Coordination mechanisms applied to logistical systems for local disaster preparedness: a Latin American case

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Abstract

Purpose – The study aims to present an agent-based simulation model (ABM) for exploring interorganizational coordination scenarios in local disaster preparedness. This approach includes local actors and logistical processes as agents to compare various strategic coordination mechanisms.

Design/methodology/approach – The ABM model, developed in the Latin American context, specifically focuses on a case study of Colombia. Three coordination mechanisms (centralized, decentralized and cluster-type) have been evaluated using three performance indicators: effectiveness, efficiency and flexibility.

Findings – Simulation results show that the decentralized scenario outperforms in terms of efficiency and flexibility. On the contrary, the centralized and cluster-type scenarios demonstrate higher effectiveness, achieving a greater percentage of requirements coverage during the disaster preparedness stage. The ABM approach effectively evaluates strategical coordination mechanisms based on the analyzed performance indicators.

Research limitations/implications – This study has limitations due to the application of results to a single real case. In addition, the focus of the study is primarily on a specific type of disaster, specifically hydrometeorological events such as flash floods, torrential rains and landslides. Moreover, the scope of decision-making is restricted to key actors involved in local-level disaster management within a municipality.

Originality/value – The proposed ABM model has the potential as a decision-making tool for policies and local coordination schemes for future disasters. The simulation tool could also explore diverse geographical scenarios and disaster types, demonstrating its versatility and broader applicability for further insights and recommendations.

Keywords Agent-based modeling, Complex systems, Humanitarian logistics, Disaster preparedness, Interorganizational coordination

Paper type Research paper

1. Introduction

The record of disasters that have occurred in the world has grown dramatically since the 1990s (Negi, 2022). During the last 50 years, extreme events and climate change phenomena have generated negative impacts on the environment, the living conditions and the economy of the most vulnerable populations, causing destruction, loss of materials and lives, and displacement, mainly in low- and middle-income countries (Shrivastav and Bag, 2023; Yan, 2023). The United Nations Office for Disaster Risk Reduction (UNDRR) argues that knowledge and reduction risk in a world plagued by uncertainty is key to achieving sustainable development (UNDRR, 2022). However, there is concern about inequality between nations, the increase in poverty in the world, and the impact of human action on the warming of the atmosphere and oceans; which multiplies the risk on ecosystems on a global scale, with unprecedented climate change records in the last thousands of years (IPCC, 2021; UNDRR, 2022).

In response to the aforementioned, research in the field of disaster risk reduction has achieved global interest

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(Kusumastuti *et al.*, 2022). At the same time, humanitarian logistics (HL) has grown as a field of knowledge that set the processes of supply, storage, distribution and coordination of people, goods, services and necessary equipment to serve communities that are victims of disasters (Talebian Sharif and Salari, 2015). Given the increased frequency and intensity of disasters around the world, humanitarian logistics chains must be prepared to act effectively (Negi, 2022). It could be reflected in positive effects for communities, as well as their living conditions and the reduction of human suffering (Oksuz and Satoglu, 2023). Research findings highlight many challenges in HL, such as: limited coordination, redundancy, resource scarcity, complex and chaotic operational environment, and lack of preparedness (John *et al.*, 2019; Negi, 2022; Shokr *et al.*, 2022), which must be addressed from multiple perspectives to deal with the needs of the most vulnerable populations (Maghsoudi and Moshtari, 2021). As supply chains are dynamic and complex systems, the difficulty in managing operations in the humanitarian theater is critical, due to the higher levels of resource scarcity and uncertainties; this complexity, caused by the growing trends of the extreme natural phenomena, will be increase even more in the future (Timperio *et al.*, 2022; Stumpf *et al.*, 2023).

Given the threats of natural disasters on the safety of human life, it is critical that humanitarian agencies carry out adequate preparation processes and reserve emergency supplies in advance to respond effectively (Negi, 2022; Zhang and Kong, 2023). The preparedness phase, framed in the disaster management cycle, is of high importance, as it involves resources, studies and strategic decisions oriented toward effective anticipation of the materialization of disasters (Anvari *et al.*, 2023; Liu *et al.*, 2023). Relevant logistics operations during preparedness include warehouse and shelter location, purchasing and inventory prepositioning; design of the physical network for transportation; and planning and administrative capacity building for the response (Anvari *et al.*, 2023). As preparedness consists of long- and medium-term planning, it is accepted that the success of the response phase is highly dependent on appropriate preparation, by minimizing operational redundancies and waste of resources (John *et al.*, 2019; Corbett *et al.*, 2022; Shokr *et al.*, 2022). Although disaster preparedness remains low, especially among governments and local actors in disaster-prone areas, local knowledge and relationships are still recognized as vital to humanitarian success (Corbett *et al.*, 2022; Oksuz and Satoglu, 2023).

Several authors such as Besiou *et al.* (2021) and Jahre and Jensen (2021) propose the term localization as the active involvement of local agencies so that they lead, support and develop their own management of HL preparedness. Thus, the contribution of local community networks in the success of humanitarian action is highlighted (Corbett *et al.*, 2022). Nevertheless, although local efforts are recognized to improve efficiency in disaster response and the efficient use of scarce resources, several authors point out the need to develop more research in the fields of disaster preparedness and localization in HL field (Besiou *et al.*, 2021; Oksuz and Satoglu, 2023). The incorporation, appropriation and strengthening of local actors implies a systematic change in the management of disaster logistics, aimed at operational efficiency and effectiveness, and the strengthening of long-term relationships, despite the cultural and organizational barriers that generate challenges in coordination within the humanitarian sector (Corbett *et al.*, 2022; Negi, 2022).

With the need to increase operational performance in disaster preparedness and response, humanitarian organizations have propended *ex ante* disaster coordination, through long-term agreements, aligning their strategies, standardizing processes and intersectoral trust (John *et al.*, 2019; Shao *et al.*, 2023). Some coordination strategies found in the humanitarian context are summarized in centralization, decentralization, information sharing, strategic stocks and cluster mechanism (Jahre and Jensen, 2021; Ruesch *et al.*, 2022). Thus, it has been recognized that the way of the coordination is one of the priorities and a crucial factor in disaster management (John *et al.*, 2019; Shalash *et al.*, 2022; Zain *et al.*, 2023). It is also admitted that research focused on coordination in the field of supply chains has concentrated more in the commercial sector than in the humanitarian field (John *et al.*, 2019). Furthermore, most studies are addressed to the coordination during the response phase, which shows a lack of research interest aimed at preparedness coordination (Jahre and Jensen, 2021; Corbett *et al.*, 2022; Dhingra, 2022; Anjomshoae *et al.*, 2023).

