief Operations, Hyperconnected Supply Chains*

1 Introduction

Natural disasters affect millions of people and cause damage to communities all around the world. Humanitarian response efforts take place immediately after a disaster and gather many different actors that plan for pre- and post-disaster efforts. Governments, humanitarian organizations, private sector partners, as well as volunteers aim to be prepared for potential disasters and respond to them successfully to help people and communities overcoming the consequences of disasters. As the intensity and frequency of natural disasters are expected to increase with the impact of global warming and climate change, the importance of Humanitarian Supply Chains (HSCs) operations, which concentrates most of the efforts (Van Wassenhove, 2006), is ever increasing. Besides, since human lives can be at stake after a disaster, it is crucial for HSCs to be effective while trying to help as many people as possible within the shortest possible time. However, achieving these goals is challenging for HSCs that concentrates most of the relief efforts (Van Wassenhove, 2006). Indeed, the efforts toward better coordinating actors, minimizing costs and environmental impacts, managing HSC operations and resources with a holistic view, and accounting for long-term impacts, are hampered by multiple factors. Among these are urgency contexts forcing decision-makers and other actors to work under pressure; damaged post-disaster infrastructures (unusable roads, lack of electricity and clean water); lack of collaboration culture; competition for limited funding and donations; HSC actors often having their agendas, making it hard to rally behind a shared goal; donors and media putting pressure on actors to improve monitoring and provide evidence for the quality of their relief operations; and missing concrete modelling of coordinated operations and the underlying structure. (e.g. (Tomasini and Wassenhove, 2009); (İlhan, 2011); Ergun, 2013). As a result, current practices and operations of HSCs are being highly criticized for their performance (Haavisto and Goentzel, 2015), and emerged the need for reorganizing HSCs and improving their operations.

In the literature, there is a recognized need for the effective measurement of HSC performance (Beamon and Balcik, 2008). Indeed, the current approaches, indicators, and dimensions used to measure performance are deemed ineffective (Abidi et al., 2014). Notably, there are growing concerns regarding integrating environmental considerations in operating humanitarian supply chains. Furthermore, the highly volatile environment in the humanitarian context requires more attention in measuring and improving the resilience of HSCs so they can adapt to unexpected changes. In the last decades, several approaches have been introduced to improve the efficiency and effectiveness of HSCs. For example, as reported by (Jahre et al., 2016), there have been significant innovations in preparedness toward improving the efficiency and effectiveness during response efforts: prepositioning inventory, advanced coordination between stakeholders (public and private), as well as enhanced education and training. Relative to the environment, there has been a drive toward sustainable HSC operations and reverse logistics (Peretti et al., 2015). Green efforts include the collection of relief item waste that can be reused, repaired or recycled appropriately (Farahani and Rezapour, 2011). The innovations above are insufficient for the HSCs to meet performance expectations, as on one side they do not alter the flawed core of their current schemes, and on the other side, disasters are becoming more frequent yet highly uncertain in terms of their occurrence and their impact.

To overcome all these challenges and improve the HSCs' performance, Physical Internet concepts can be applied as their induced capabilities have already been proven to be attractive for concurrently improving the efficiency, resilience, and sustainability of commercial supply chains. However, PI requires changes of long-lasting habits and paradigms, adaptation to new cutting-edge approaches, and some investment. So, the potential value and suitability for HSCs' operations still need to be investigated, especially given the inherent differences between commercial and humanitarian supply chains. Abdoulkadre et al. have been the first to investigate the conceptual applicability of PI concepts on HSCs, and to propose concrete PI-induced transformative avenues for HSCs (Abdoulkadre et al., 2014). This has revealed the need for further research on rigorous design and modelling of hyperconnected HSC scenarios and implementation efforts, and on assessing the potential impacts of such efforts on HSC performance.

