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Agent-based model for material convergence in humanitarian logistics

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Modelo basado en agentes para la convergencia de materiales en logística humanitaria

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ABSTRACT: Humanitarian logistics has taken a big boost as a study area because of the increased frequency of natural disasters worldwide. Within this area, there is a particular issue that has received little attention in the literature, regarding the aid received in the aftermath of a disaster. This problem may occur as an oversupply of goods, the arrival of unneeded products, or the supply of expired goods. The lack of coordination between the actors involved in relief operations can be conceived as one of the leading causes of this problem, which is called material convergence. This paper focuses on the material convergence problem, to humanitarian logistics introducing a computational theoretical approach to this problem using agent-based modeling where flows, actors and their relationships are characterized by measuring the impact on the logistics performance of the response system. Followed by the simulation, an experimental analysis of the results is performed with three different system configurations. Finally, a scenario is proposed that facilitates coordination between actors where logistics performance indicators show better results regarding response speed and coverage.

RESUMEN: La logística humanitaria ha tomado un gran impulso como área de estudio, esto a causa del aumento en la frecuencia de desastres naturales a nivel global. Dentro de esta área existe un problema en particular poco tratado en la literatura, el cual se encuentra relacionado con las ayudas recibidas luego del acontecimiento de un desastre. Este problema puede presentarse como un exceso en la oferta de suministros, la llegada de productos no necesitados o el abasto de bienes vencidos. La falta de coordinación entre los actores involucrados en las operaciones de ayuda puede concebirse como una de las causas de la problemática, denominada convergencia de materiales. Este artículo se centra en la problemática de la convergencia de materiales en logística humanitaria. Se presenta una aproximación teórica computacional del problema utilizando modelado basado en agentes, donde se caracterizan los flujos, los actores y sus interrelaciones, para medir el impacto en el desempeño logístico. Seguido de la simulación se realiza un análisis experimental de los resultados con tres diferentes configuraciones del sistema. Por último, se establece qué factores facilitan la resolución al problema descrito donde los indicadores de desempeño logístico presentan mejores resultados en términos de velocidad de respuesta y cobertura.

1. Introduction

Humanitarian logistics has become an emerging research topic which has attracted the attention of scientists for multiple reasons since the events occurred in the Indic Ocean tsunami in 2004 [1]. In recent years, there has been an increase in the number, magnitude and impact of natural disasters around the world. Between 1999 and 2012, disasters affected 4.4 thousand millions of people, causing death to 1.3 million and damages for two trillion dollars [2]. Additionally, the United Nations Office for Risk Reduction has predicted that the amount of both natural and man-made disasters will continue to increase both in quantity and impact. Logistics management is essential for reducing the impacts since near the 80% of efforts in relief operations are related to logistics [3]. A way to improve the coverage in these events is through the right management of logistics processes. Particularly, some of these efforts are made in the supply of the humanitarian aid, which represent a significant challenge [3]. When a request for humanitarian aid is issued by the country where a disaster has occurred, donors send lots of supplies, which may

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result in material convergence although some of the aid received may be useless or unsolicited [4].

The arrival of useless products for the disaster attention makes difficult the humanitarian aid organization efforts, due to many factors: the amounts received do not meet the demand, there exists the supply of unsolicited items or not effective aid, items in poor conditions that cannot be handled to the affected people, requiring additional staff for goods management. In brief, the received supplies volume, being unsolicited, may exceed the response capacity of the system [4].

Coordination is an alternative to tackle the material convergence problem, taking into account the complex and dynamic character of the situation, the inherent uncertainty, and variability. Coordination between actors is considered one of the main factors influencing logistics performance in disaster relief situations [3, 5, 6].

Higher levels of coordination between the supply chain actors mean better performance levels. However, factors like the nature of decision making in an environment where there is no standardization, limited transparency in resource management, high fragmentation in the chain and a strong decentralization, constitute a challenging scenario for the coordination of the humanitarian supply chain [7].

Among the various challenges that make difficult to effectively implement coordination in the humanitarian supply chain, the following are highlighted [4, 8]:

- Lack of a centralized addressing, generating a waste of resources, shortage of others and duplication of efforts.
- The presence of many actors operating at the same time in the disaster area causes competition and obstruction for basic resources. These actors include governments, businesses, nongovernmental organizations (NGOs), military and relief agencies.
- Lack of planning and preparation, even for foreseeable disasters.
- Lack of robust information systems, leading to inability to share information between different actors.