The highly complex operational environment of the humanitarian theater, characterized by the lack of resources and high uncertainty during preparation, limit the possibility of effective coordination, since it is necessary to involve all key sectors in this phase (John *et al.*, 2019). Furthermore, depending on the type of event, different operational schemes are required for safe preparation (Bayram and Yaman, 2024). Collaborative efforts are necessary to manage these highly complex environments, even as more *ex ante* disaster planning studies with static modeling approaches have become widespread (Liu *et al.*, 2023). For studies of problems associated with complex systems, it is assumed that simulation is a relevant methodology (Hooshangi and Alesheikh, 2018). In this sense, humanitarian supply chains are dynamic and complex systems where there is strong uncertainty (Stumpf *et al.*, 2023). Thus, the existing body of literature highlights that humanitarian logistics problems can be supported using three simulation paradigms: discrete-event simulation (DES), agent-based modeling (ABM) and system dynamics (SD) (Timperio *et al.*, 2022). A promising framework for analyzing complex relationships between the agents involved in a complex system is ABM (Lemoine *et al.*, 2016). This paradigm is relevant, as well as adaptable, in the study of singular actors, which have autonomy and independence, that are involved in coordination problems for disaster management (Altay and Pal, 2014; Krejci, 2015). An advantage offered by the ABM paradigm is the bottom-up analysis approach, where macro-level inference of systems is promoted, based on micro-level behavior rules, in both time and space; ABM is well adjusted to the understanding of social processes that has enhanced its application in areas of social, economic and political sciences (El-Sayed *et al.*, 2012; Krejci, 2015). Therefore, the ABM simulation paradigm is considered a relevant scheme for studying complex systems, and useful for studying the local disaster preparedness system, by incorporating actions and interactions between agents and their effects on time and global performance. This can lead to unforeseen or counterintuitive results at a systemic level.

Agent-based models have already been proposed in the specialized HL literature. Recently, ABM have been used in search and rescue operations (Hashemipour *et al.*, 2018; Hooshangi and Alesheikh, 2018; Bui *et al.*, 2020); in transportation, fleet management and last mile distribution problems (Das and Hanaoka, 2014; Bae *et al.*, 2018; Wang and Zhang, 2019); to study the effect of information sharing and crowd flows on the distribution of humanitarian aid in post disaster scenario (Liao *et al.*, 2023); to address the issue of care for refugees based on the well-being quantification (Boshuijzen-van Burken *et al.*, 2020); the location of temporary relief sites (Kadosh *et al.*, 2023); to study the evacuation decision-making process supported by a multidimensional sustainability approach (Sopha *et al.*, 2021); to evaluate the impact of different coordination scenarios on inventories in distribution centers in postdisaster environments (Lebcir and Roy, 2023); and to analyze the roles played by a cluster leader in the coordination of humanitarian agents (Ruesch *et al.*, 2022).

Despite the academic and investigative interest to address issues involved in the humanitarian and disaster sectors, to the authors knowledge, publications focused on to understand the role of strategic coordination mechanisms applied to the preparedness phase, considering the problem of interorganizational integration regarding key local actors, have been limited. Even though it is recognized that existing studies on coordination have predominantly focused on relief operations during the response, few have focused on the *ex ante* phases of disasters (Jahre and Jensen, 2021; Anjomshoae *et al.*, 2023). Therefore, the purpose of this research is focused on designing and implementing an ABM simulation model to analyze the effect of coordination mechanisms applied in the disaster preparedness phase in a specific geographical context, delimited by the actions of local humanitarian organizations, and through the evaluation of performance indicators of efficiency and effectiveness. The research motivation is supported by authors such as Stumpf *et al.* (2023) who affirm the lack of empirical studies that address the systemic view of humanitarian supply chains, and especially from preparedness, toward decision-making supported on fact-based evidence; while Jahre and Jensen (2021) argue that even though scientific advances and new technologies are of high interest today, a significant contribution to real cases of disaster management continues to be focused on the development of coordination mechanisms rather than on specific tools. In this sense, it is also the intention of this work to discuss considerations related to the possibility of replicating the simulation model and its methodological proposal in other geographical contexts.

To fulfill the research purpose, the design and implementation of an ABM have been developed on a real case of Colombia, in South America. According to the National Disaster Risk Management Unit of Colombia (UNGRD), this country has 12% of its territory located in areas of high susceptibility to flooding and the population at flood risk represents 28% of the national population; in addition, 18% of the population is located in areas of high threat from landslides; thus, in Colombia, phenomena of hydrometeorological origin are high priority events (UNGRD, 2016). In particular, the city of Manizales, in the central zone of Colombia, is characterized by urban development located in hillside areas, added to insufficient development in rainwater conduction, a climate of high rainfall and seismicity, which exacerbate the potential for flash flood and landslide events (Orozco-Álzate and Valencia-Ríos, 2021). The decision on the type of hydrometeorological events was taken in line with Yan (2023) who argue that more research should be carried out on hydrological and meteorological issues, given their climatic impact manifested in the territories. In addition, the Global Assessment Report on Disaster Risk Reduction 2022 (UNDRR, 2022) highlights that the climate emergency points to a new reality, as well as understanding and reducing risk in a world of uncertainty is fundamental to achieving sustainable development in the regions. Importantly, the United Nations Development Program (UNDP) informs that, for the second half of the current century, in the region where Manizales is located, and because of climate change, there will be an increase in precipitation between 10% and 30%, which will further increase the risks of flooding and landslides there (UNDP, 2015).

The structure of this article is as follows: Section 2 describes the developed methodological approach for the conceptual and computational design of the ABM, including the description of the practical case. Section 3 shows the results of the proposed simulation scenarios. Section 4 contains the discussion of the results, presents the final remarks and suggests lines of future work.

2. Methodological development

2.1 Study context

In response to the call to promote the incorporation and representation of local actors in coordination efforts in the HL, added to the need for greater research from the academic sector to promote the efficient use of scarce resources during disaster preparedness (Corbett *et al.*, 2022; Oksuz and Satoglu, 2023), a real case was defined to obtain relevant information and data. The focus of the work is the local disaster preparedness system of Manizales, in Colombia. As the city is located on the Andes mountains, there exists a complex geomorphological environment (Orozco-Álzate and Valencia-Ríos, 2021). The city is located in an area of tropical mountain forest, with records of up to 280 days of rain per year (with more than 2000 mm of annual rainfall on average), and has fragile soils due to rainfall; these climatic conditions, added to the mountainous topography, generate intense erosion processes, with risks of landslides and floods due to the strong storms that occur in the territory (Hardoy and Velásquez Barrero, 2014). Moreover, due to its geographical location, Manizales faces significant seismic and volcanic risks, which consequently result in high vulnerability to landslides and floods as evidenced by recent emergency situations (UNGRD, 2016).

The seasonal behavior of rainfall in the city has a bimodal dynamic (two intense periods of rain per year, in the months of March, April, May, September, October and November), where it exceeds 200 mm of rainfall in the months of greatest intensity. This condition produces a high erosive potential in the territory, which leads to negative repercussions on the economic and agricultural activities in the area (Echeverri

Tafur and Obando Moncayo, 2010). In addition, hydrometeorological risks are exacerbated due to human activity. Socioeconomic conditions in Colombia lead economically oppressed communities to illegally occupy high-risk areas, whether on hillsides or river basins, which generates greater vulnerability (Hardoy and Velásquez Barrero, 2014; UNGRD, 2018). As such, the city presents a complex and diverse set of risks, making it a compelling case study for comprehensive disaster risk management.

In Manizales, key strategies recognized as milestones in Colombia have been developed (Cardona, 2019):

- The first earthquake-resistant design and construction standard in Colombia was developed there.
- Relocation strategies have been applied to communities and neighborhoods at non-mitigatable risk areas.
- The city has a network of hydrometeorological stations, to monitor threats and warn the population and authorities in case of emergency.
- A volcanological observatory continuously monitors the volcanoes and regional seismic activity.