2 Simulation-Based Research Methodology and Simulator

Due to the complexity of humanitarian systems, the use of simulation has appeared to be a suitable solution to answer our research question (Sheard and Mostashari, 2011). However, to ensure the reliability of the results and to avoid a series of pitfalls when the time comes to modeling and coding the simulation (Law, 2014), a functional framework for creating and developing the simulation has been followed and adapted to our experiment context. Adapted from the simulation study process of Law, the methodology consists of eight steps; 1) Research problem and solution design, 2) Grasp data and define a model, 3) Construct a computer program and verify, 4) Make pilot runs and observe results and validate, 5) Perform the experiment design, 6) Make production runs and verify, 7) Analyze output data and validate and 8) Document and present result. Such methodology is not necessarily a sequential process and may require going back over some steps as new elements are added and the vision becomes clearer (see Figure 1).

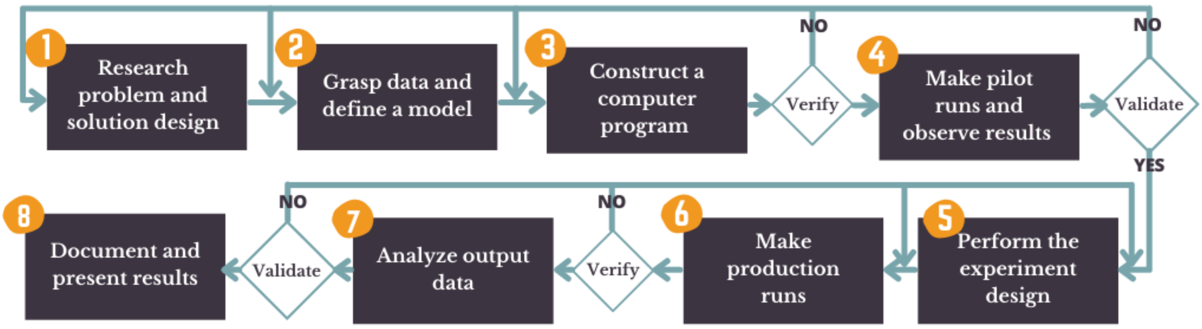

Figure 1 Adapted simulation study process (Law, 2014)

In parallel, a prototypical agent-oriented discrete events simulator was designed as a technological framework to support adequate simulation creation and development (Grest et al., 2021) (see Figure 2). The simulator architecture includes three key systems for properly experimenting: the scenario system, the virtual humanitarian ecosystem, and the performance system. The scenario system, as a configuration interface for the tester, provides to the ecosystem context elements and supply chain parameters inputs to integrate in order to form a particular scenario as a unique virtual humanitarian ecosystem to observe. Different settings at the scenario system level and runs of simulation will offer a set of scenarios to compare thanks to the performance system that keeps track of the evolution of performance indicators over time.

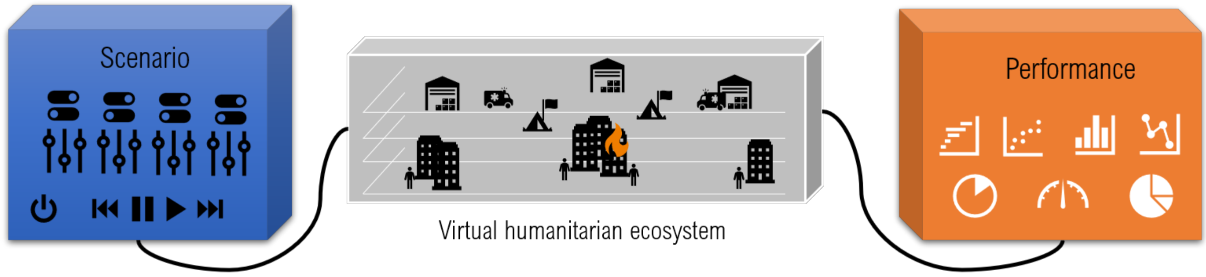

Figure 2 Prototypical agent-oriented discrete-events simulator embedding three different interrelated systems (Grest et al., 2021)

3 Case-Based Simulation Assessment of Hyperconnected HSCs

We illustrate end-to-end the functional framework by describing our approach in assessing the perspective of the PI for humanitarian operations through an Indonesian case study and a simple set of scenarios.

