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A Simulation model for short and long term humanitarian supply chain operations management

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Abstract: Traditionally, the design of supply chains for humanitarian operations has been developed distinctly for the different disaster management phases, with little attention to relief to development continuum. For the immediate response phase, this design has an emphasis on speed, whereas for the reconstruction phase, it has an emphasis on cost-reduction. In this paper, we develop a sustainable humanitarian supply chain network for the relief to development continuum. Hence, this network ensures an effective and smooth transition from response to reconstruction operations. We develop three network structures which integrate the lean and agile principles at a different extent. To determine the best characteristics of such a sustainable supply chain, we use discrete event simulation (DES) modeling. We validate and compare each network structure through several scenarios fed by data sets available from the United Nations World Food Program (WFP) for operations conducted in the Republic of Congo (RoC).

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1 Introduction

In this paper, we aim to develop simulation models to design suitable sustainable humanitarian supply chains. In the last decades, humanitarian operations have received an increased interest (Behl and Dutta 2019; Çelik et al. 2017; Kovács and Moshtari 2019) due to the impacts of natural and man-made disasters. To ensure rapid and efficient response, organizations rely on logistics operations and supply chains (Balcik et al. 2019; Lewin et al. 2018) which represent an important cost (Van Wassenhove 2016). Humanitarian supply chains usually consist of international suppliers, international distribution centers, regional distribution centers, local distribution centers (or dispensing points) and delivery points (or end-users) (Dufour et al. 2018; Kara and Rancourt 2019). Their performance depends on the location, size and number of such distribution centers, on the replenishment policies and on the selected transportation modes (Duran et al. 2013). On the other hand, even though the number of disasters has been increasing, little attention has been given to developing sustainable humanitarian supply chains (Halldórsson and Kovács 2010) with the three following properties: agility, adaptability, and alignment (Dubey and Gunasekaran 2016).

Humanitarian operations are defined according to the disaster management cycle (Altay and Green 2006; Çelik et al. 2012; Kovács and Spens 2007, 2009; Van Wassenhove 2006), which is divided in pre- and post-disaster phases. The supply chain is usually designed during the pre-disaster phase when item pre-positioning is done. Once a disaster strikes, the post-disaster phase starts, first with (immediate) response and then through reconstruction. The response phase is short-term and the most critical. Its goal consists of restoring in the shortest possible timeline emergency and basic services to the highest number of people in need. The reconstruction phase then aims to restore the system and the services on the long-term while using the resources as best as possible. To develop such sustainable supply chains, it is important to determine the most appropriate characteristics of the supply chain and to ensure a smooth transition from the response to the reconstruction phases (also known as the relief to development continuum, Demusz 1998) which requires changing from an effective (and rapid) to an efficient supply chain.

In addition, simulation modeling has been used to design, observe, understand, analyze and improve large-scale complex systems (Mei et al. 2015). Undeniably, its ease to grasp complex behaviors, interactions and operations makes it a powerful tool for analyzing and improving humanitarian supply chain operations.

In this article, we aim to design a sustainable humanitarian supply chain. To determine the best structure, we rely on simulation modeling and analyze the impact of different structures on key performance indicators for specific operations conducted by the United Nations World Food Program (WFP) in the Republic of Congo (RoC). The remainder of the paper is structured as follows. Section 2 presents a literature review on humanitarian logistics and simulation modeling applied to humanitarian logistics. Section 3 presents the characteristics of the specific case and provides three structures of the supply chain. Section 4 presents summarized and detailed simulation results. Finally, conclusions are drawn in Section 5.

2 Literature review

Humanitarian supply chains have been widely studied by the OR/MS community (Anaya-Arenas 2014; Balcik et al. 2016; Behl and Dutta 2019; Çelik 2016) with an emphasis on network design, transportation management and inventory management. These reviews highlight the use of a reorder point method for inventory management as well as the lack of a standardized modeling framework and of continuity for the reconstruction phase. In this section, we conduct a literature review related to 1) lean and agile principles in the humanitarian supply chain, and 2) simulation modeling for the humanitarian supply chain.

2.1 Lean and agile principles in the humanitarian supply chain

In humanitarian logistics, effectiveness is usually defined by the rapid deployment of items, whereas efficiency is usually defined by a cost reduction. Therefore, many authors have suggested to apply the agile principles in the response phase and the lean principles in the reconstruction phase (Cozzolino et al. 2012; Dubey and Gunasekaran 2016; Naim and Gosling 2011; Oloruntoba and Kovács 2015). Naylor et al. (1999) define the lean and agile principles in the commercial supply chain as the development of “a value stream to eliminate all waste, including time, and to ensure a level schedule” and as “using market knowledge and a virtual corporation to exploit profitable opportunities in a volatile marketplace”, respectively. Therefore, the lean principles focus on efficiency, including cost reduction, and agility principles focus on effectiveness, including flexibility and speed. The lean principles are usually more appropriate for products with long lead time and predictable demand, whereas the agile principles are more appropriate for products with short lead time and unpredictable demand (Christopher et al. 2006).