Humanitarian organizations have great interest defining what kind of coordination mechanisms are adequate, to implement the best strategy. Humanitarian logistics covers different operations in different time slots, involving multiple actors, each with their own interests, capacities, and expertise. The following section explains some theories and approaches used in the research development, material convergence, as well as the structure of the humanitarian supply chain. Followed by this section, the methodology and both computational and conceptual models developed in the research are presented. An analysis of the results based on experimental designs supported by the conclusions of the study is then performed.

2. Theories and approaches

2.1. Material convergence

A formal definition of materials convergence was given by [9], who describe it as the movement towards the area impacted by the disaster. They identify various types of convergences, highlighting convergence of personnel, information, and materials. The material convergence includes both supplies and equipment, sent by each of the entities that respond to a disaster [10].

The main problem with material convergence is related to the amount of low or non-priority humanitarian aid that arrives at the disaster area, which seizes valuable resources for this effort. Additionally, the problem generated by the materials convergence has a bigger impact given the limited availability of resources and poor infrastructure and potentially affected by the impact of the disaster. According to [11], the percentage of non-priority received aid can range between 50 and 70%.

The material convergence has positive and negative impacts, related with the priority thereof. Supplies such as water and blood can make a difference, while others such as clothing, hinder the flow of critical supplies in some cases, taking resources that could be used for more important tasks [12]. The main idea with the material convergence is based on the fact that the disaster response system has a limited capacity that is affected by the supply of goods of little or no profit for the victims, who need resources to be managed properly.

2.2. Donations nature

Some of the reasons for the inappropriate material convergence is the information donors have, who do not know the disasters specific needs. Another situation occurs with the donations made by large companies that see an opportunity to position their brand or reduce inventories and at the same time seeking for taxes reduction opportunities.

According to [12], there are relevant factors conducive to the material convergence. The amount of donations has a direct relationship with factors as household income per capita, population density, the existence of organizations that group donations, among others. People who are closer to disaster area, are more willing to make donations in kind, than those farther away who tend to make financial donations. The main contribution of the developed models by these authors, is that they allow an approximation of the expected in-kind donations depending on where the disaster occurs.

Another factor that moderates the amount of donations received by a disaster is the existing information. In [10], several cases of disasters are explained where information modifies the destination and the type of donations.

2.3. Logistic impacts of the material convergence

The material convergence has implications for the logistic performance in the disaster attention, mainly by the resource allocation that could be assigned to tasks that are more important. These impacts are classified on entry points and destiny points [11].

Impacts on entry points

Entry points are defined as places where material flows enter to the disaster area and, where the first logistics implications of the convergence occur. The congestion caused by the arrival of large amounts of supplies, is one of the main problems in the entry points. At these points, a first control of the humanitarian aid should be done and make the decision if the passage to the disaster area is allowed; however, this process is rarely made.

The amount of aid that arrives after a disaster can represent a capacity overflow problem of the facilities, having to appeal to nearby facilities causing more problems and increasing the logistics distribution costs. Another situation referred in [11] is derived from the lack of proper documentation, poor packages and mix of priority and non-priority goods, among other causes that require a significant resource allocation.

Impacts on destiny points

One of the main features observed due to the lack of shipments' documentation in destination points is the inappropriate reception of aid by a humanitarian organization. On the other hand, vehicles that transport the non-priority donation freight cause congestion and take up space that could be used by vehicles with priority goods [11].

Having little or none control in the supplies entering the impacted zone requires allocating important resources to noncritical tasks. High priority goods may also cause the material convergence when they arrive in huge amounts. This phenomenon occurs because of the dynamic demand of the supplies. A high priority good can become later to a low priority good, causing a problem in the donations management on the destination points of the humanitarian aid.

2.4. Humanitarian logistics

A first step in the characterization of the humanitarian logistics is differentiating it from the commercial logistics. Table 1 presents the main differences [4].

One of the main differences between the commercial and humanitarian logistics is the origin of the supplies flow. In the commercial chain, the goods flows are closer to the actors. Likewise, the origin of the flows in commercial logistics is known and begins at the extraction stage of raw materials while the humanitarian chain begins with the donation of finished goods [13], which are sent from different origins and by various actors [4].

Other difference observed that fosters the problem derived from the materials convergence is related to the demand. Commercial logistics is designed to satisfy the customer demand although it has an uncertainty that can be compared with the humanitarian logistics demand.

