Proceedings of the 2020 Winter Simulation Conference
K.-H. Bae, B. Feng, S. Kim, S. Lazarova-Molnar, Z. Zheng, T. Roeder, and R. Thiesing, eds.

A SIMULATION MODEL FOR SHORT AND LONG TERM HUMANITARIAN SUPPLY CHAIN OPERATIONS MANAGEMENT

Marilène Cherkesly
Yasmina Maïzi

Département d'Analytique, Opérations et Technologies de l'Information
École des Sciences de la Gestion
Université du Québec à Montréal
Case postale 8888, succursale Centre-ville
Montréal, QC H3C 3P8, CANADA

ABSTRACT

Traditionally, the design of supply chains for humanitarian operations has been developed distinctly for the different disaster management phases, with little attention to the 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 that integrate the lean and agile principles to different extents. To determine the best characteristics of such a sustainable supply chain, we use discrete event simulation modeling. We validate and compare each network structure through several scenarios fed by data sets available from the United Nations World Food Programme for operations conducted in the Republic of Congo.

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 one. 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 Programme (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 cost reduction. Therefore, many authors have suggested to apply agile principles in the response phase and 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, lean principles focus on efficiency, including cost reduction, and agility principles focus on effectiveness, including flexibility and speed. Lean principles are usually more appropriate for products with long lead time and predictable demand, whereas 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 agile principles are more appropriate for the immediate response phase to reach effectiveness, while 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 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 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, see 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 are 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 decision support 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 for logistics and supply chains. 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 support 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.

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 the 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.

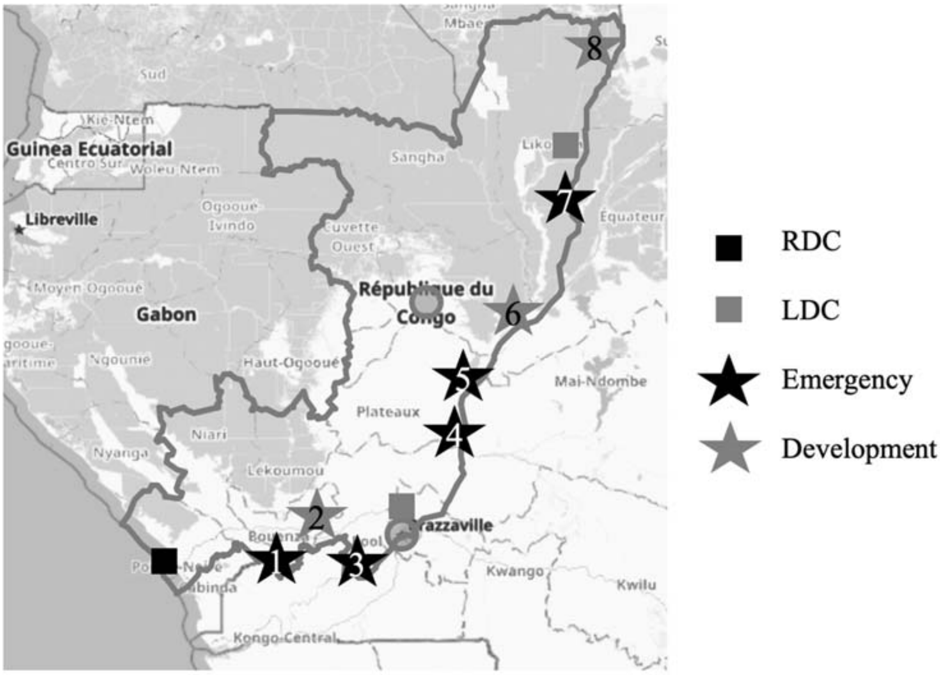
3 DESIGN OF HUMANITARIAN SUPPLY CHAIN NETWORKS

We have developed three networks: i) a network referred to as *Emergency*, designed for the response phase which focuses on effectiveness and agility, ii) a network referred to as *Developmen*t, designed for the reconstruction phase, which focuses on efficiency and leanness, and iii) a 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 (number and location of LDCs, transportation modes, and replenishment frequency). The latter 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 durations 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 (SO), which usually involve logistics. 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 PRRO, 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).



© OpenStreetMap contributors

Figure 1: Structure of the supply chain network for the Republic of Congo (République du Congo).