Oloruntoba and Gray (2006) have proposed a framework where lean principles are applied for the upstream humanitarian supply chain (demand forecasting, procurement and transportation sourcing) with an inventory decoupling point, and agility principles are applied to the downstream supply chain (site selection, needs assessment). Cozzolino et al. (2012) consider that the agile principles are more appropriate for the immediate response phase to reach effectiveness, while the lean principles are more appropriate for the reconstruction phase to reach efficiency. They have conducted an empirical study based on historical operations of the WFP in Sudan. Their framework shows that WFP applies agile principles to the emergency operations (EMOPs) which are short-term (3 to 12 months), while the lean principles are applied in protracted relief and recovery operations (PRROs) which are longer term operations aimed at stabilizing the food and living conditions of the beneficiaries. More recently, Shafiq and Soratana (2019) have proposed a framework that integrates lean and agile principles at specific stages of the humanitarian supply chain. According to the post-disaster phase (response or reconstruction), the type of disaster (sudden onset – earthquake, hurricane, terrorist attack – or slow onset – famine, poverty, refugee crisis, (Van Wassenhove 2006), and the components (hard – delivery of supplies – or soft – capacity building, policy making, education, health services), the supply chain structure varies. For the response phase and with sudden onset disaster, all stages of the supply chain is suggested to be agile. For all other contexts, a transition from lean to agile principles before the distribution of supplies to delivery points is proposed.

2.2 Simulation modeling for the humanitarian supply chain

Discrete-Event simulation (DES), Agent-Based Modeling (ABM) and System Dynamics (SD) are the main simulation paradigms that are used as decisions supports tools in logistics and supply chain management (Barahona et al. 2013; Feng et al. 2012; Hooshangi et al. 2018; Mustapha et al. 2013; Stauffer et al. 2018). Tako et al. (2012) conduct a thorough analysis on the application of DES and SD in the logistics and supply chain context. The findings of this study show an extent use of these paradigms to model most logistics and supply chain issues for strategic, tactical and operational decisions (e.g. supply chain structure, supplier selection, facilities and capacity planning, system performance, cost reduction, replenishment policies, inventory planning and management, distribution and transportation planning, dispatching rule). In addition, the literature has rich and diversified studies using simulation as decision supports tools in logistics and supply chain management and each of these studies addresses specific issues.

Golroudbary et al. (2019) use a hybrid modelling approach (combining ABM and SD) to address the reliability of the logistic delivery system while considering uncertainty due to human behaviors. Krejci (2015) defines a combined modeling approach (ABM and DES) to present a conceptual framework for a hybrid simulation model used to evaluate decision making in theoretical humanitarian logistics operations taking into account human uncertainty behaviors. Wang et al. (2019) use an ABM approach and evaluate different transportation scenarios to optimize the capability of supplying humanitarian

relief goods. This literature shows rich and diversified studies using simulation as decision supports tools in logistics and supply chain management, each of these studies addresses specific issues.

2.3 Contributions of this paper

In the OR/MS literature related to humanitarian supply chain design, little attention has been given to the relief to development continuum, i.e., designing supply chains that are sustainable for both types of operations. Moreover, location, distribution, transportation optimization or inventory management decisions are usually addressed separately. In this study, we define an innovative hybrid design that addresses facility location, transportation and inventory management decisions within uncertainty conditions. We test and illustrate the performance of this structure using DES modeling paradigm. To the best of our knowledge, this is the first time that a quantitative methodology is used to assess the impacts of lean and agile principles in the humanitarian supply chain.

3 Design of humanitarian supply chain networks

We have developed three networks: i) a first network, referred to as Emergency, designed for the response phase which focuses on effectiveness and agility, ii) a second network, referred to as Development, designed for the reconstruction phase which focuses on efficiency and leanness, and iii) a third network, referred to as Continuum, for both response and reconstruction phases, i.e., for the relief to development continuum, which benefits from a hybrid structure incorporating agile and lean principles and aims to propose a sustainable supply chain for the immediate response and reconstruction phases. In this section, we first describe how data collection was conducted, and then explain the structure of each network.

3.1 Data collection

According to the 2019 Human Development Index, the RoC is ranked 138 out of 189 countries. In November 2019, its government declared a state of natural disaster and humanitarian emergency due to the severe floods. In addition to these severe floods, its food production does not satisfy the needs of the population and armed conflicts are frequent. Therefore, international organizations such as the WFP provide assistance to the population of the RoC and its internally displaced population.