Step 1. Research problem and design. The hypothesis under study is the following: a reorganization of HSCs toward a hyperconnected version will positively impact the performance results of humanitarian players in assisting affected people. From there, an experiment needs to be undertaken to assess the impacts of such an original association understudied to date. To do so, a comparison through performance results will be conducted between a humanitarian supply chain baseline scenario representing current practices and some hyperconnected alternatives to test. Such a set of scenarios are instances at the factor definition level (see step 5) and are derived from a common model - detailed in the following step - named the theoretical model. For building the model, Indonesia, one of the most disaster-prone countries, will be used as a case study. Since HSCs are complex systems, using simulation for experimenting is necessary. Consequently, by recreating an environment prone to disasters and by programming the behaviors to be tested the evaluation will be performed through performance indicators. Furthermore, the study perimeter is limited to the improvement of HSCs' performance in delivering relief items to victims of natural disasters. Finally, from this design, different working areas have been identified and are detailed in the following sections.

Step 2. Grasp data and define a model. Gasping data for building the baseline scenario has started with a field survey within the Indonesian Red Cross (IRC) to enable the identification of the main objectives, strategies, and available resources within the country. Major findings were that IRC's logistics network is organized in a hierarchical structure and heavily depends on the population positioning. Indeed, the country is administratively divided into provinces which are composed of regencies. Therefore, IRC has positioned district warehouses in nearly every regency nearby major cities. Those are covered by a dedicated province warehouse which itself is supplied by a regional warehouse. The survey also enabled us to get a process-oriented vision regarding how IRC prepares and responds to natural disasters. Specifically, once a disaster occurs, small teams are sent to make a people and material damage assessment. Then, a global relief item need is calculated and sent to the warehouse in charge of the affected zone. In parallel, Points of Delivery (POD) for relief item distribution are deployed nearby population-dense areas and wait for supplies arrival. Next, the warehouse in charge responds to the demand with inventory on hand, finds an appropriate fleet, organizes the delivery to the PODs, and manages shortages. Finally, regarding the grasping data phase, historical records about past natural disasters have also been analyzed to generate statistics related to their impact and occurrence frequency in Indonesia. In addition, we have learnt about the need for the disaster type as well as the affected territory and population consideration into the model (Cosgrave and Herson, 2008).

Based on the knowledge gained, the theoretical model integrates four essential components in a relief context: i) the territory emulator that represents a territory and its key social and geographical characteristics having an influence on the relief organization, ii) the disaster generator that generates natural disasters events and impacts on people and materials, iii) the demand estimator that estimates the demand in relief items based on victims number and damages and iv) the humanitarian response simulator representing the humanitarian supply chain and logistics operations. In this paper, we base the model on an Indonesian case study and limit the study perimeter to the Aceh province and its 21 district parts of the mainland, as it is the site of major natural disasters in the past and displays disparity in terms of population distribution. Currently, only earthquakes, as a disaster type, are considered due to their frequent occurrence in this region. Regarding damages, only districts hit from a strong (with light damage) to extreme (very heavy damage) value according to the MMI shaking scale are regarded as requiring humanitarian assistance. From there, the focus is on affected people as Internally Displaced Persons (IDP) and are regarded as beneficiaries or a household in demand for five typical Red Cross items: blankets, jerrycans, hygiene kits, kitchen sets and tarpaulins. Rapidly, PODs are deployed in affected districts and wait for supplies coming from the pre-positioned warehouses of the IRC network. Need requests are managed and fulfilled using on-hand inventory. When inventory is missing, supply sources are identified within the IRC network only, and a replenishment order is sent meanwhile available items are delivered by trucks.