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 (choice of transportation mode, potential locations of RDC and LDCs, demand patterns) and distribution policies (replenishment frequency, inventory management policy). 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 Ebola outbreak (201126) and one for the supply corridors (200934). Each project is associated with exactly one delivery point in our network. Detailed information on each operation including its associated project number (from WFP), its type of operation (EMOP, DEV, SO, and PRRO), its duration, and the total food delivery (in mT) is reported in Table 1. This information is used in our simulation models.

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 enables 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.

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). The focus of this work is to study the supply chain starting from Dubai and ending at delivery points, with an emphasis on the supply chain from the RDC to the delivery points. Therefore, Dubai represents the source of the network and the delivery points are the sinks. The characteristics of the different proposed supply chain networks vary according to their final goal, i.e., 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	Road
Replenishment frequency from RDC to LDCs	Reorder point	Three days	Three days
Replenishment frequency from LDCs to delivery points	Reorder point	Every week	Reorder point or every week

In the 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 as its corresponding delivery point. In the Development and Continuum networks, LDCs are centralized and have been located according to the geography of the RoC and of the operations. Capacities of the RDC and LDCs are defined to ensure a full delivery of supplies to each delivery point during the operation's duration.

Different transportation modes are considered to supply the RDC in each network. 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 emphasis, sea transportation is used. In addition, for all the networks, road transportation (i.e., trucks) is used to supply LDCs from the RDC (hub-and-spoke delivery) because of its accessibility. We assume that the fleet is operated by a third party logistics provider similarly to transport on demand,and that they have a sufficient fleet size.

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, i.e., a replenishment from the RDC to a LDC is triggered as soon as the inventory at the LDC reaches a minimum threshold. This minimum threshold is defined as the maximum quantity of consumed food for all its assigned operations during the lead time (transportation time from the RDC to the LDC). In the Development and Continuum network, we ensure a more regular pattern to replenish the LDCs. That is, the LDCs are replenished every three days according to the maximum between the demand and the transportation capacity. Finally, the inventory management policy from the LDCs to the delivery points varies according to the network. In the Emergency network, the delivery points are supplied as needed based on a reorder point system (similarly to the supply of the RDC to the LDCs). In the Development network, all delivery points are supplied once a week. Finally, in the Continuum network, emergency operations are supplied according to a reorder point system, while development operations are replenished once a week.

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 from Rockwell Automation technologies inc., as it provides a suitable and effective representation of the supply chain (Feng et al. 2012; Tako et al. 2012). Considering the lack of real-life output, our models, their behaviors and the results were validated based on expert judgement. Because the modeled system in this present study consists of considering both emergency and development operations, we ran our model as a terminating system.

We have implemented one simulation model per network. To build these models and compare their performance, the following Key Performance Indicators (KPIs) are used:

- **Total time – 85 % demand** : the percentage of the total time period needed to deliver 85 % of the total demand.
- **Total time – 100 % demand**: the percentage of the total time period needed to deliver 100 % of the total demand.
- **Days out of stock**: the number of days an operation is out of stock.
- **Maximum inventory level**: the maximum inventory level (in mT) reached in the network.

The first three KPIs measure effectiveness in terms of response time (and reactivity), while the maximum inventory level measures efficiency and the use of resources. For emergency operations, the network should send most resources in the least amount of time and should have a low number of days out of stock, while for the development operations, the network should have a lower inventory level.

We ran multiple scenarios to verify the setting of parameters. In each scenario, different parameters were modified: i) the fleet capacity at the RDC and the LDCs, ii) the inventory levels at the RDC and the LDCs, and iii) the delivery frequency at LDCs and delivery points. These scenarios allowed us to determine the best structure for each simulation model. Our results show that the Emergency network integrates agile principles (fast response) for immediate response operations (see Section 4.2.1), while the Development network integrates lean principles (better use of resources) for reconstruction operations (see Section 4.2.2). Finally, to design a hybrid network structure, we conducted additional scenarios in two progressive steps. First, we ran the Emergency and the Development models with all the operations according to their respective characteristics. Second, starting from the Development model, we gradually added new LDCs. When a new LDC was added, the fleet capacity at the RDCs and LDCs as well as the delivery frequencies at LDCs and delivery points were also modified. This gradual modification of the network characteristics through several scenarios allowed us to design the final hybrid network structure and determine the most appropriate parameters, i.e., the Continuum model.