However, the city is not infallible nor is it shielded from severe events, such as those that occurred in 2003, 2008, 2011 and 2017, which have induced academic, business, public and social reflection regarding climate change and risk management, since this situation is heavily linked to the Latin American reality, considering whether effective disaster risk management is not viable, or is simply a lost cause (Cardona, 2019).

2.2 Data collection

Aligned with what is suggested by Yan (2023), who maintains that more research should be connected to climate threats in lower income countries and based on the most relevant disaster records experienced in recent years, the data approach and information taken from local actors in the chosen case of Manizales was oriented, as main concern, to natural events caused by hydrometeorological phenomena. Thus, the process of approaching the local actors in the city was based on the collection of information from two main fronts, as described below.

Firstly, the key actors related to disaster preparedness processes have been identified (in particular, organizations involved in a municipality level), based on several authors reviewed (Cozzolino, 2012; Kabra *et al.*, 2015; Fontainha *et al.*, 2017). Likewise, an analogous review was carried out regarding the logistical processes that are involved in the local preparedness phase (Nikbakhsh and Zanjirani Farahani, 2011; Connelly *et al.*, 2016; Jahre *et al.*, 2016).

From the above, a qualitative instrument was designed to identify the resources and capabilities of each local actor, as well as the logistical processes and their respective requirements that must be fulfilled in the frame of the preparedness phase. This consideration was aligned to the need of real data to feed the agent-based model. A strategy of structured interviews focused on the main local humanitarian organizations in Manizales was developed. An initial version of the instrument was tested as a pilot to obtain convenience, clarity, and effectiveness in its final application. The pilot was carried out with two of the local actors: the office of Risk Management Unit (local government) and local Red Cross. The interviews were conducted in the main offices of each local organization. Eight key local actors in the city participated in the field work. The final questionary and a summary of the general features of the interviews conducted are shown in Appendix 1.

2.3 Agent-based simulation model design

The simulation approach is widely acknowledged as an appropriate methodology for studying the inherent difficulties in complex systems; particularly, the ABM enables flexibility in decision making processes in complex and dynamic environments (Das and Hanaoka, 2014; Bae *et al.*, 2018; Sopha *et al.*, 2021). ABM is an appropriate alternative to describe complex behavior of systems with multiple agents, individually seen, that generate a global result at a system-level (Krejci, 2015; Bae *et al.*, 2018), making it a flexible approach to address the complexity from individual behavior, the learning capacity, and possibility of interaction of the agents modeled (Altay and Pal, 2014). Furthermore, according to the specialized literature, ABM has been considered as a pertinent way to address several HL issues (Klumpp *et al.*, 2015; Hooshangi and Alesheikh, 2018). With this in mind, an ABM was designed to assess the overall performance of the system of inter-organizational coordination of the key local actors within the disaster preparedness phase. The methodological approach applied in this work is similar to that proposed by Lebcir and Roy (2023), who started from field work based on qualitative tools, to continue with the design and computational implementation of ABM to evaluate the global performance of the simulated system. In this paper, the framework PARTE, proposed by Hammond (2015), is used to describe the conceptual design of the model applied to the study case based on Manizales, Colombia. PARTE describes properties (P), actions (A), rules (R), time (T) and environment (E) defined for the set of modeled agents of the system.

2.3.1 Properties (P).

Two types of agents for the ABM were considered: local actors and logistical processes. The actors are seen from an organizational scope since the interest is to analyze the relationships among them and the effects of coordination on the performance of the preparedness system. Eight local actors were identified from the case: local government agency, civil defense, Red Cross, two firefighter units and three local relief units. They are considered independent and autonomous from each other. Actors also have their own resources (among which are: personnel, information, communication equipment, vehicles and facilities). These agents have three states: idle, busy, and busy without available resources.

The conception of capacity (as a means and requirement for the actions of the actors) has been defined in two ways:

1 operational capability (or roles, functions) as a means of representing the specific responsibilities assigned to the actors regarding the local preparedness processes; and
2 the capability to act, given in terms of the available resources, which the actors consider as a condition in their intention to contribute for the execution of the preparedness processes.

Here, the union of the two perspectives of capability (both the functional assignment and the availability of resources for action) is achieved together with the actions of the actors.

Local actors have the possibility to share resources during the execution of logistical processes. It is assumed that the actor resources are reusable over time, and the states of the modeled agents (both actors and processes) are variables over time. The sequence of decisions of the agents is represented in Figure 1.

Thirteen preparedness processes were identified: develop emergency plans, define emergency routes, establish communications networks, develop early warning systems, acquire emergency vehicles, acquire communication equipment, develop collaborative agreements, carry out emergency drills, carry out education to response staff, preposition of inventories, locate emergency warehouses, locate distribution centers and locate emergency shelters. Preparedness processes require different resources (which are defined in the same terms as the resources of the local actors). Each process has a completion time, as well as execution frequencies, given that must be repeated over time. The states of the preparedness processes have three possible states: waiting to be executed, in execution and executed.

2.3.2 Actions (A).

The structure of the local preparedness system can be seen as a system that consists of three sets: actors, processes and resources, as follows:

- The set of actors $A = \{1, 2, 3, \ldots, N\}$ of size N, where $i \in A$ denotes a local actor.
- The set of processes $P = \{1, 2, 3, \ldots, M\}$ of size M, where $j \in P$ denotes a logistical process.
- The set of resources $R = \{1, 2, 3, \ldots, L\}$ of size L, where $k \in R$ denotes a type of resource that a local actor owns or that a preparedness process requires.

Given that the modeled agents are of two types (actors and processes), the modeled actors will be active agents, while the modeled processes are considered passive agents. Thus, the agents that develop activities, make decisions, and apply actions in the system are the local actors (humanitarian organizations that constitute the local disaster management system). Therefore, the actions proposed and programmed in the ABM correspond to those taken by the local actors related to interorganizational coordination for the formation of teams oriented toward executing preparedness processes.

Local actors, as the active agents in the model, start in an "idle" state and with preestablished functions assigned to the preparedness processes (see Figure section 1a). Subsequently, the model proceeds to determine the influence schemes between local actors. Thus, the influence level (IL_i) is calculated for each actor i, according to equation (1):

$$IL_i = \frac{1}{L} * \sum_{k=1}^{L} \frac{IR_{ik}(t_0)}{\sum_{i=1}^{N} IR_{ik}(t_0)}, with \sum_{i=1}^{N} IL_i = 1 \qquad (1)$$