Humanitarian supply chain structure

The literature on humanitarian supply chain has identified different models to determine the configuration of actors, from donors to recipients or the affected people by the disaster. Generally, the literature reports that humanitarian

Table 1 Differences between comercial and humanitarian logistics

Characteristics	Commercial logistics	Regular humanitarian logistics	Post-disaster logistics
Objective	Costs minimization	Social costs minimization	Social costs minimization
Flow origin	Self-contained	Self-contained	Impacted by the materials convergence
Demand knowledge	Known with relative certainty	Known with relative certainty	Dynamic unknown, lack of information
Decision making structure	Structured interaction controlled by some decision makers	Structured interaction controlled by some decision makers	No structured interactions, multiple actors
Frequency of logistic activities	Repetitive, relatively stable flows	Repetitive, relatively stable flows	Sporadic, big impact
Support systems	Stable and functional	Stable and functional	Impacted, inconstant

supply chain is composed of three echelons. Donors compose the first echelon, which can be tens of thousands of suppliers sending goods to the disaster area. A second echelon would be found in the different points of entry; these activities centers are mainly located in ports and airports. The last is made of destiny points where supplies are delivered to victims. As with donors, these delivery points can become tens or even hundreds of thousands of people [4].

In [14], a specific configuration of the humanitarian supply chain is described, where a new echelon is added, which consists of local distribution centers that are intermediate points between the entry points and the affected people by the disaster. Likewise, [15] consider the prepositioning of warehouses in the supply chain structure. Figure 1 shows the structure of the humanitarian supply chain, it can be distinguished the different approaches presented.

Along the humanitarian supply chain, several actors are involved, which are located in the different levels. Actors can be classified as donors, humanitarian staff, and affected people.

In humanitarian case, donors act as suppliers; the humanitarian staff is the agent in charge of supply, storage and distribution logistic operations. Affected people compose the last echelon generating the demand. A different actor can execute roles as donors and humanitarian staff: government agencies, military organizations, relief agencies, non-governmental organizations as well as private companies.

In the work presented by [11], the disaster area is described as a series of concentric rings as follows: the central point is defined as the disaster site, the next ring the contiguous area, which followed the next area and the remote area. The flow of supplies travels from outside in these rings, while information travels from the inside out. Figure 2 shows the description above in detail.

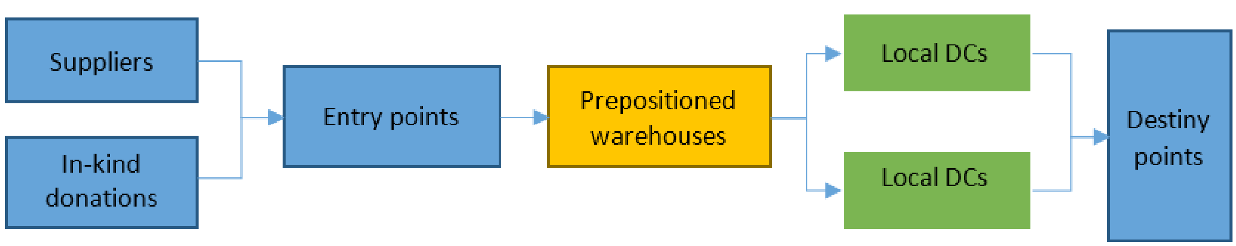


Figure 1 Humanitarian supply chain structure

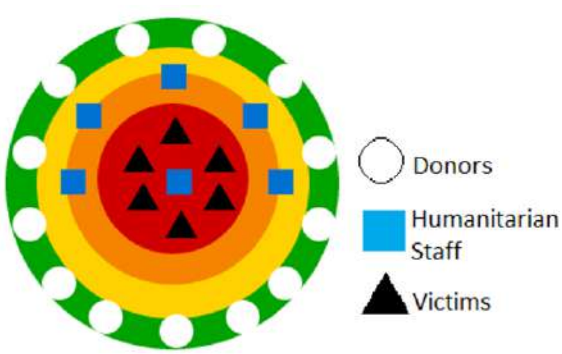


Figure 2 Spatial location of the humanitarian supply chain actors

3. Methods and materials

This section presents both conceptual and computational models, based on the agents' paradigm for assessing the impacts of coordination and the material convergence problem.

3.1. Conceptual model

The starting point for the development of the proposed conceptual model are the roles identified above. Donors are players who send both financial and in-kind donations. These agents may be individual donors, non-governmental organizations as well as private companies. Humanitarian workers are the actors responsible for the consolidation of humanitarian aid and the distribution of these supplies in the impacted area. Affected people are the generators of demand and determine the value of donations received.

The proposed model takes into account the first two actors identified above, and demand is considered uncertain. Finally, a consumption rate of the humanitarian aid, where the priority or usefulness of donations received, is dynamic over time.