In this study, we use public information and data. Transportation distances and duration are estimated using real-life distances, whereas the operations are those from the WFP conducted in the RoC from 2015 to 2018. WFP characterizes the operations as emergency operations (EMOP), protracted relief and rehabilitation operation (PPRO), development operations (DEV) and special operations, which usually involve logistics, (SO). According to the classification proposed by Cozzolino et al. (2012), the response phase operations contain EMOP, also referred to emergency operations in the remainder of the paper, and the reconstruction phase operations contain PPRO, DEV and SO, also referred to development operations in the remainder of the paper. Figure 1 provides a map of the regional distribution center (RDC), located in Pointe-Noire, and of each operation's location (also referred to as delivery points).

3.2 Structure of the humanitarian supply chain network

To design our networks, some assumptions were made inspired by the structure of existing humanitarian supply chain networks and distribution policies. These assumptions were validated with experienced professionals and with the conducted literature review. In the following, we describe the characteristics of the operations and the different networks.

3.2.1 Characteristics of the operations

From 2015 to 2018, WFP reports eight operations in the RoC: one for the country program (200648), five for population displacements and refugees (201039, 201066, 201093, 200147, 200799), one for the



Figure 1: Structure of the supply chain network

Ebola outbreak (201126) and one for the supply corridors (200934). Characteristics are reported in Table 1.

Each operation has a demand pattern according to its characteristics. For EMOP (delivery points 1, 3, 4, 5, and 8), we have considered that 85% of the total demand is revealed on day 1, and that the remainder is uniformly distributed during the residual operation's duration. In fact, in emergency operations, an assessment of needs is usually conducted shortly after the disaster and allows to know a large portion of the demand rapidly. For PPRO, DEV operations and SO (delivery points 2, 6, and 7), the demand is uniformly distributed during the duration of the operation as we have considered the consumption of food to be relatively constant for such operations. In addition, we assume that the replenishment policy for emergency operation is based on a reorder point system, i.e., emergency delivery points can order when needed from their LDC, whereas development operations are replenished only once a week.

Table 1: Characteristics of the WFP operations in RoC from 2015 to 2018

Delivery point	1	2	3	4	5	6	7	8
Project	201039	200648	201066	201093	201126	200934	200147	200799
Type of operation	EMOP	DEV	EMOP	EMOP	EMOP	SO	PRRO	EMOP
Duration (months)	3	36	6	5	3	36	24	36
Food delivered (mT)	2,208	14,600	35	2,000	5,525	4,563	8,320	1,770

3.2.2 Characteristics of the supply chain networks

In humanitarian supply chain networks, food is usually supplied internationally and located in international distribution centers. WFP often uses the United Nations Humanitarian Response Depot

(UNHRD), for which the main warehouse for the African continent is located in Dubai. From there, the food is sent to regional distribution centers (RDCs) and then to local distribution centers (LDCs) where it is distributed to the delivery points (beneficiaries). Note that the focus of this work is to study the last-mile of the supply chain, starting from the RDCs and ending at delivery points. The characteristics of the different proposed supply chain networks vary according to their end-goal, i.e., an emphasis on agility, cost-reduction, or the integration of both. Table 2 summarizes the characteristics of each supply chain network.

Table 2: Supply chain characteristics for the three proposed supply chain networks

	Emergency	Development	Continuum
Transportation mode from Dubai to RDC	Air	Sea	Sea
Transportation mode from RDC to LDCs	Road	Road	
Replenishment frequency from RDC to LDCs	-	Twice a week	Every three days

In RoC, the RDC has been located in Pointe-Noire (see Figure 1), close to a large city with an international airport and a seaport. The location of LDCs depends on the supply chain network. In the Emergency network, we have considered one LDC per operation located at the same location. In the Development and Continuum networks, LDCs are centralized and have been located according to the geography of RoC and of the operations. Sufficient capacities of the RDC and LDCs are strategically defined.

Different transportation modes are considered to supply the RDC in each network, whereas road transportation is used to supply LDCs because of its accessibility. In the Emergency network, because of the need of fast delivery, air transportation is used, whereas in the Development and Continuum networks, because of the cost-reduction importance, sea transportation is used.

The inventory management policy from the RDC to LDCs varies according to the network. In the Emergency network, it is based on a reorder point system, that is, a replenishment is triggered as soon as the inventory reaches a minimum threshold defined as the maximum quantity of consumed food during a delivery period. In the Development network, LDCs are replenished twice a week. Finally, in the Continuum network, LDCs are replenished every three days.