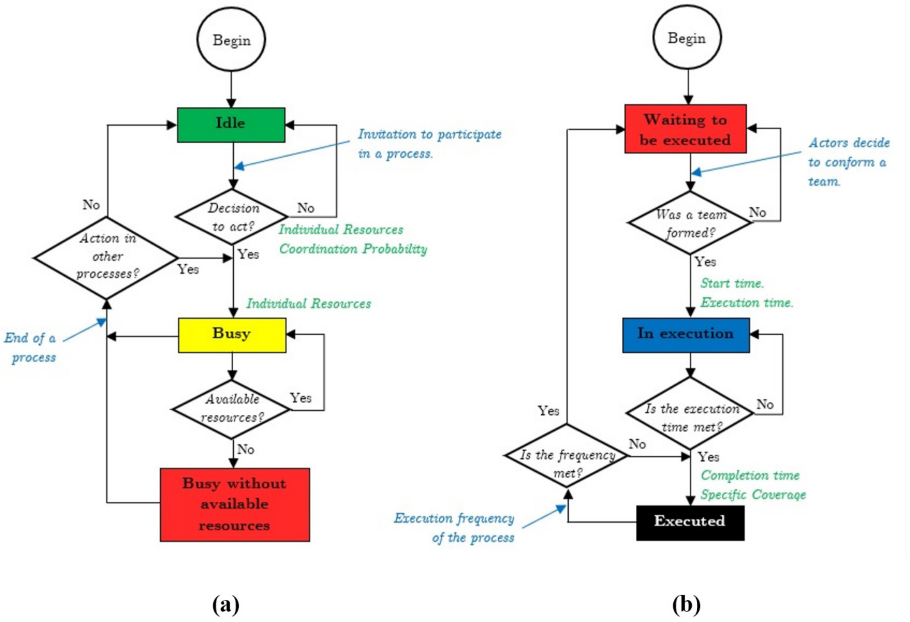
where IL_i corresponds to the average of the ratio between the availability of each resource k that actor i possess regarding the availability that the N actors have. For an actor i, the individual resources available [$IR_{ik}(t_0)$] are organized as a vector:

$$IR_{ik}(t_0) = \{IR_{i1}(t_0), IR_{i2}(t_0), IR_{i3}(t_0), \ldots, IR_{iL}(t_0)\}$$

$IR_{ik}(t_0)$ represents the available resources of the actor i, according to the L types of resources, at the start of the simulation (i.e. in time t_0).

The process agents begin in a "waiting to be executed" state (see Figure section 1b). To rank their relative importance, a priority level (PL_j) for each process j, as can be seen in equation (2):

Figure 1 States diagram of the agents



(a) (b)

Source: Created by authors

$$PL_j = \frac{1}{L} * \sum_{k=1}^{L} \frac{RR_{jk}(t_0)}{\sum_{j=1}^{M} RR_{jk}(t_0)}, with \sum_{j=1}^{M} PL_j = 1 \tag{2}$$

where PL_j corresponds to the ratio of the resources that requires the process j regarding the requirement of all the M processes at the start of the simulation (i.e. in t_0). RR_{jk} is a vector that represents the resource requirements of the process j, in terms of the L types of resources, thus:

$$RR_{jk} = \{RR_{j1}, RR_{j2}, RR_{j3}, \ldots, RR_{jL}\}$$

Based on the initial state, preassigned functional capabilities, and levels of influence, local actors take the action of beginning interactions with each other to share available resources that allow them to execute the preparedness processes. The execution sequence of the processes follows a hierarchy order based on their priority level (PL_j). Actors are assumed to have the flexibility to participate in more than one process at a time if their available individual resources allow it.

Importantly, an actor i can participate in a team of actors (TOA_j) for a process j, only if i has the preestablished function to execute j. In this case, the actor with the greatest influence (IL_i), and assigned to the process j, oversees integrating a TOA_j to start the execution of j. Other actors with pre-established function to the process and with acting capacity, based on the available resources [IR_{ik}(t)], take the decision to participate in TOA_j, based on a coordination probability function CP_i(t), as described below.

A TOA_j is formed to execute the process j, but the execution of j is only allowed if the resources shared by involved actors cover at least 80% of the process requirements (this is a minimum compliance criterion). In this case, each actor in TOA_j changes its state as "busy" (Figure section 1a), while the process j changes its state to "in execution" (Figure section 1b). When an actor decides not to coordinate, it is forced to abandon the process. In case that the actor is not involved in the execution of any process, its state remains as "idle."

While a process j remains "in execution," the resources used by the actors involved in a TOA remain occupied. This implies a reduction in the available capacities of the actors to be able to participate in other preparedness processes. When a process ends its execution, the state changes to "executed" (Figure section 1b), and the resources return to the respective actors. If an actor occupies all its resources at the same time, it changes its status to "without available resources." When the actor recovers its resources and is not contributing to any other process, its state changes to "idle" (Figure section 1a).

The procedures described continue iteratively. A flowchart of the disaster preparedness system modeled is presented in Figure 2. In addition, it is considered that the processes have a frequency of execution over time, and a period of four years is determined as a stop criterion for the simulation. During the simulation period, the model must calculate the global performance indicators: effectiveness, efficiency and flexibility in the system. These indicators are discussed in the next section.

2.3.3 Rules (R)

Local actors decide to form a TOA_j based on the coordination probability function [CP_i(t)], which is used to quantify the propensity of each local actor to coordinate with others to execute preparedness processes:

$$CP_i(t) = (1 - IL_i) * \sum_{l=1}^{W} \big(CP_l(t-1) * E_l(t)\big) + IL_i * CP_i(t-1)$$
$$with\, 0 \le CP_i(t) \le 1 \tag{3}$$

Equation (3), adapted from Zhao *et al.* (2012), consists of two parts. The first part measures the degree of exogenous influence over an actor to make the decision to coordinate. That is, the influence that other actors exert on the decision of the actor i. Element ($1 - IL_i$) represents the level of influence of the other actors on i. The subset $W \subseteq A$ gathers the actors with function assigned to a process; $CP_l(t - 1)$ represents the coordination probability of each actor l, belonging to W, in time ($t - 1$), while E_l(t) represents the relative influence of an actor l in time in (t). E_l(t) is calculated similarly to equation (1), according to the resources IR_{lk}(t) of the actor l, in a time (t), but measured in relative terms with the resources of the W actors.

The second part of equation (3) measures the degree of endogenous influence of the actor i to take the decision to coordinate. IL_i is the influence level of actor i, and $CP_i(t - 1)$ represents the coordination probability of i taken in the time ($t - 1$).

Based on the coordination probability function, the actor i takes the decision to coordinate according to the following criteria:

$$If \begin{cases} rand \le CPi(t),\ actor\, i\, does\, decide\, to\, coordinate\, in\, the\, process\, j \\ rand > CPi(t),\ actor\, i\, decides\, not\, to\, coordinate\, in\, the\, process\, j \end{cases}, with\, 0 \le rand \le 1$$

Regarding the execution of the processes, the level of compliance [LC_j(t)] is proposed as an indicator of effectiveness. It takes the resources assigned by the actors in relation to the requirements of the process [equation (4)]:

$$LC_j(t) = \frac{1}{L} * \sum_{k=1}^{L} SC_{jk}(t),\ with\, 0 \le LC_j(t) \le 1 \tag{4}$$

SC_{jk}(t) represents the specific coverage of a team of actors (TOA_j) on a type of resource k required by the process j, and it is defined according to equation (5):