3.2. Conceptual model agents

An agent can be anything that perceives what occurs around through sensors and acts over this environment using actuators [16]. The actions of the agents receive the name of agent rationality, which is influenced by the performance indicators that assess the agent or by the previous knowledge that the actor has over the environment. A rational agent selects the action that maximizes the performance measures for any sequence of perceptions [16]. Table 2 presents the rationality of the agents' model deployed.

Donor agent

The main objective of this agent is to provide demand supplies to the disaster area. Since the donor agent is not located at the disaster site, there is a partial perception. In order to update the agent state, two kinds of knowledge are required. First, we need to know how the system evolves without the agent involvement, and then how its actions affect the system.

According to the above discussions, the following states are defined for the donor agent: 1) Donor agent is initially in state "No donate". 2) When its sensors are activated, the donor agent goes to "Donate" state. 3) "Serve" state, in which the donations are delivered to the impacted area. Figure 3, presents the state diagram for this agent.

The actions performed by this agent are triggered by the disaster occurrence. However, in the proposed model, the disaster strike is not simulated. The lack of supplies triggers the agent's sensors. The different behaviors are triggered by the donor or donations arrival. This agent has two possible states. On the one hand, the agent may have the capacity to attend the disaster ("Served" state). Conversely, the agent may have a shortage or deficit, so it is considered to be in a "No served" state. Figure 4 shows the general humanitarian staff agent performance.

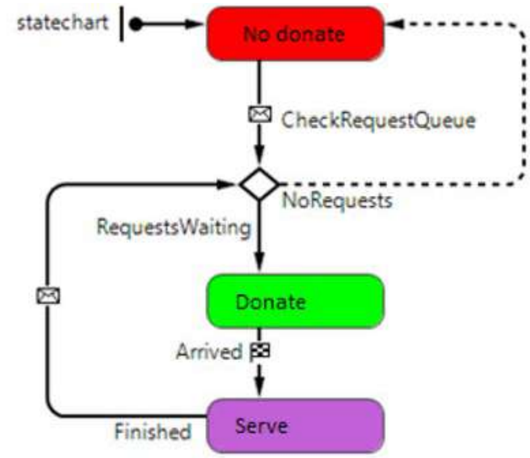


Figure 3 States diagram of the donor agent

Table 2 Conceptual model agents' rationality

Agent	Performance measures	Environment	Actuators	Sensors
Donor	Amount of donations send	Humanitarian aid flow, demand	Make donations	Disaster information received
Humanitarian staff	Demand meet, delivered donations	Disaster site, victims, demand	Receive donations, deliver donations	Amount of victims, supplies shortage

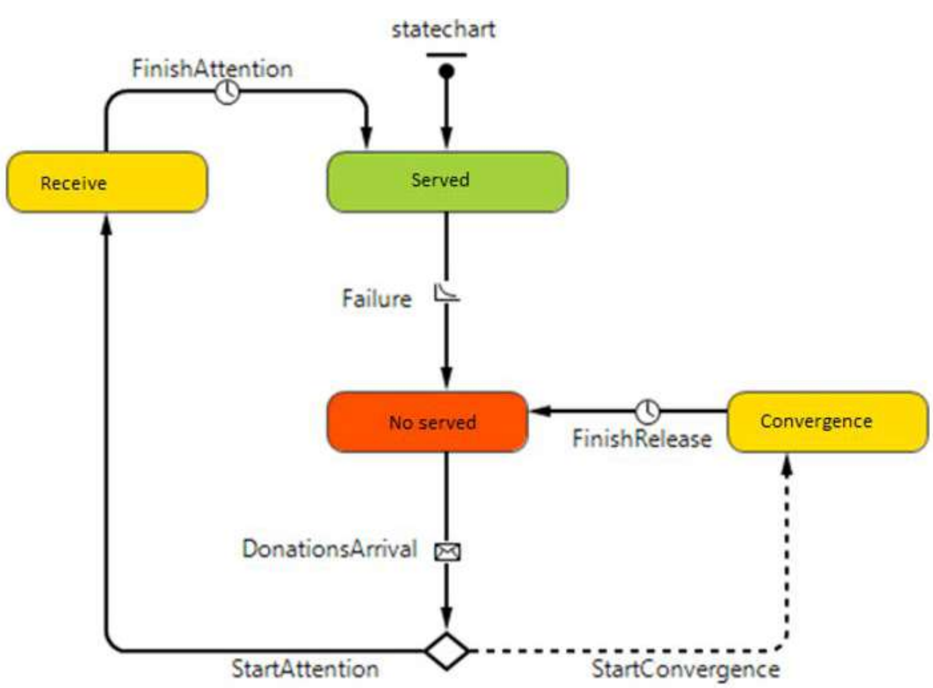


Figure 4 States diagram of humanitarian staff agent

Table 3 Transitions and states of the conceptual model

Agent	States	Trigger by	Transition
Donor	No donate	Initial state	Donate
	Donate	Message state	Attend
	Serve	Agent arrival	Donate / No donate
Humanitarian staff	Served	Initial state	No served
	No served	Occurrence rate	Receive / Convergence
	Receive	Message send	Served
	Convergence	Message send	No Served