4 Scenarios and simulation results

In this study, we design and test via simulation modeling an innovative humanitarian supply chain network that ensures a smooth transition from the response to the reconstruction phases. Our DES modeling was implemented using Arena 16.0 (Rockwell automation technologies inc.) as it provides a suitable and effective representation of the supply chain (Feng et al. 2012; Tako et al. 2012).

We have implemented one simulation model per network and conducted several scenarios to determine the most appropriate hybrid solution. In each scenario, different parameters were modified. Because the modeled system in this present study consists of considering both emergency and development operations, we ran our model as a terminating system.

4.1 Verification and validation

Considering the lack of real-life output, our models, their behaviors and the results were validated according to our expertise. Therefore, we have conducted an extensive set of scenarios to verify and validate that our networks and simulation models had the appropriate characteristics for their main purpose (emergency or development operations). We also ran multiple scenarios to validate the setting of parameters and to determine the best structure for each setting (only immediate response phase, only reconstruction phase, and the integration of immediate response and reconstruction phases). For all scenarios, we assume that the fleet is operated by a third party logistics provider.

The first set of scenarios uses the Emergency network with only emergency operations and modifies i) the fleet capacity at the RDC, ii) the inventory level at the RDC, and iii) the fleet capacity and inventory levels. We were able to show that our model validates the integration of agile principles in immediate response operations (see Section 4.2.1).

The second set of scenarios uses the Development model with only development operations and modifies i) the fleet capacity at the RDC and the LDCs, ii) the inventory levels at the RDC and the LDCs, iii) the fleet capacity and inventory levels at the RDC and LDCs, and iv) the delivery frequency at LDCs while ensuring a sufficient number of available vehicles and inventory levels at the RDC and the LDCs. These scenarios helped us identify two LDCs: one resupplying the Northern part of the RoC, and one resupplying the Southern part of the RoC. We were able to show that our model validates the integration of lean principles in reconstruction operations (see Section 4.2.2).

The third and last set of scenarios is used to design a hybrid network structure. We conduct this last set of scenarios in two progressive steps. First, we run the Emergency and the Development models with all the operations according to their respective characteristics. Second, starting from the Development model, we gradually add new LDCs. When a new LDC is added, the number of vehicles at the RDCs and LDCs is modified. This gradual modification of the network characteristics through several scenarios allowed us to design and validate the final hybrid network structure, i.e., the Continuum model.

4.2 Simulation results

To compare the performance of each network, the following Key Performance Indicators (KPIs) are used:

- **Total time – 85% demand** and **Total time – 100% demand**: the percentage of the total time period needed to deliver 85% and 100% of the total demand, respectively.
- **Days out of stock**: the number of days an operation is out of stock.
- **Maximum inventory level**: the maximum inventory level at a given time in the network.
- **Total costs**: the total costs including inventory and transportations costs.

The first three KPIs allow to measure effectiveness in terms of response time (and reactivity), while the other KPIs measure efficiency and the use of resources.

4.2.1 Results for the emergency network with only emergency operations

The Emergency network with only emergency operations (delivery points 1, 3, 4, 5, and 8) is used as a reference model. We have left out the total costs of this initial analysis as we cannot compare it when the basis of the operations is different.

Table 3: Detailed results for the emergency network with only emergency operations

Delivery points	1	3	4	5	8	Average
Total time – 85% demand (%)	11.2	1.1	19.8	61.5	6.8	20.1
Total time – 100% demand (%)	31.5	1.1	37.3	96.7	11.2	35.6
Days out of stock	10	2	18	57	25	22.4
Maximum inventory level	440	12	440	440	440	354.4

Table 3 summarizes the simulation results and validate the model with a rapid delivery of supplies for most delivery points. In particular, for operations 1, 3, 4, and 8, the network has the required characteristics for emergency operations: 85% of the demand can be delivered within less than 20% of the total duration of the operation, while the total demand is delivered within less than 40% of total duration of the operation, and no delivery point is out of stock for more than 25 days. On the other hand, delivery point 5 stands out as it takes more than 60% and 95% of the total duration of the operation to deliver 85% and 100% of the total demand, respectively, and it is out of stock for 57

days. In addition, we can note that the average reactivity is 64%, but is lower for delivery point 5, which also has 57 days of out of stock. Given the parameter settings of our simulation model, and the characteristics of delivery point 5 (high demand and one of the furthest delivery point from the RDC), these results remain consistent.

4.2.2 Results for the development network with only development operations

The Development network with only development operations (delivery points 2, 6, and 7) is used as a reference model. We have left out the total costs of this initial analysis as we cannot compare it when the basis of the operations is different.