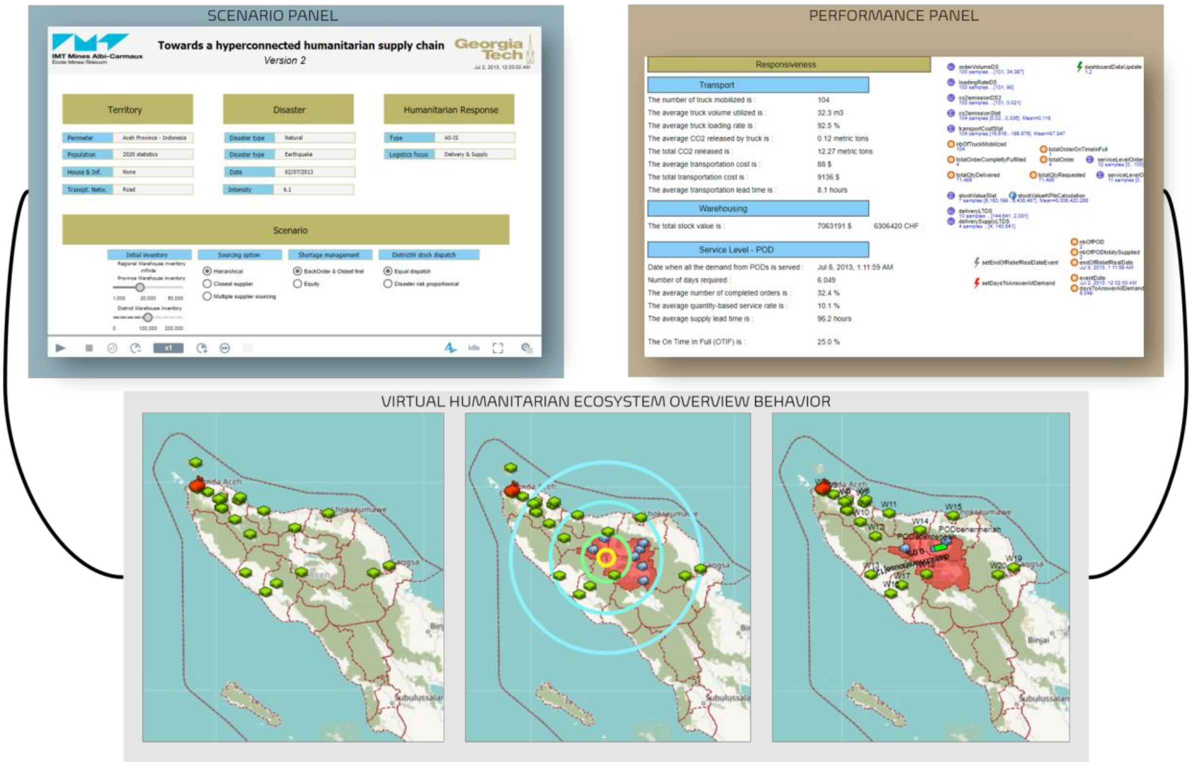

Figure 3 Simulation systems connection and operating overview

Step 3. Construct a computer program and verify. Derived from the previous theoretical model, an agent-based and discrete-event-oriented simulation program has been initiated in Java coding language using the AnyLogic software (see Figure 3). Based on the simulator, the simulation consists of three interrelated components. The first is the scenario system where a user can configure a scenario to test. The configuration consists in a first step of defining the environment and context in which a second system, the virtual humanitarian ecosystem, is about to evolve. The environment is related to a country or region where past disasters, defined by the context, are replayed and kept the same for running an experiment with a set of scenarios. Secondly, the user finalizes setting a scenario by indicating the operational approaches of the humanitarian response system at specific parameters level, called factors of the experiment. The third component is the performance system where performance indicators will be monitored. Regularly, the virtual humanitarian ecosystem feeds the performance system with data to enable real-time performance measurement and monitoring. Therefore, through the Indonesian case study and the run of multiple scenarios, a comparison between the PI-oriented suggestions and the baseline is possible and enables concluding the relevance of the PI approach for the humanitarian sector. Documented tests have been performed to ensure the adequate execution of each programmed component compared to the defined theoretical model.