Humanitarian staff agent

The transition from the "Served" state to the "No served" state occurs because the system failure or because the absence of supplies. The transition to the "Receive" and "Convergences" states are triggered by sending a message to the donor agent, which answers this message with the humanitarian aid. Table 3 summarizes the states and its transitions for both modeled agents.

3.3. Computational model

The computational model was implemented in AnyLogic® simulation software that allows the integration of simulation paradigms. This process was carried out in four phases: Definition of states and transitions, definition of variables and parameters, definition of performance measures, and software implementation.

Definition of variables and parameters

The model building focuses on the actions of the humanitarian agent with the respective variables and parameters, these can be seen in Table 4 below.

Additionally, Table 5 shows the calculated variables by the system.

Definition of performance measures

Table 6 shows the defined performance measures. These metrics must be build according to the modeled environment.

Table 4 Conceptual model variables and parameters

Type	Name	Description	Measure
Variables	Priority probability	Defines the probability that a donation is priority kind	P(x=priority)
	Stock out rate	Defines the rate of system failure	V.A exp~(λ)
	Donor agent	Link between both agents	-
Parameters	Attention time	Time that takes to deliver a donation to affected people.	Constant
	Release time	Time that takes to the agent to dispose the no priority aid	Constant

Table 5 Conceptual model calculated variables

Name	Code	Description
Convergence time	TCOV	Amount of time that a warehouse remains in convergence state.
Attention time	TATT	Amount of time that a warehouse remains in served state.
Priority donations	QDRP	Amount of priority donations received in period t.
Non-priority donations	QDNP	Amount of non-priority donations received in the period t.
Warehouses in convergence	WHCV	Amount of warehouses in convergence state in period t.

Table 6 Conceptual model performance measures

Performance measure	Description	Measure
QAC	Average amount of warehouses in convergence state.	$\sum_{t=o}^{T} \frac{WHCV}{N}$ (1)
QDP	Amount of priority donations.	$\sum_{t=0}^{T} QDPR$ (2)
QNP	Amount of no priority donations	$\sum_{t=0}^{T} QDNP$ (3)
TEA	Time in served state.	$\sum_{t=0}^{T} TATT$ (4)
TEC	Time in convergence state.	$\sum_{t=0}^{T} TCOV$ (5)

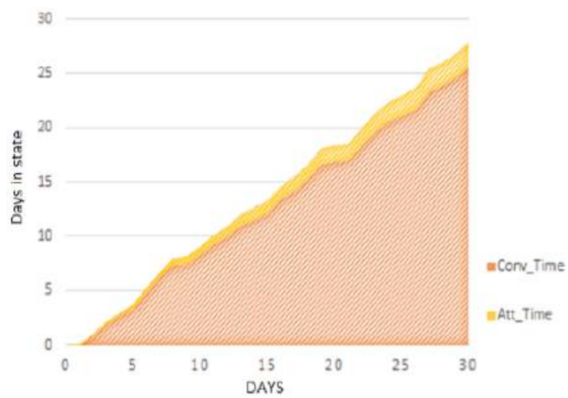
4. Results

This section presents the computational results of the proposed model, and a sensitivity analysis on three variables (probability of priority donations, number of warehouses and probability of stock out that influence the performance of the system. Table 7 shows the values used for the first experiment.

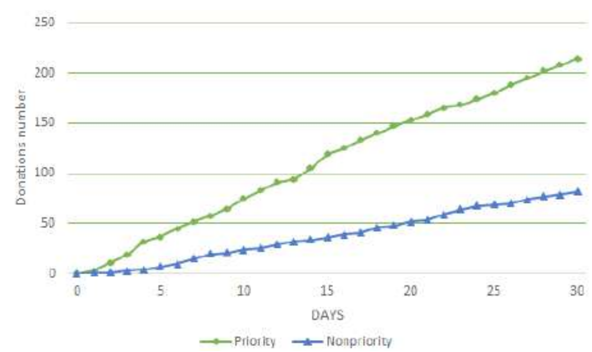
The probability that a donation is a priority is variable over time. The equation of the constructed variable, "Probability of priority", presented in Table 7, set the limits of this probability between [0.4 to 0.6]. Additionally, service times and convergence (TATT and TCOV) were modeled as random variables following a triangular distribution (0.5*x*, *x*, 1.5*x*), where *x* represents attention or releasing time. On the other hand, we define ten stores for the scenario running and a replication length of 30 days.