Table 4: Detailed results for the development network with only development operations

Delivery points	2	6	7	Average
Total time – 85% demand (%)	84.6	83.2	83.6	83.8
Total time – 100% demand (%)	99.4	98.3	99.7	99.1
Days out of stock	1	2	3	2
Maximum inventory level	147	237	190	191.3

Table 4 summarizes the simulation results and validate the model by showing that, instead of prioritizing a rapid delivery of supplies, a more stable delivery pattern is used. In particular, for all delivery points, we can note that more than 80% and more than 95% of the total duration of the operation are needed to deliver 85% and 100% of the total demand, respectively. This is consistent with the fact the demand is uniformly distributed throughout the operation. In this model, we can also note that the number of days a delivery point is out of stock is at most three, which is again consistent with the demand pattern. Finally, the maximum inventory levels are lower than with the previous model, again consistent with the characteristics of development operations, as we aim to reduce the costs for development operations.

4.2.3 Summarized results for the networks with all operations

In this section, we present summarized results for the Emergency, Development and Continuum networks with all delivery points. Table 5 displays the average total time needed to deliver 85% and 100% of the total demand. Table 6 displays the average days out of stock, the average maximum inventory level and the average total costs. The results are presented according to each network.

Table 5: Summarized results for the average total time to deliver 85% and 100% of the total demand

Network	Operations	Average total time – 85% demand (%)	Average total time – 100% demand (%)
Emergency	Development	18.5	33.5
	Emergency	19.3	37.5
Development	Development	70.7	83.8
	Emergency	62.8	75.0
Continuum	Development	44.0	59.1
	Emergency	20.5	35.4

Table 6: Summarized results for the number of days out of stock, the maximum inventory level and the total costs

Network	Days out of stock	Maximum inventory level	Total costs (M USD)
Emergency	106	25 568.9	157.1
Development	362	1 527.0	63.2
Continuum	439	1 859.6	64.9

We can realize that using the Emergency network ensures that, on average, for both types of operations, less than 20% and less than 40% of the total duration of the operation is required to deliver 85% and 100% of the total demand. We can also note that it has 106 days out of stock which

is the lowest, while the maximal inventory level is the highest (13 times higher than the two other networks). This results in higher costs (157.1 M USD), which are more than two times higher than for the other two networks. This is consistent as this network is designed for fast delivery independently on the type of operation and does not aim at cost reduction.

On the other hand, with the Development network, on average more than 60% and 75% of the total duration of the operation is required to deliver 85% and 100% of the total demand. In addition, there are 362 days out of stock which is the second largest, while the maximal inventory level is the lowest. This network has the lowest costs (63.2 M USD). This is consistent as this network is designed to reduce the total costs without ensuring fast delivery. This implies that, an essential characteristic of emergency operations, namely fast delivery, cannot be attained with this network.

Finally, the third network (Continuum) seems to provide the most interesting results in terms of effectiveness and efficiency. In particular, for emergency operations, an average of 20.5% and 35.4% of total duration of the operation is required to deliver 85% and 100% of the total demand. This is very similar to the Emergency network and ensures rapid delivery for emergency operations. For development operations, an average of 44.0% and 59.1% of the total duration of the operation is required to deliver 85% and 100% of the total time. This average is lower than the Development network, which suggests a faster delivery while remaining slightly lower than with the Emergency network. In addition, this network has the highest number of days out of stock which is due to one delivery point. A detailed analysis and explanation is provided in Section 4.2.4. With this network, the maximum inventory level and the total costs are similar to that of the Development network and are much lower than the Emergency network (the maximum inventory level is 13 times lower and the total costs are 2.4 times lower). Therefore, this model allows for both an effective and fast response for emergency operations, while also ensuring an efficient response and lower costs. This suggests that this network seems to provide appropriate results for both emergency and development operations, which is not the case for the two previous networks.

4.2.4 Detailed results

Figures 2 and 4 present detailed results for the total time to fill 85% and 100% of the demand, respectively, for each emergency operation and according to each network. The results are compared with the Emergency model with only emergency operations, referred to as 'Emergency' in the figures. Figures 3 and 5 present similar results, but for the development operations and compare the results with the Development model with only development operations, referred to as 'Development' in the figures. These results show that with respect to the total time to fill 85% and 100% of the demand, the Emergency and Continuum networks obtain similar results to the basic 'Emergency' model for all emergency operations, independently of the delivery point, implying that these two models reach rapid delivery for emergency operations. For most development operations, the Development and Continuum models have a similar behaviour to the basic 'Development' model. Therefore, the only model that behaves appropriately for both emergency and development operations for the total time to fill 85% and 100% of the demand is the Continuum model.

Figure 6 presents detailed results for the number of days out of stock for each model. In Table 6, we had noted that the number of days out of stock was the highest with the Continuum network. By further analysis, we can see that for delivery points 1, 3, 4, 5 and 7, the Continuum model has the lowest or second lowest number of days out of stock. Delivery point 2 has the most days out of stock (303), which can be explained by the fact that this delivery point has one of the largest demands. Note that the networks have not been designed to reduce the number of days out of stock.