Step 4. Make pilot runs, observe results, and validate. Our interviews and data analysis could not provide us with all the required parameters and inputs precisely. As a result, in defining the baseline scenario, we made some assumptions and estimated some parameters. To validate these assumptions and estimations, we run pilot tests to ensure that the simulated behavior is close to the historical. Initial results from our pilot studies suggest that our assumptions and estimations are consistent with humanitarian situation reports found. Additionally, workshop sessions with practitioners have also been organized to validate the baseline scenario and associated assumptions such as trucks being dedicated to one organization at a time and returning [to warehouses] empty after delivering items.

Step 5. Experiment design. In this section, the complete design of the experiment intended is presented first and at the end, a portion of it with factors currently implemented in the simulation and used to run a first experiment phase. Once the baseline scenario has been validated, the design of the experiment phase consists of designing scenario variants for making comparisons (Chung, 2004). Alternatives rely on the change of the value of some parameters by the tester. Such input variables are called factors and their values are named levels (Banks, 1998). Since the manipulation of factors has a direct effect on the outputs, some effort should also be spent on defining the performance measurement system for the experiment.

- **Complete experiment design and factor definition**

Experiment design starts with defining factors and associated levels. Since we aim at testing new PI-oriented practices we identified two entry points for change, as triggers of the performance, lying in the network design and in the disaster operations management levels (Grest et al., 2020).

Regarding the network design, we first suggest challenging the node interconnection from a unilateral structure to a multi-directional one. Such a connection allows better spreading of the information within the network while gaining visibility over the nodes' capabilities. As a first step, the connection will be tested within the same network to form a - *physical intranet* - aiming at taking advantage of existing capabilities. Secondly, the connection will be expanded to adjacent networks to form the - *physical internet* - which will offer a larger vision of opportunities for partnerships and/or coordination. Another network design factor to consider is related to asset management. In this case, we wish to test to what extend dynamic capabilities against supply disruptions would bring more agility to the response.

Now regarding the disaster management operations factors, while conceptualizing hyperconnected approaches, we primarily focus on the logistics and related decisions at the sourcing, transporting, and warehousing level. Considering the sourcing, current practices mainly consider a vertical/hierarchical approach and attempt to distribute the relief items and other resources from big central warehouses to smaller ones. Instead, we suggest utilizing multi-directional sourcing to improve response effectiveness with faster deliveries, efficiency with higher resource utilization, and resilience with a more robust sourcing network. Moreover, organizations are currently conducting their transportation operations independently and the consolidation efforts within the organizations are limited. Because of the high volume and frequency of the deliveries and possible limitations on transportation means availability during the disaster response, increasing transportation consolidation both within and between organizations will improve the response performance with higher utilization of transportation means and enable organizations to make faster deliveries. Also, by applying PI concepts and using encapsulation standards, it is possible to achieve more efficient and effective warehousing operations. For example, convenient handling of the relief items will allow organizations to dispatch items faster, utilization of warehouse spaces will increase, and standardized storage units will allow different organizations to share warehouse spaces easily. Further, since the capabilities of humanitarian organizations during the response phase highly depend on their preparedness level, we also considered possible steps to improve the preparedness of the organizations. The main challenge while preparing for natural disasters is the high uncertainty regarding the time, location, and impact of the disaster; at this point, we also wish to study how anticipating potential disasters and their impacts would help organizations in smartly pre-positioning relief items and other resources before disasters.