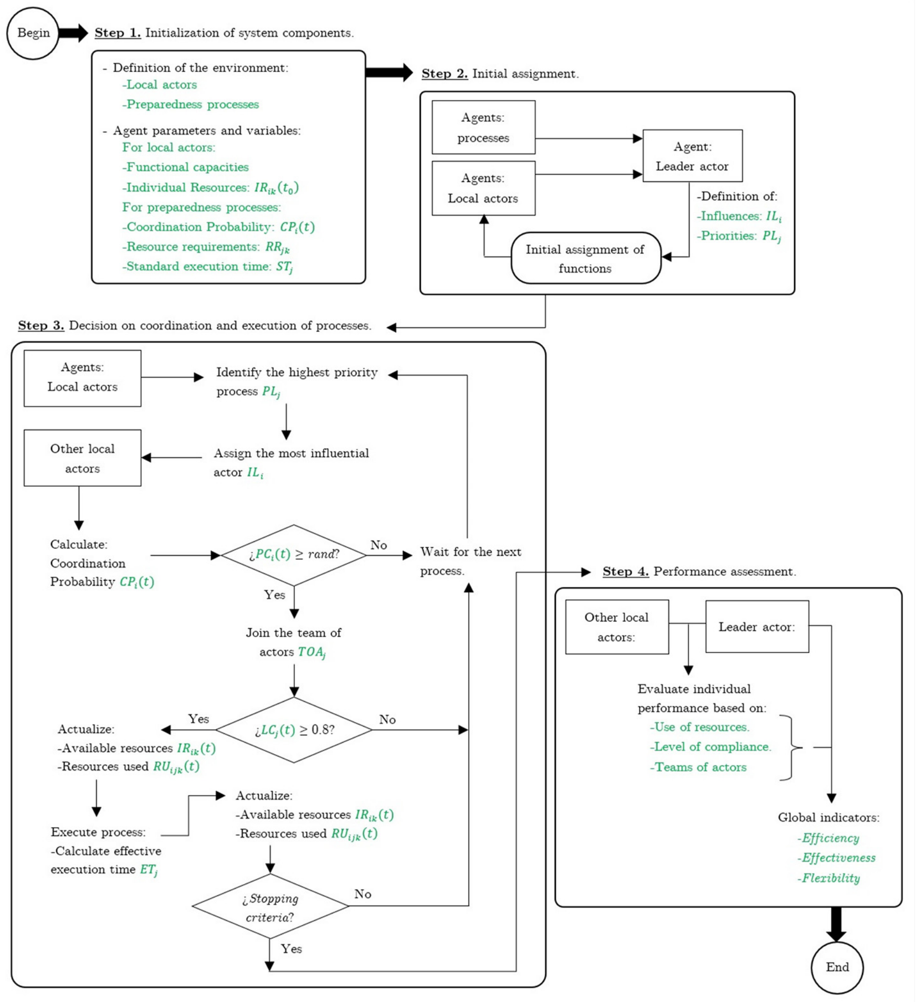
$$SC_{jk}(t) = \begin{cases} 1\ if \sum_{i=1}^{TOA_j} RU_{ijk}(t) > 0 \\ 0\ if \sum_{i=1}^{TOA_j} RU_{ijk}(t) = 0 \end{cases},\ if\, RR_{jk} > 0, \forall\, k \in R \tag{5}$$

RU_{ijk}(t) corresponds to the resources used by the actor i, as a part of the TOA_j, to comply with the resource k required by process j. This analysis is performed if resource k is requested by j (i.e. $RR_{jk} > 0$).

Based on the level of compliance of each process, an overall level of compliance OLC(t) is proposed [equation (6)], as the average of the individual compliance LC_j(t) of the M preparedness processes:

$$OLC(t) = \frac{1}{M} * \sum_{j=1}^{M} LC_j(t),\ with\, 0 \le OLC(t) \le 1 \tag{6}$$

Figure 2 Flowchart of the conceptual model



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As an indicator of efficiency, the level of use of resources by local actors is defined. It calculates the use of individual resources UIR_i(t) for an actor i. For this, the actor compares the resources used [RU_{ijk}(t), according to its current participation in the M processes], in relation to its own total resources $IR_{ik}(t_0)$, as is shown in equation (7):

$$UIR_i(t)=\frac{1}{L}*\sum_{k=1}^{L}\left(\frac{\sum_{j=1}^{M}RU_{ijk}(t)}{IR_{ik}(t_0)}\right), if\ IR_{ik}(t_0)>0,\ with\ 0 \leq UIR_i(t)\leq 1 \qquad (7)$$

The overall use of resources OUR(t) emerges as a global indicator of efficiency [equation (8)], that relates the resources used by the N local actors in the system, given a time (t), as follows:

$$OUR(t)=\frac{1}{N}*\sum_{i=1}^{N}UIR_i(t),\ with\ 0\leq OUR(t)\leq 1 \qquad (8)$$

The flexibility of the system FS is presented as a third performance indicator. In equation (9), the average quantity of execution alternatives of the preparedness processes is calculated. As the relationships between the actors occur depending on several factors, the different combinations (TOA) constituted to execute a specific process are accumulated each time. At the end of the simulation, the number of different teams constituted will be averaged to obtain a global indicator of the system:

$$FS=\frac{1}{M}*\sum_{j=1}^{M}DTOA_j,\ with\ DTOA_j\geq 0 \qquad (9)$$

Whit $DTOA_j$ as the quantity of different TOA_j that are achieved for the execution of a process j throughout the simulation.

2.3.4 Time (T)

Each preparedness process j has a standard execution time (ST_j). Given that local actors must coordinate and form teams of actors to cover the process requirements, if the minimum execution criterion is met (i.e. if shared resources are equal to or greater than 80% of the process requirements), the team of actors proceeds with the execution. Thus, an effective execution time ET_j is defined depending on the level of compliance of the process $[LC_j(\mathrm{t})]$ and its standard execution time (STj), according to equation (10):

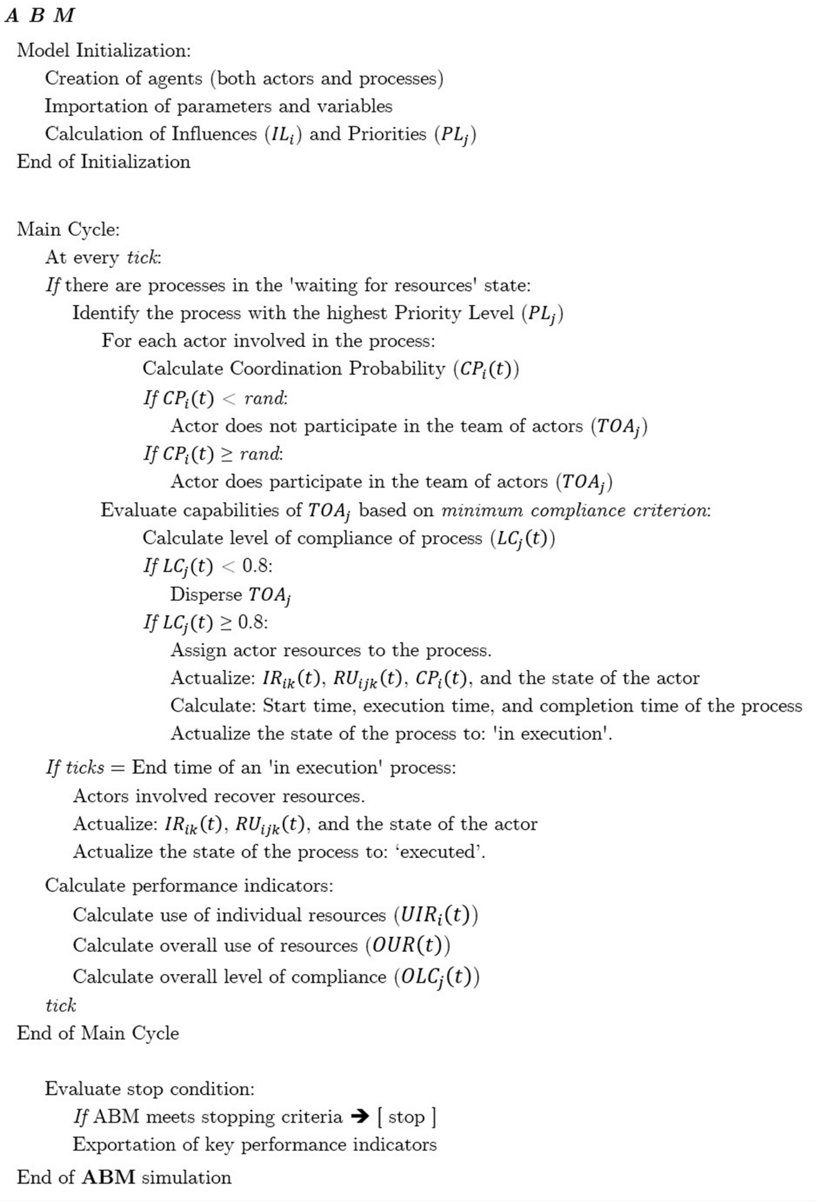
$$ET_j = ST_j * \left(\frac{1}{LC_j(t)}\right) \tag{10}$$