Figure 7 presents detailed results for the maximum inventory level and shows that for all delivery points the Continuum network is always low, while often being the lowest inventory level or the second lowest inventory level. This is translated in lower costs (inventory costs) which are shown in Figure 8.

According to the conducted analysis and on the tested data, the Continuum network shows better results than the Emergency network for development operations (i.e., cost reduction) and shows better

results than the Development network for emergency operations (i.e., speed of delivery). It seems to be a good hybrid solution between these two extreme networks.

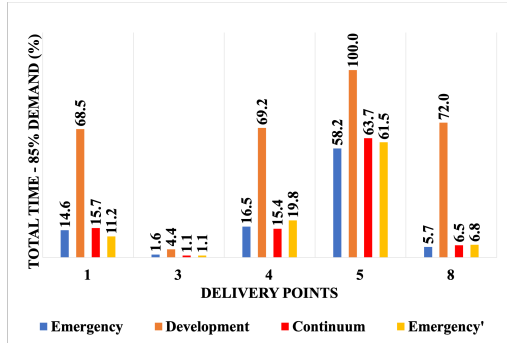


Figure 2: Total time to fill 85% of the demand for the emergency operations

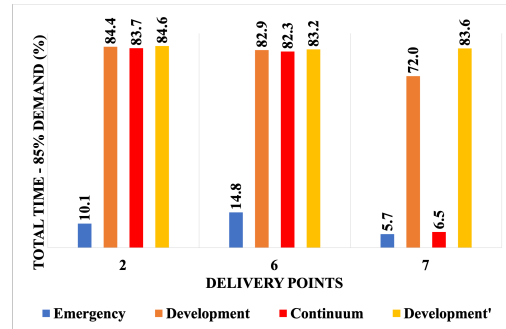


Figure 3: Total time to fill 85% of the demand for the development operations

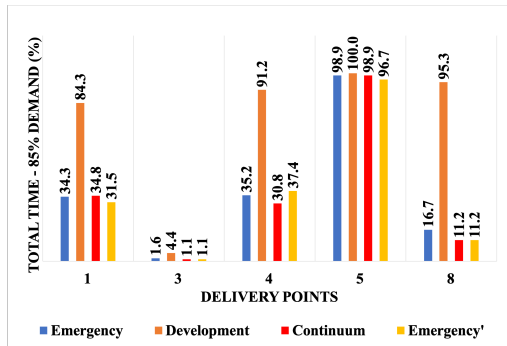


Figure 4: Total time to fill 100% of the demand for the emergency operations

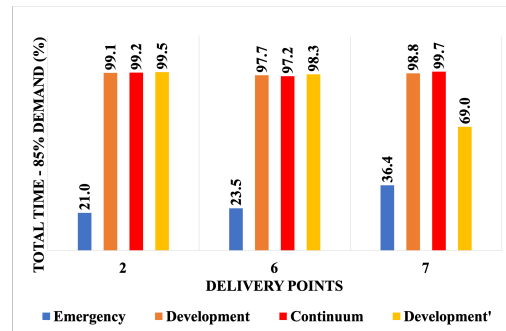


Figure 5: Total time to fill 100% of the demand for the development operations

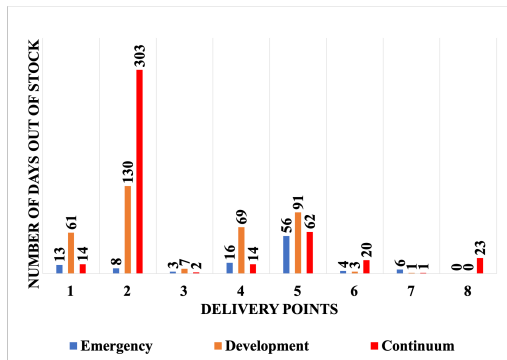


Figure 6: Number of days out of stock

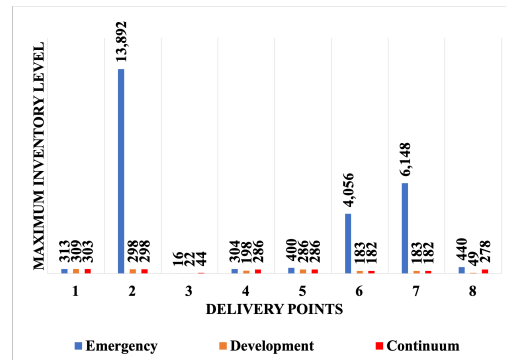


Figure 7: Maximum inventory level

5 Conclusions

In this study, we determine the characteristics of a sustainable humanitarian supply chain network structure using discrete event simulation and assess the performance of that network. Our preliminary simulation results provide insights on the strategic location of the RDC and the LDCs according to the delivery points. Moreover, fleet capacity, delivery frequencies as well as ideal inventory levels have been evaluated through various scenarios to highlight an ideal hybrid structure.