- **Complete experiment design and performance measurement system**

While measuring the performance of HSCs, our focus will be on four main dimensions: effectiveness, efficiency, resilience and sustainability. Effectiveness is the extent to which the beneficiaries' needs and requirements are met (Beamon and Balcik, 2008). Two main performance indicators related to effectiveness will be response speed (delivery lead times) and response coverage (number of people receiving help). Efficiency measures the rightness of needs evaluation, speed of adaptation to changes, and resource utilization (Neely,1995). As mentioned before, HSCs are working with limited resources and budgets, and must use these limited resources with high utilization rates for accurately assessed needs. Cost of different operations, such as warehousing, transportation and procurement, and the utilization of trucks and warehouses will be used as indicators of efficiency. Resilience can be defined as the ability to resist disruptions or return to the original or a more desirable state after being disturbed (Hosseini, 2016). Considering the continuously changing conditions and potential disruptions on the supply chain networks, resilience plays a key role in smoothly conducting response efforts with minimum impact from unexpected consequences of natural disasters. To measure the resilience of HSCs, we are planning to test their performance under scenarios with different disruption levels. Finally, the UN defines sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (UN World Commission, 1987). Since HSCs are conducting very large-scale operations, following green supply chain practices can have a large impact on global warming and climate change issues. In our model, CO2 emissions resulting from transportation efforts will be the indicator for sustainability. This set of performance indicators can be expanded with more detailed and specific indicators as well; at this level of the research, we are considering very generic indicators.

- **Article experiment description**

As the simulation progresses, factors previously identified are integrated. So far, the programming work mainly focused on the node interconnection at the network design level, as it is a keystone for most of the following PI-oriented factors. Currently, the connection is specific to nodes within the IRC network in the situation of sourcing when selecting a supplier is required. For this factor named - *sourcing* -, three levels are considered: i) the hierarchical approach (i.e., depending on the type of warehouse, another type is preselected as a supplier), ii) the closest supplier approach (i.e., the closest supplier is selected if he can fulfil the received demand) and iii) the multiple sourcing approach (i.e., a list of suppliers is suggested based on proximity and available inventory). A second factor tests two shortage management approaches namely the FIFO that fulfils the first orders received compared to the - *equity* - approach where all demands are at least partially fulfilled by splitting the inventory on hand. Finally, the third tested factor concerns inventory dispatch before the event occurrence and investigates an equal repartition versus a division based on hazard risk. Regarding performance, we focus on the effectiveness of the response through the delivery indicator monitoring the quantity of item distributed over time compared to the demand from beneficiaries and when they match.

Step 6. Make production runs and verify. A first successful experiment run has been initiated based on the experiment design previously depicted. With 3 levels (hierarchical, closest supplier, and multiple sourcing) for the sourcing approach factor and 2 levels (FIFO and equity) for the shortage management factor and 2 levels (equal and risk proportional) for the district warehouses initial stock dispatch, a set of 12 scenarios have been simulated. According to the field data gathered from practitioners, the conditions are the following: initial total district warehouse inventory is set to 100,000, initial province warehouse inventory to 20,000, and runs last for eight virtual days. Verification steps include error message detection and ensuring the correct collection of output data.