In Figure 5(a), the darker strip represents the intended time for the provision of non-priority donations, while the lighter stripe represents the spent time to process the priority donations. The spent time to process the priority aid corresponds to 8.7% of the time spent on non-priority aid. Likewise, Figure 5(b) shows how most of the time corresponds to the convergence time of the stores.

As for the type of the received donations, 67.5% was priority kind. The system takes about five days to dispose of nonpriority donations, while for disposing of priority donations takes about 12 minutes. Figure 5(b) shows the amounts of priority and nonpriority donations. Figure 6 shows the number of warehouses in "convergence" state and "in attention" state during the simulation. On average, 1.5 warehouses are in "convergence" state while 2.4 warehouses are "in attention" state. We can conclude that even when the occurrence of the convergence state is less frequent, resources that should be employed to solve this state are bigger than those used in the aftermath of the disaster.



(a)



(b)

Figure 5 Experiment simulations results I

Table 7 variables and parameters

Type	Name	Measure
Variable	Priority probability	$1-(1-e^{-0.004t}+0.4e^{-0.004t})$
	Stock out rate	VA~exp(0.2) days
Parameter	Attention time	5 hours
	Release time	1 day

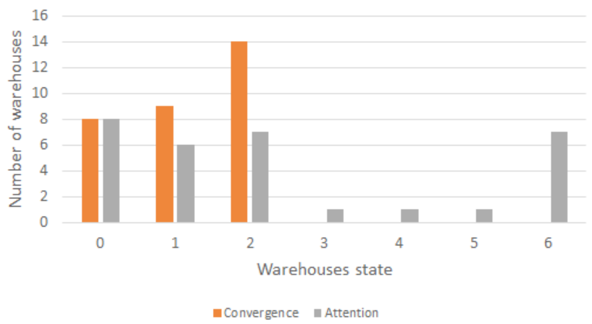


Figure 6 Experiment simulations results II

4.1. Results analysis

An experimental design was conducted to analyze the effect on the convergence state of several factors such as the probability of the priority donations, the number of warehouses and the stock-out rate. The method used for the experiments is a randomized block design. Table 8 shows the treatments utilized in the experiments.

Blocking factor: Probability of priority donations

Figure 7 shows the results of the adjusted linear model using as blocking factor the probability of priority donations. In Figure 7(a), we observe an effect of the number of warehouses on the convergence time since the means in the boxplots are dispersed. In Figure 7(b), we find that there is no a significant difference between the treatments means related to the stock-out rate. On the other hand, the interaction graph in Figure 7(c) shows a limited interaction between factors. Besides, we made the Tukey non-additivity test in order to confirm the interaction assumption. The p-value for this test was 0.005118, so the non-additivity hypothesis can be discarded. The normality and homoscedasticity assumptions were revised using the Shapiro test with correspondent p-values of 0.8465 and 0.6329.

Blocking factor: Number of warehouses

In this case, there is a significant interaction between the probability of priority donations and the probability of stock-out, as seen in Figure 8(c). Additionally, according to the Figure 8(a), it seems to be a significant effect of the probability of priority donations. The non-additivity test presents a p-value of 0.6316, thus confirming the interactivity between factors. On the other hand, the p-values for the homoscedasticity and normality tests are 0.422 and 0.1529. However, the two-way ANOVA shows that the effects on the response variable are not significant.

Blocking factor: Probability of stock-out

Figure 9 shows the graphical results of the adjusted model. Both the number of warehouses as the probability of priority donations have effect in the model. The Shapiro test has a p-value of 0.0711 while the Spearman test has a corresponding p-value of 0.2294. These values explain that the assumptions of homoscedasticity and normality are valid. However, we can see in Figure 9(c) that there is no significant interaction between factors.

Tables 9 and 10 summarizes the results of the three experiments.

The greater the number of available warehouses, the longer the spent time of the system in the convergence state. This phenomenon occurs because the non-priority donations are uniformly distributed between the warehouses. A centralized warehouse allows decreasing the amount of non-priority donations that arrive downstream the humanitarian supply chain. However, centralization requires information exchange and coordination among actors to help to reduce the impact of uncertainty.