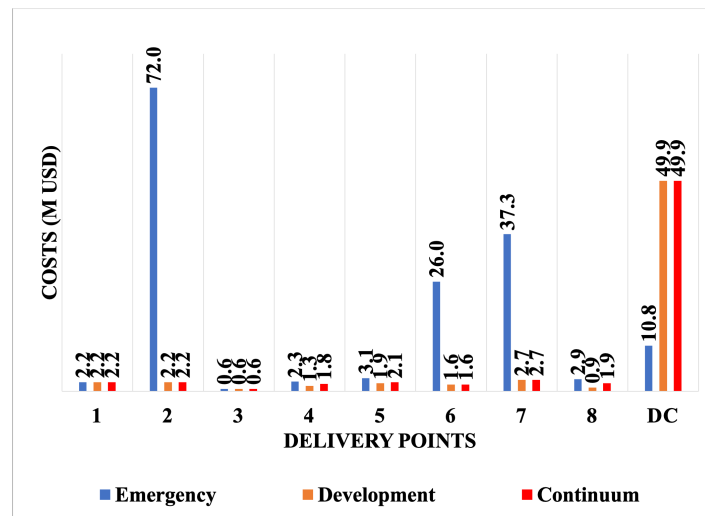


Figure 8: Total costs

The first contribution of this paper is to demonstrate via simulation modeling that a traditional emergency supply chain network structure reveals poor performances when applied to development operations and, similarly, a development supply chain network structure reveals poor performances when applied to emergency operations.

The second contribution is to suggest a hybrid structure that combines agile and lean principles. This structure ensures a smooth and effective transition from the immediate response phase to the reconstruction phase. The Continuum network outperforms the Emergency network with development operations, and the Development network with emergency operations. Moreover, it displays similar results to those provided by the Emergency network with only emergency operations and by the Development network with only development operations. Therefore, the Continuum network represents a good hybrid solution to ensure efficient and effective humanitarian supply chain operations management for different response phases.

This study opens avenue for future research work, such as extensively investigating larger number of scenarios, that will ensure a generic framework, providing hence optimal positioning of RDCs and LDCs on generic geographical areas.

References

- Altay, N., & Green, W. G. (2006). OR/MS research in disaster operations management. *European journal of operational research*, 175(1), 475–493.
- Anaya-Arenas, A. M., Renaud, J., & Ruiz, A. (2014). Relief distribution networks: a systematic review. *Annals of Operations Research*, 223(1), 53–79.
- Balcik, B., Bozkitir, C. D. C., & Kundakcioglu, O. E. (2016). A literature review on inventory management in humanitarian supply chains. *Surveys in Operations Research and Management Science*, 21(2), 101–116.
- Balcik, B., Silvestri, S., Rancourt, M. È., & Laporte, G. (2019). Collaborative prepositioning network design for regional disaster response. *Production and Operations Management*, 28(10), 2431–2455.
- Barahona, F., Ettl, M., Petrik, M., & Rimshnick, P. M. (2013). Agile Logistics simulation and optimization for managing disaster responses. In *Proceedings of the 2013 Winter Simulation Conference*, 3340–3351.
- Behl, A., & Dutta, P. (2019). Humanitarian supply chain management: a thematic literature review and future directions of research. *Annals of Operations Research*, 283(1), 1001–1044.
- Çelik, M. (2016). Network restoration and recovery in humanitarian operations: Framework, literature review, and research directions. *Surveys in Operations Research and Management Science*, 21(2), 47–61.