4.1 Simulation Results

We first conducted our analysis for the Emergency network with only emergency operations and the Development network with only development operations. This was a benchmark for our complete models. Our final set of experiments contains all three proposed networks (Emergency, Development, and Continuum) on all operations and we compare their performance.

4.1.1 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. Table 3 summarizes the simulation results. Let us recall that for emergency operations, 85 % of the total demand is revealed on the first day of the operation while the remainder is uniformly distributed during the residual duration. For delivery points 1, 3, 4, and 8, our results show that the network is effective in terms of response time and number of days out of stock. In fact, 85 % of the demand can be delivered within less than 20 % of the total duration operations, while the total demand (100 % demand) is delivered within less than 40 % of total duration of operations. Moreover, these delivery points are never out of stock for more than 25 days. Therefore, the network seems to be reactive and effective in terms of response time for delivery points 1, 3, 4, and 8. On the other hand, the network has a different performance with delivery point 5 and does not seem as effective. In fact, more than 60 % of the mission time is needed to deliver 85 % of the demand and 95 % of the mission time is needed to deliver the total demand. Considering the characteristics of delivery point 5 (high demand and one of the furthest delivery points from the RDC), these results remain consistent and show that the Emergency network is agile and effective for emergency operations.

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 (mT)	440	12	440	440	440	354.4

4.1.2 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. Table 4 summarizes the simulation results. We can see 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 that 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.

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	2.0
Maximum inventory level (mT)	147	237	190	191.3

4.1.3 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, i.e., emergency operations (delivery points 1, 3, 4, 5, and 8) and development operations (delivery points 2, 6, and 7). For these results, an additional KPI is considered. That is, *total costs* including inventory and transportations costs are used to compare the three networks with all the operations. 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 for 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 (mT)	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 achieved 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 4.1.4. 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.

4.1.4 Detailed Results

Table 7 presents detailed results for the total time to deliver 85 % and 100 % of the demand, respectively, for each emergency operation and according to each network. The results are compared to the model with only emergency operations, referred to as Emergency' in the table. Table 8 presents similar results, but for the development operations and compares the results with the model that has only development operations, referred to as Development' in the table. 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 deliver 85 % and 100 % of the demand is the Continuum model.

Table 7: Total time to deliver 85 % and 100 % of the demand for the emergency operations.

	Total time – 85 % demand (%)					**Total time – 100 % demand (%)**				
Delivery points	**1**	**3**	**4**	**5**	**8**	**1**	**3**	**4**	**5**	**8**
Emergency	14.6	1.6	16.4	58.2	5.7	34.3	1.6	35.2	98.9	16.7
Development	68.5	4.4	69.2	100.0	72.0	84.3	4.4	91.2	100.0	95.3
Continuum	15.7	1.1	15.4	63.7	6.5	34.8	1.1	30.8	98.9	11.2
Emergency'	11.2	1.1	19.8	61.5	6.8	31.5	1.1	37.4	96.7	11.2

Table 8: Total time to deliver 85 % and 100 % of the demand for the development operations.

	Total time – 85 % demand (%)			**Total time – 100 % demand (%)**		
Delivery points	**2**	**6**	**7**	**2**	**6**	**7**
Emergency	10.1	14.8	5.7	21.0	23.5	36.4
Development	84.4	82.9	72.0	99.1	97.7	98.8
Continuum	83.7	82.3	6.5	99.2	97.2	99.7
Development'	84.6	83.2	83.6	99.5	98.3	69.0

Table 9 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.

Table 9: Number of days out of stock.

Delivery points	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Emergency	13	8	3	16	56	4	6	0
Development	61	130	7	69	91	3	1	0
Continuum	14	303	2	14	62	20	1	23

Table 10 presents detailed results for the maximum inventory level and shows that for all delivery points the Continuum network is always low, while often providing the lowest inventory level or the second lowest one. This is translated in lower costs (inventory costs), which are presented in Table 11. According to the conducted analysis, 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 in particular when the supply chain needs to be used for both emergency and development operations.

Table 10: Maximum inventory level (mT).

Delivery points	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Emergency	313	13,892	16	304	400	4,056	6,148	440
Development	309	298	22	198	286	183	183	49
Continuum	303	298	44	286	286	182	182	278

Table 11: Total costs (M USD).