In summary, the number of warehouses and the probability of priority donations explain the spent time of the convergence state. Nevertheless, there is no enough statistical evidence to confirm that the stock-out rate has a significant effect in the time of the convergence state.

5. Conclusions and future work

This paper presented a computational theoretical approach using an agent-based simulation model to analyze and solve the material convergence problem in the humanitarian logistics context. We analyzed several factors, such as the probability of priority donations, the number of warehouses and the stock-out probability, in order to study their effect on the performance of the humanitarian relief chain in the aftermath of a disaster.

Two different types of key agents (donors and humanitarian staff) were modeled to achieve a greater understanding of the impact of material convergence on the performance of the humanitarian relief chain. Coordination mechanisms such as inventory prepositioning and centralization were also examined to assess the possible benefits and drawbacks derived from the pre-disaster planning stage.

The agent-based approach presented here can provide a foundation for future extensions. The impact of material convergence on last mile distribution of supplies could be included in the agent-based formulation to get a more holistic view of the system. Likewise, new types of agents with more specific states could be added to make the model more realistic. Additional coordination mechanisms such as collaborative procurement via contracts could be incorporated into the agent-based formulation to get insight into the possible effects on the humanitarian system performance.

Table 8 Treatments of the experimental design

Treatment	Prob.(Priority)	# of warehouses	Stock-out rate
1	0.4	3	0.1
2	0.4	5	0.2
3	0.4	10	0.3
4	0.4	12	0.5
5	0.5	3	0.1
6	0.5	5	0.2
7	0.5	10	0.3
8	0.5	12	0.5
9	0.6	3	0.1
10	0.6	5	0.2
11	0.6	10	0.3
12	0.6	12	0.5
13	0.7	3	0.1
14	0.7	5	0.2
15	0.7	10	0.3
16	0.7	12	0.5

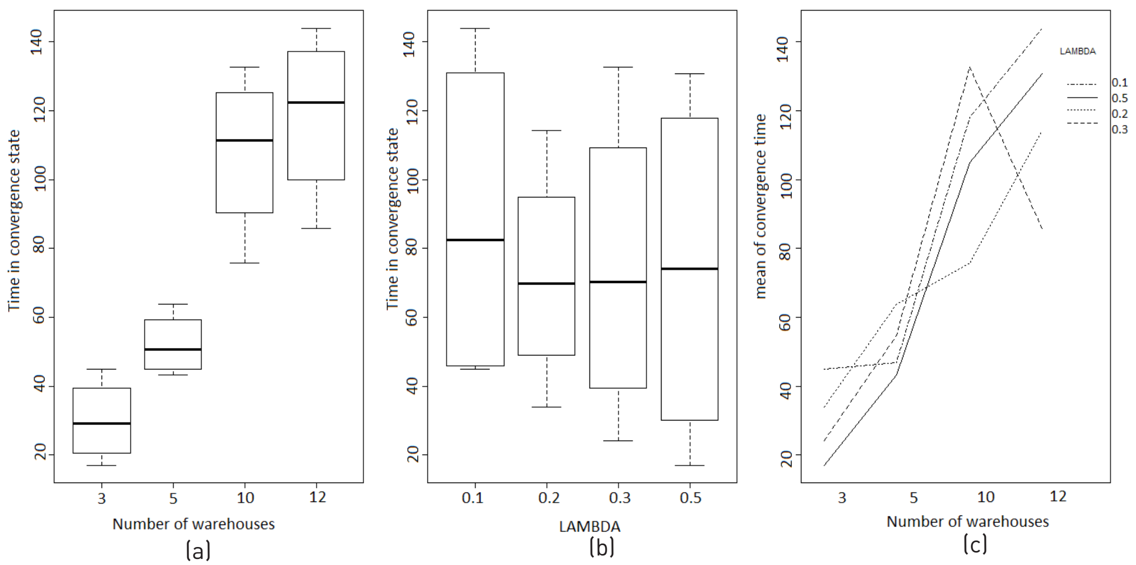


Figure 7 Graphical analysis of the blocking factor: probability of priority donations