Simulation time is defined as discrete pass. The progress in the simulation is manifested through the decisions and interactions among the agents: actors seek to comply with the processes "waiting to be executed" according to their priority level (see Figure 3). As a stopping criterion, a period of four years is defined, which represents a governance period in Colombia.

2.3.5 Environment (E)

A spatial location for the agents in the ABM was not defined because the scope and the purpose of the model are focused on studying the interorganizational coordination mechanisms for the strategical disaster preparedness phase and their impact on the global performance. Actors need others to form TOA and thus meet the requirements of the processes. In this sense, coordination probability is essential for individual decision-making, and this has repercussions on the change of states of the actors. As the actors decide to coordinate, they change their status from "idle" to "busy" (even "busy without available resources," if they use all their individual capacity), which

Figure 3 ABM pseudocode



```
A B M
 Model Initialization:
     Creation of agents (both actors and processes)
     Importation of parameters and variables
     Calculation of Influences ($IL_i$) and Priorities ($PL_j$)
 End of Initialization

 Main Cycle:
     At every tick:
     If there are processes in the 'waiting for resources' state:
         Identify the process with the highest Priority Level ($PL_j$)
             For each actor involved in the process:
                 Calculate Coordination Probability ($CP_i(t)$)
                 If $CP_i(t) < rand$:
                     Actor does not participate in the team of actors ($TOA_j$)
                 If $CP_i(t) \geq rand$:
                     Actor does participate in the team of actors ($TOA_j$)
             Evaluate capabilities of $TOA_j$ based on minimum compliance criterion:
                 Calculate level of compliance of process ($LC_j(t)$)
                 If $LC_j(t) < 0.8$:
                     Disperse $TOA_j$
                 If $LC_j(t) \geq 0.8$:
                     Assign actor resources to the process.
                     Actualize: $IR_{ik}(t)$, $RU_{ijk}(t)$, $CP_i(t)$, and the state of the actor
                     Calculate: Start time, execution time, and completion time of the process
                     Actualize the state of the process to: 'in execution'.
     If $ticks =$ End time of an 'in execution' process:
         Actors involved recover resources.
         Actualize: $IR_{ik}(t)$, $RU_{ijk}(t)$, and the state of the actor
         Actualize the state of the process to: 'executed'.
     Calculate performance indicators:
         Calculate use of individual resources ($UIR_i(t)$)
         Calculate overall use of resources ($OUR(t)$)
         Calculate overall level of compliance ($OLC_j(t)$)
     tick
 End of Main Cycle

     Evaluate stop condition:
         If ABM meets stopping criteria ➔ [ stop ]
         Exportation of key performance indicators
 End of ABM simulation
```

Source: Created by authors

implies changes in the conditions of their individual resources and decision rules. When the processes in "waiting to be executed" state change to "in execution," and then "executed," their own states and the way in which the actors identify priorities change. This condition generates a dynamic environment in the system.

2.4 Implementation of the ABM

The computational implementation of the ABM has been done in the Netlogo 6.2.2 software. Netlogo is a multi-agent programming and modeling environment (Wilensky and Rand, 2015), and an integrated platform for ABM, which allows to simulate multiple agent entities and complex systems overtime, allowing the visualization of outputs in real time, and that has been applied in several logistical issues in the specialized literature (Yang and Chen, 2019; Calabrò *et al.*, 2020; Chen *et al.*, 2022). The coded model includes the decision rules, behavior rules, and other assumptions defined in the conceptual design. To guarantee the methodological rigor of the ABM, verification and validation procedures were carried out.

ABM verification procedures were applied based on Wilensky and Rand (2015). First, the coding process was developed under a "step-by-step" scheme, starting from simple modeling structures to construct a model more complex, through improved versions. Second, the ABM was coded in a modular program, which compiles the main procedures in a grouped way, to simplify the structured code. Check tests were also used whit the aim of guaranteeing the correct operation and thus avoiding execution errors. Finally, a graphical interface was developed in Netlogo, which allows visual control and monitoring of the procedures.

As a validation method, a sensitivity analysis was carried out with the aim to identify how the simulation outputs are affected by the variation of the main input variables, such as:

- the percentage of processes assigned to local actors;
- the percentage of available resources of the actors; and
- their initial coordination probability.

Thirty-one scenarios were established for the sensitivity analysis under an approach *ceteris paribus*. Thirty replicates were run per scenario, simulating a period of 1440 days (equivalent to four years). General results show that the model is sensitive to the three key inputs. According to the processes assigned to the actors, it is observed that this factor is favorable to the indicators of performance: the greater the number of processes assigned to the actors, the better the global compliance of the processes, as well as the greater the global use of resources, and the greater the number of teams of different actors on average per process. In terms of the resources available to the actors, a similar effect is found on the system. The simulated scenarios show that the greater the availability of resources for the actors, the better the performance indicators measured for the local preparedness system. Finally, it was found that the simulation model is also sensitive to the coordination probability variable, as the results indicate that the greater the probability of coordination, the better the results of global compliance, use of resources, and flexibility of the system. However, in the scenarios with the highest coordination probability values, counterintuitive results are obtained in the effectiveness and flexibility indicators: when local actors have an interest in complying with the highest priority processes, the less relevant processes remain abandoned, negatively affecting the overall performance of the system. This dynamic only seeks to satisfy a local optimum, since at a global level a very low performance is manifested around the fulfillment of the requirements demanded in the system. Complementary results of the validation process, based on sensitivity analysis, can be found in Appendix 2.

2.5 Simulation scenarios

Given that most of the disaster preparedness logistical processes are involved in the strategic perspective (e.g. processes related to emergency plans, the development of individual capacities, as well as for the development of long-term and intersectoral relationships) (Scholten *et al.*, 2014), it is necessary to evaluate coordination mechanisms concerning to preparedness stage from a strategic perspective. As strategic coordination mechanisms, the decentralized, centralized and cluster schemes are alternatives for managing intersectoral relations in the humanitarian context. This is proposed in consideration of what was suggested by Kamyabniya *et al.* (2019), who maintain that it is necessary to incorporate useful coordination mechanisms to disaster management. Furthermore, Jahre and Jensen (2021) recognize that the study of how to coordinate and what mechanisms to implement has received more attention in recent times.