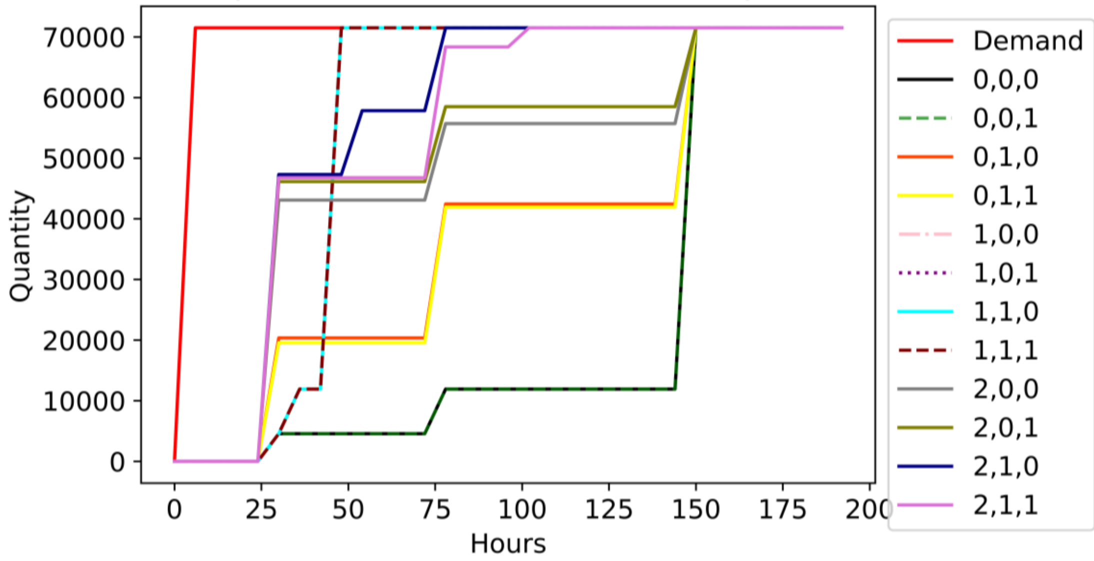

Figure 4 Scenarios performance results in delivering relief items to beneficiaries in the aftermath of a disaster

Steps 7 and 8. Analyze output data, validate, and present results. Once the runs were completed, we gathered performance data from all the scenarios to start analyzing the results. We issued the following graph which shows each scenario's performance in delivering relief items compared to the cumulative demand over time (see Figure 4, red line). Scenarios are referred to using a tuple format of three figures (X,Y,Z). The first tuple number defines the level for the sourcing factor (0 = hierarchical, 1 = closest supplier, and 2 = multiple sourcing). The second tuple number defines the level for the shortage management factor (0 = FIFO and 1 = equity) while the third tuple number describes the initial district warehouse stock dispatch (0 = equal and 1 = risk proportional). The baseline is the scenario (0,0,0) and the associated performance result is illustrated by the black line. It appears to be the slowest scenario in delivering items. Indeed, it requires almost 6 days to serve all the demand (which is coherent with practitioners' feedbacks) while over this time only 17% of the demand is satisfied. The introduction of the equity approach for shortage management (scenario (0,1,0) and (0,1,1)) allows serving around 24% more beneficiaries in the same amount of time. The iterations ((2,0,0) and (2,0,1)) using the multiple sourcing approach without the equity also fulfil the total demand in 6 days. However, compared to the baseline, they multiply by ten the number of people served over this period. In contrast, scenarios using the multiple supplier sourcing approach without the equity rule serve even better the demand and, in less time (3.25 days for scenario (2,1,0) and 4.25 days for scenario (2,1,1)). Finally, the fastest scenarios are those using the closest supplier sourcing rule by cutting the delivery time by 68% compared to the baseline. From these observations, it seems the sourcing approach has a significant impact on the supply lead time and quantity served compared to the other factors. Especially, the test of two hyperconnected approaches (closest supplier and multiple sourcing) breaking with the hierarchical structure and allowing horizontal and vertical sourcing connection have seriously improved the response performance results in terms of time and distribution. The equity approach for dealing with the shortage leads to an increase in the number of people served in a timely manner. In contrast, the stock dispatch factor does not seem to have a real impact on this performance indicator. The reason may come from the too slight difference regarding the stock dispatch based on the proportionality defined compared to the equal dispatch. An additional reason may come from the current consideration of a single disaster to respond to.

4 Agenda and Further Research

In this paper, we explained the need for efficient, effective, resilient, and sustainable humanitarian response in response to a disaster. We developed a simulation platform in AnyLogic software and investigated the novel approach of using PI concepts in the HSC realm. In a computational study involving past disaster scenarios that occurred in Indonesia, we simulated operations lead by the baseline and hyperconnected behaviors and showed significant improvement in terms of response speed and coverage. The paper serves as one of the initial investigations for utilizing PI in HSC operations, and as such, it opens several avenues for future research, including optimizing the pre-positioning of the relief items and other resources before disasters to better serve the population. In addition, in the post-disaster time, there is a need for a more efficient and robust work plan for the distribution of the relief items to the PODs. However, the current measures are not sufficient and new indicators to evaluate the operations need to be considered. Those indicators should be more beneficiary-oriented and reflect the life quality of the affected populations in the aftermath of a disaster.

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