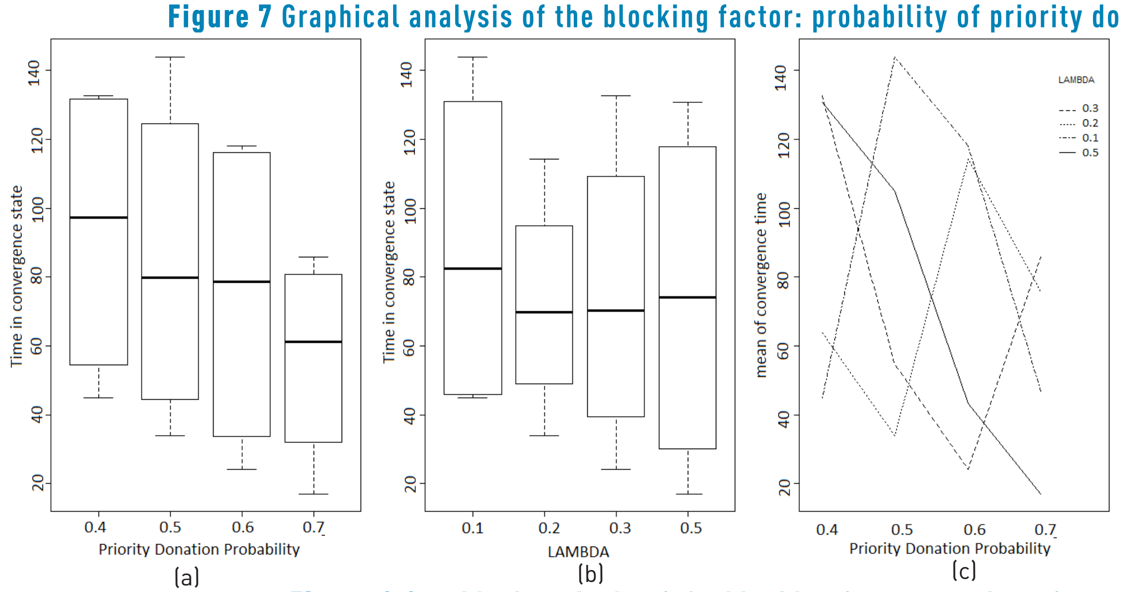


Figure 8 Graphical analysis of the blocking factor: number of warehouses

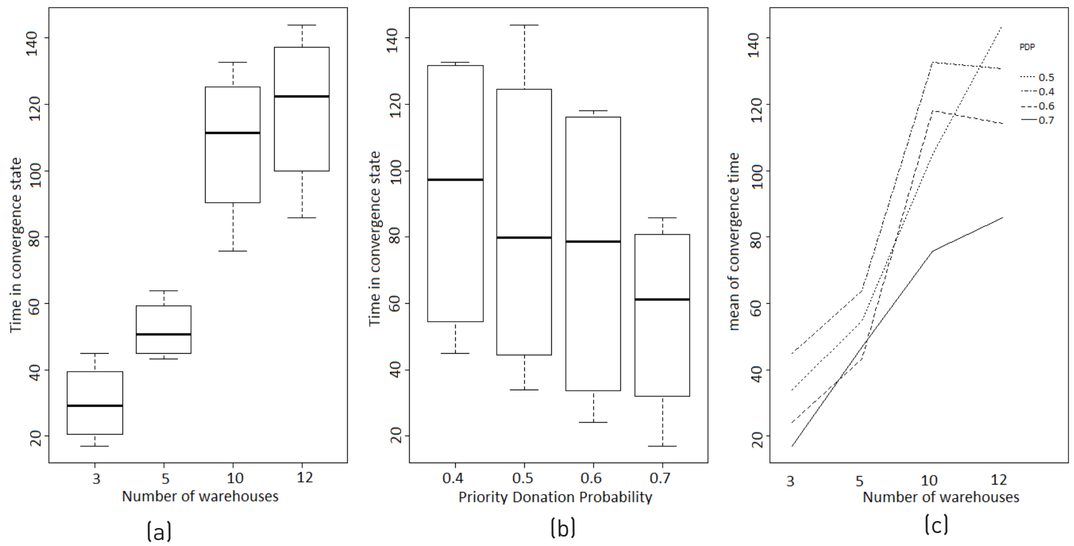


Figure 9 Graphical analysis of the blocking factor: probability of stock-out

Table 9 Summary of statistical tests

Blocking factor	Tukey test	Shapiro test	Spearman test
Priority donations	0.005118	0.8465	0.6329
Number of warehouses	0.6316	0.422	0.1529
Stock Out Probability	8.16e-05	0.0711	0.2294

Table 10 ANOVA p-values

Blocking factor	Number of warehouses	Priority donations	Probability of stock-out
Number of warehouses	-	0.2575	0.9464
Priority donations	0.0003762	-	0.6517617
Probability of stock out	7.082e-06	0.01222	-

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