2.5.1 Decentralized scenario

The consideration of a decentralized approach for the management of the preparedness system responds to the way in which local actors behave in accordance with the action rules defined in the conceptual model. That is, each actor has autonomy and independence to decide, based on a coordination probability function, its participation in teams of actors that seek the execution of the different logistical processes. This decentralized approach assumes the free and spontaneous action of the agents, under their sense of autonomy, to decide whether to act in a team of actors to execute a preparedness process. In the words of Kamyabniya *et al.* (2019), the decentralized structure, where autonomous decisions prevail, is more challenging than the management required in structures in which one or several organizations have operational control. When various actors participate in a system, but they have individual purposes that are not collectively agreed, problems arise in interorganizational integration, which is why it is crucial that the agents agree on certain rules of behavior (Shoham and Leyton-Brown, 2008; García and Van Veelen, 2018). Given this, it is pertinent to consider alternative mechanisms, such as those explained below.

2.5.2 Centralized scenario

The lack of coordination in relief operations can be caused by the absence of an actor in charge of humanitarian action (Shalash *et al.*, 2022). Shokr *et al.* (2022) argue that the presence of a coordinating actor that facilitates resource flows in the system promotes effective development of the humanitarian logistics chain. In this sense, it has been noted in the literature that a key actor that must assume the role of facilitator, leader and generator of trust for the integration of the system of humanitarian organizations is the local government (Oksuz and Satoglu, 2023; Xu *et al.*, 2023). The centralization of the system emerges as an alternative mechanism that addresses the assignment of a leading actor (for this case, the local government) to coordinate and assign the other necessary actors to comply with the logistical processes. Thus, the centralization of the system is modeled in the ABM through the change in the decision process to configure the teams of actors (*TOA*). To do this, it will no longer be the local actors who make their decision to participate jointly, autonomously and based on the coordination probability function, but the assignment of actors to *TOA* will be done by the leading actor. Leader agent will do so based on the available capabilities of the actors (individual state) and their ability to meet the requirements demanded by the specific preparedness process.

2.5.3 Cluster-type scenario.

Published studies on cluster-based coordination have been supported by the scheme designed by the United Nations, which promoted the integration of organizations in strategic humanitarian areas, such as health, education, gender-based violence, wash and sanitation, and disability (Dhingra, 2022; Shalash *et al.*, 2022). In practical terms, the cluster integration approach has been acknowledged by the humanitarian sector (Anjomshoae *et al.*, 2023), so aspects related to coordination within and between clusters have been added to the discussion agendas (Jahre and Jensen, 2021). Consequently, the question of how to design cluster generation schemes and how to generate fair inclusion schemes, which are issues demanded by small humanitarian organizations, are aspects that continue to be discussed and developed (Corbett *et al.*, 2022).

The cluster-type coordination mechanism was adapted through a scheme of actions where teams of actors are formed adding those that have availability of resources corresponding to each process requirements. For this, in the model initialization stage, a cluster creation procedure is added for each logistical process, so that in the cluster of each process the actors that achieve the best contributions to the resource requirements are assigned. During the execution of the simulation model, the additional participation of other actors is allowed, but eventually, so that when the execution of a process is complete, the temporary actors leave the cluster.

3. Results

The simulation results based on the proposed scenarios (decentralized, centralized and cluster-type) are Summarized in Table 1. Each scenario was run in 50 iterations to obtain the three global indicators: effectiveness, efficiency and flexibility.

The results shown in Table 1 are complemented by Figure 4. The confidence intervals (CI) were calculated with a confidence level of 95% (two-tailed test with $\alpha = 0.05$). Simulation results make evident that, regarding the effectiveness, the centralized (with a mean of 83.74%) and cluster-type (mean of 84.3%) mechanisms present better results compared with the decentralized scenario (mean of 77.07%). The effectiveness is increased in those scenarios by a tendency to form more quickly *TOA* for the execution of the preparedness processes. In addition, effectiveness in centralized and cluster-type scenarios tends to have less deviation in the executed runs (see Table 1, and Figure section 4a).

Regarding efficiency, it can be noticed that the decentralized scheme presents a better level of use of resources by the actors (47.24%), compared to the centralized (33.41%) and cluster-type (33.19%) scenarios (see Table 1, and Figure section 4b). Centralized and cluster-type mechanisms produce in the actors an interest in focusing their efforts on the prioritized processes. Thus, local actors tend to form teams of actors not only based on the availability of resources but also seek a better use of them. This is achieved by assigning actors that contribute the most to the types of resources required by processes.

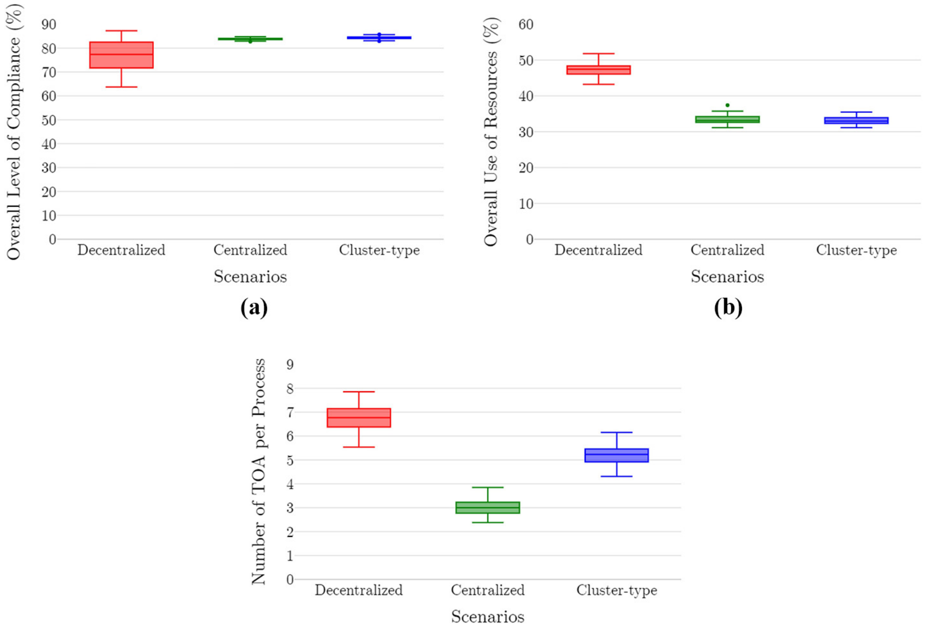
According to the system flexibility (Table 1, and Figure section 4c), the decentralized scenario (average of 6.8 alternatives per

Table 1 Global results for scenarios simulated

Performance dimensions	Measures**	Scenarios* Decentralized	Centralized	Cluster-type
Effectiveness: Overall level of compliance – OLC (%)	Max	87.28	84.76	85.71
	Mean	77.07	83.74	84.30
	Min	63.74	82.71	82.91
	SD	6.53	0.44	0.62
	CV (%)	8.47	0.52	0.73
Efficiency:	Max	51.77	37.40	35.49
Overall use of resources – OUR (%)	Mean	47.24	33.41	33.19
	Min	43.20	31.12	31.14
	SD	1.77	1.24	1.06
	CV (%)	3.74	3.72	3.19
Flexibility: Number of TOA conformed for each process on average	Max	7.85	3.85	6.15
	Mean	6.80	3.02	5.25
	Min	5.54	2.38	4.31
	SD	0.53	0.33	0.38
	CV (%)	7.82	11.08	7.22