- Çelik, M., Ergun, Ö., Johnson, B., Keskinocak, P., Lorca, Á., Pekkün, P., & Swann, J. (2012). Humanitarian logistics. In *New directions in informatics, optimization, logistics, and production*, 18–49. INFORMS.
- Çelik, M., Ergun, Ö., Keskinocak, P., Soldner, M., & Swann, J. (2017). Chapter 36: Humanitarian Applications of Supply Chain Optimization. In *Advances and Trends in Optimization with Engineering Applications*, 479–491. Society for Industrial and Applied Mathematics.
- Christopher, M., Peck, H., & Towill, D. (2006). A taxonomy for selecting global supply chain strategies. *The International Journal of Logistics Management*, 17(2), 277–287.
- Cozzolino, A., Rossi, S., & Conforti, A. (2012). Agile and lean principles in the humanitarian supply chain. *Journal of Humanitarian Logistics and Supply Chain Management*.
- Demusz, K. (1998). From relief to development: negotiating the continuum on the Thai-Burmese border. *Journal of Refugee Studies*, 11(3), 231–244.
- Dubey, R., & Gunasekaran, A. (2016). The sustainable humanitarian supply chain design: agility, adaptability and alignment. *International Journal of Logistics Research and Applications*, 19(1), 62–82.
- Dufour, É., Laporte, G., Paquette, J., & Rancourt, M. È. (2018). Logistics service network design for humanitarian response in East Africa. *Omega*, 74, 1–14.
- Duran, S., Ergun, Ö., Keskinocak, P., & Swann, J. L. (2013). Humanitarian logistics: advanced purchasing and pre-positioning of relief items. In *Handbook of global logistics*, 447–462. Springer, New York, NY.
- Feng, K., Bizimana, E., & Agu, A. A. (2012). Optimization and simulation modeling of disaster relief supply chain: a literature review. MPRA Paper No. 58204, posted 02 Sep 2014.
- Golroudbary, S.R., Zahraee, S. M., Awan, U., And Kraslawski, A. (2019). Sustainable operations management in logistics using simulation and modeling : a framework for decision making in delivery management. *Procedia Manufacturing* 30, 627–634.
- Halldórsson, Á., & Kovács, G. (2010). The sustainable agenda and energy efficiency. *International Journal of Physical Distribution & Logistics Management*.
- Hooshangi, N., & Alesheikh, A. A. (2018). Developing an agent-based simulation system for post-earthquake operations in uncertainty conditions: a proposed method for collaboration among agents. *International Journal of Geo-Information*, 7, 27.
- Kara, B. Y., & Rancourt, M. È. (2019). Location Problems in Humanitarian Supply Chains. In *Location Science*, 611–629. Springer, Cham.
- Kovács, G., & Moshtari, M. (2019). A roadmap for higher research quality in humanitarian operations: A methodological perspective. *European Journal of Operational Research*, 276(2), 395–408.
- Kovács, G., & Spens, K. M. (2007). Humanitarian logistics in disaster relief operations. *International Journal of Physical Distribution & Logistics Management*.
- Kovács, G., & Spens, K. (2009). Identifying challenges in humanitarian logistics. *International Journal of Physical Distribution & Logistics Management*.
- Krejci, C. (2015). Hybrid simulation modeling for humanitarian relief chain coordination. *Journal of Humanitarian Logistics and Supply Chain Management*, 5(3), 325–347
- Lewin, R., Besiou, M., Lamarche, J. B., Cahill, S., & Guerrero-Garcia, S. (2018). Delivering in a moving world looking to our supply chains to meet the increasing scale, cost and complexity of humanitarian needs. *Journal of Humanitarian Logistics and Supply Chain Management*.
- Mei, S., Zarrabi, N., Lees, M., & Sloot, P.M.A (2015). Complex agent networks: an emerging approach for modeling complex systems. *Applied Soft Computing*, 37, 311–321, December.
- Mustapha, K., Mcheick, H., & Mellouli, S. (2013). Modeling and simulation agent-based of natural disaster complex system. *Procedia Computer Science*, 21, 148–155.
- Naim, M. M., & Gosling, J. (2011). On leanness, agility and leagile supply chains. *International Journal of Production Economics*, 131(1), 342–354.
- Naylor, J. B., Naim, M. M., & Berry, D. (1999). Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain. *International Journal of production economics*, 62(1–2), 107–118.

Oloruntoba, R., & Gray, R. (2006). Humanitarian aid: an agile supply chain. *Supply Chain Management: an international journal*.

Oloruntoba, R., & Kovács, G. (2015). A commentary on agility in humanitarian aid supply chains. *Supply Chain Management: An International Journal*.

Shafiq, M., & Soratana, K. (2019). Lean and Agile paradigms in humanitarian organizations. *Logistics and supply chain management. LogForum*, 15(1).

Stauffer, J.M., Pedraza-Martinez, A.J., Yan, L., & Van Wassenhove, L.N. (2018). Asset supply networks in humanitarian operations: A combined empirical simulation approach. *Journal of Operations Management* 63, 44-58.

Tako, A. A., & Robinson, S. (2012). The application of discrete event simulation and system dynamics in the logistics and supply chain context. *Decision Support Systems*, 52(4), 802-815.

Van Wassenhove, L. N. (2006). Humanitarian aid logistics: supply chain management in high gear. *Journal of the Operational research Society*, 57(5), 475-489.

Wang, Z., & Zhang, J. (2019). Agent-based evaluation of humanitarian relief goods supply capability. *International Journal of Disaster Risk reduction*, 36.