Delivery points	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**DC**
Emergency	2.2	72.0	0.6	2.3	3.1	26.0	37.3	2.9	10.8
Development	2.2	2.2	0.6	1.3	1.9	1.6	2.7	0.9	49.9
Continuum	2.2	2.2	0.6	1.8	2.1	1.6	2.7	1.9	49.9

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. The first contribution of this paper is to demonstrate via simulation modeling that a traditional emergency supply chain network structure reveals poor performance when applied to development operations and, similarly, a development supply chain network structure reveals poor performance when applied to emergency operations. The second contribution is to suggest a hybrid structure that combines the best features of each of the two previous networks. 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 operation, 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. While the results show that the Emergency network is the most appropriate with only emergency operations and the Development network is the most appropriate with only development operations, the Continuum network represents a good hybrid solution to ensure efficient and effective humanitarian supply chain operations management for different response phases, i.e., with both emergency and development operations. This study opens avenues for future research work, such as extensively investigating a larger number of scenarios, that will ensure a generic framework, providing hence optimal positioning of RDCs and LDCs on generic geographical areas.

ACKNOWLEDGMENTS

The authors thank the Canadian Natural Sciences and Engineering Research Council (NSERC) under Discovery Grant 2017-06106 for its financial support.

REFERENCES

Altay, N., and W. G. Green. 2006. “OR/MS Research in Disaster Operations Management”. *European Journal of Operational Research* 175(1):475–493.

Anaya-Arenas, A. M., J. Renaud, and A. Ruiz. 2014. “Relief Distribution Networks: A Systematic Review”. *Annals of Operations Research* 223(1):53–79.

Balcik, B., C. D. C. Bozkir, and O. E. Kundakcioglu. 2016. “A Literature Review on Inventory Management in Humanitarian Supply Chains”. *Surveys in Operations Research and Management Science* 21(2):101–116.

Balcik, B., S. Silvestri, M.-È. Rancourt, and G. Laporte. 2019. “Collaborative Prepositioning Network Design for Regional Disaster Response”. *Production and Operations Management* 28(10):2431–2455.

Barahona, F., M. Ettl, M. Petrik, and P. M. Rimshnick. 2013. “Agile Logistics Simulation and Optimization for Managing Disaster Responses”. In *Proceedings of the 2013 Winter Simulation Conference*, edited by R. Pasupathy, S.-H. Kim, A. Tolk, R. Hill, and M. E. Kuhl, 3340–3351. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Behl, A., and P. Dutta. 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., Ö. Ergun, B. Johnson, P. Keskinocak, Á. Lorca, P. Pekgün, and J. Swann. 2012. “Humanitarian Logistics”. In *New Directions in Informatics, Optimization, Logistics, and Production*, edited by J. Cole Smith, 18–49. Maryland, United-States: Institute for Operations Research and the Management Sciences (INFORMS).

Çelik, M., Ö. Ergun, P. Keskinocak, M. Soldner, and J. Swann. 2017. “Humanitarian Applications of Supply Chain Optimization”. In *Advances and Trends in Optimization with Engineering Applications*, edited by T. Terlaky, M. F. Anjos, and S. Ahmed, 479–491. Philadelphia, Pennsylvania: Society for Industrial and Applied Mathematics.

Christopher, M., H. Peck, and D. Towill. 2006. “A Taxonomy for Selecting Global Supply Chain Strategies”. *The International Journal of Logistics Management* 17(2):277–287.

Cozzolino, A., S. Rossi, and A. Conforti. 2012. “Agile and Lean Principles in the Humanitarian Supply Chain”. *Journal of Humanitarian Logistics and Supply Chain Management* 2(1):16–33.

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., and A. Gunasekaran. 2016. “The Sustainable Humanitarian Supply Chain Design: Agility, Adaptability and Alignment”. *International Journal of Logistics Research and Applications* 19(1):62–82.

Dufour, É., G. Laporte, J. Paquette, and M.-È. Rancourt. 2018. “Logistics Service Network Design for Humanitarian Response in East Africa”. *Omega* 74, 1–14.

Duran, S., Ö. Ergun, P. Keskinocak, and J. Swann. 2013. “Humanitarian Logistics: Advanced Purchasing and Pre-Positioning of Relief Items”. In *Handbook of Global Logistics*, edited by J. H. Bookbinder, 447–462. New York, NY: Springer.

Feng, K., E. Bizimana, and A. A. Agu. 2012. “Optimization and Simulation Modeling of Disaster Relief Supply Chain: A Literature Review”. Technical Report, Munich Personal RePEc Archive Paper No. 58204, South Carolina State University.

Golroudbary, S. R., S. M. Zahraee, U. Awan, and A. Kraslawski. 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., and G. Kovács. 2010. “The Sustainable Agenda and Energy Efficiency”. *International Journal of Physical Distribution & Logistics Management* 40(1/2):5–13.

Hooshangi, N., and A. A. Alesheikh. 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):1–22.

Kara, B. Y., and M.-È. Rancourt. 2019. “Location Problems in Humanitarian Supply Chains”. In *Location Science*, edited by G. Laporte, S. Nickel and F. Saldanha da Gama, 611–629. Cham, Switzerland: Springer Nature Switzerland.

Kovács, G., and M. Moshtari. 2019. “A Roadmap for Higher Research Quality in Humanitarian Operations: A Methodological Perspective”. *European Journal of Operational Research* 276(2):395–408.

Kovács, G., and K. Spens. 2007. “Humanitarian Logistics in Disaster Relief Operations”. *International Journal of Physical Distribution & Logistics Management* 37(2):99–114.

Kovács, G., and K. Spens. 2009. “Identifying Challenges in Humanitarian Logistics”. *International Journal of Physical Distribution & Logistics Management* 39(6):506–528.

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., M. Besiou, J. B. Lamarche, S. Cahill, and S. Guerrero-Garcia. 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* 8(4):518–532.

Mei, S., N. Zarrabi, M. Lees, and P. M. A. Sloot. 2015. “Complex Agent Networks: An Emerging Approach for Modeling Complex Systems”. *Applied Soft Computing* 37, 311–321

Mustapha, K., H. Mcheick, and S. Mellouli. 2013. “Modeling and Simulation Agent-Based of Natural Disaster Complex System”. *Procedia Computer Science* 21, 148–155.

Naim, M. M., and J. Gosling. 2011. “On Leanness, Agility and Leagile Supply Chains”. *International Journal of Production Economics* 131(1):342–354.

Naylor, J. B., M. M. Naim, and D. Berry. 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., and R. Gray. 2006. "Humanitarian Aid: An Agile Supply Chain". *Supply Chain Management: An International Journal* 11(2):115–120.

Oloruntoba, R., and G. Kovács. 2015. "A Commentary on Agility in Humanitarian Aid Supply Chains". *Supply Chain Management: An International Journal* 20(6):708–716.

Shafiq, M., and K. Soratana. 2019. "Lean and Agile Paradigms in Humanitarian Organizations". *Logistics and Supply Chain Management. LogForum*, 15(1):139–153.

Stauffer, J. M., A. J. Pedraza-Martinez, L. Yan, and L. N. Van Wassenhove. 2018. "Asset Supply Networks in Humanitarian Operations: A Combined Empirical Simulation Approach". *Journal of Operations Management* 63:44–58.

Tako, A. A., and S. Robinson. 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., and J. Zhang. 2019. "Agent-Based Evaluation of Humanitarian Relief Goods Supply Capability". *International Journal of Disaster Risk Reduction* 36, 1–11.

AUTHOR BIOGRAPHIES

MARILÈNE CHERKESLY is associate professor of operations management at the School of Business of the Université du Québec à Montréal (Canada). She is also a member of the Group for Research in Decision Analysis (GERAD). She holds a Ph.D. in Mathematics, Applied Mathematics from Polytechnique Montréal Technological University, Canada. Her research interests are related to the development of operational research and data analytics techniques to optimize complex real systems in transportation, logistics, remote logistics, and humanitarian logistics. Her current projects address the design of logistics networks in remote regions and the integration of complex real-life constraints (e.g., handling, coverage, location) in transportation. Her email address is cherkesly.marilene@uqam.ca. More information can be found on https://professeurs.uqam.ca/professeur/cherkesly.marilene/.

YASMINA MAÏZI is assistant professor of operations management at the School of Business of the Université du Québec à Montréal (Canada). She holds a M.Sc. and Ph.D. degrees in industrial engineering from Conservatoire National des Arts et Métiers (France). She has an extensive professional experience in simulation within the industry. She is associate member of the Internet of Things (IoT) lab and CRI2GS lab at ESG-UQAM. Her research area focuses on modelling complex systems using simulation: A specific interest on the integration of Internet of Things (IoT) for health care operation management, the integration of digital twins in services, and finally a recent interest on digital patients. Her email address is maizi.yasmina@uqam.ca.