Notes: *Average for 50 simulation runs; **Max = Maximum; Min = Minimum; SD = Standard deviation; CV = Coefficient of variation
Source: Authors' own work

Figure 4 Performance measures for each scenario modeled



(a) **(b)** **(c)**

Source: Created by authors

process) shows better results that centralized and cluster scenarios (with averages of 3.0 and 5.2 alternatives per process, respectively). This behavior is intuitive, since centralized and cluster-type schemes could disfavor the possibility of autonomy and independence of the actors. In counterpart, a collective interest is achieved, based on trust and a wide openness to coordination by actors. It favors strategical and productive participation. The cluster-type scenario presents an intermediate flexibility, due openness of actors to temporarily participate in a cluster when required. Centralized scenario has the greatest rigidity given the procedure for assigning local actors to the process execution. In this case, the local government agent is the one who directly assigns the actors when it is required to attend a preparedness process. Considering the statistical rigor, the one-way ANOVA test was applied to determine the significant difference between the three simulated scenarios, according to each performance measure. Test statistics and critical values are summarized in Table 2.

Table 2 Test of means difference (ANOVA)

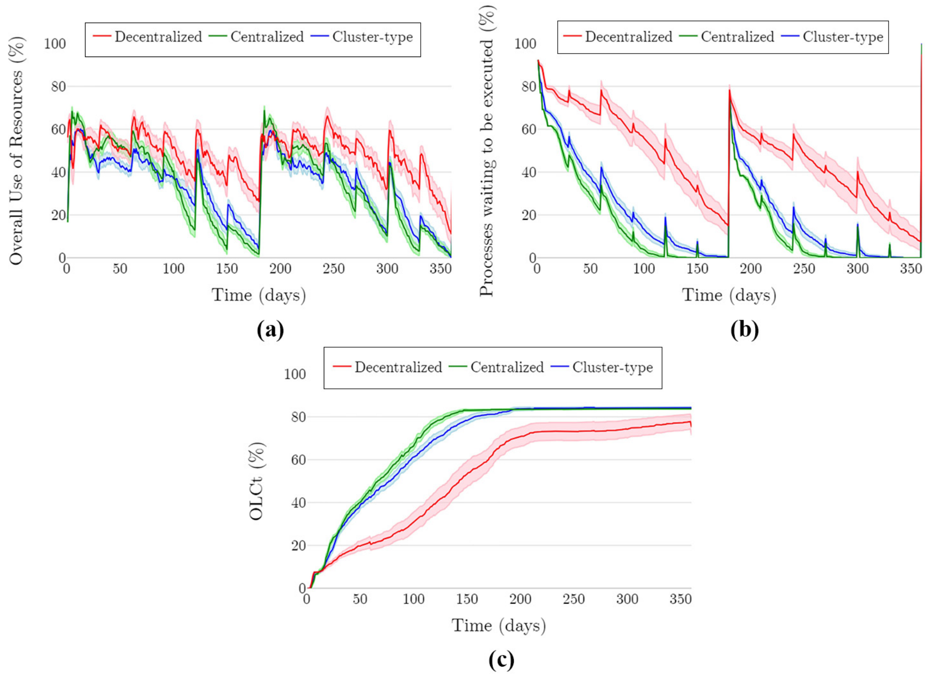
Performance measures	Test statistic*	*p*-value
Overall level of compliance – OLC (%)	56.12	7.7784×10^{-19}
Overall use of resources – OUR (%)	1682.13	5.0851×10^{-102}
Number of TOA conformed for each process on average	1008.22	1.4610×10^{-86}

Notes: *With H_o: The means of the samples are statistically equal (i.e. H_o: $\bar{x}_1 = \bar{x}_2 = \bar{x}_3$). H_a: At least one of the groups means differ. Confidence interval at the 95%
Source: Created by authors

As can be seen, the values in Table 2 demonstrate statistical significance at the 95% level to assert that there are appreciable differences in the three performance indicators for the three scenarios studied in this work.

In addition, the behavior of the modeled scenarios over time has been analyzed, considering three measures: level of use of resources by local actors, percentage of processes in ‘waiting to be executed’ state, and compliance rate of the preparedness processes. The time series shown in Figure 5 summarize the first 360 days of 1440 days simulated. Results are obtained for 50 simulation runs and CI measured at the 95% level. Figure section 5a shows how the use of resources by the actors for the centralized and cluster-type mechanisms tends to be lower compared to the decentralized scenario. The conditions modeled under the centralized and cluster-type schemes allow for a better assignment of local actors to the teams of actors not only based on the process requirements, but also favor an exploitation of the resources shared by them. Thus, local actors participate in the execution of the processes with a better use of resources. The level of use of resources shows a decreasing trend for all three scenarios until approximately day 180, which can be attributed to the reduced demand for resources generated by the compliance of the preparedness processes. After day 180, an increase in resource utilization is observed due to the renewal of the process requirements. It is important to note that most of the processes have a biannual execution frequency, as reported by the local agencies in the case study. Therefore, certain processes that were “executed” during the first 180 days of the simulation become “waiting to be executed,” and the actors need to form *TOA* once again to execute the processes that have that biannual frequency.

Figure 5 Time series for the indicators measured by scenario



Source: Created by authors

The percentage of processes in “waiting to be executed” state is significantly reduced with the implementation of the centralized and cluster-type schemes, compared to the scenario with the decentralized mechanism (Figure section 5b). This improved performance is given by the rules of assignment of actors, differently from the decentralized mechanism, because a better organization of the agents is achieved, and with this, the conformation of the teams of actors becomes more efficient. It is also observed that these two mechanisms have narrower confidence intervals with respect to the decentralized scenario. In addition, the percentage of pending processes is reduced to zero approximately on days 150 and 300, for the centralized and cluster-type scenarios. This shows that they are the most efficient and agile scenarios in complying with all the logistical processes. Therefore, implementing a coordination mechanism that seeks to group strategically local actors for the execution of the processes could be a more efficient action for disaster preparedness. It is also graphically evident that the scenarios with the best performance have narrower CI (measured at the 95% level). As occurs with the use of resources by the actors, there are sudden increases in the percentage of processes in pending condition, every 180 days of simulation (see Figure section 5b). These periodic peaks are mainly caused by the need to repeat preparedness processes that have a biannual frequency.

Regarding the global fulfillment for the preparedness processes (Figure section 5c), the centralized and cluster-type scenarios once again show better performance than the decentralized one. In the first days of the simulation, it is evident that the centralized and cluster-type mechanisms present a fast growth. After 200 days, the system reaches a steady state in terms of global coverage, given that the processes have already managed to run at least once in that period. This indicator achieves stability over time since its method of calculation implies a permanent record of the processes executed historically. The superior performance of those scenarios is a consequence of the agility and efficiency in the composition of teams of actors that achieve the best performance in the coverage of the requirements of the processes.

4. Discussion and final remarks

One of the biggest challenges in HL is interorganizational coordination (John *et al.*, 2019). In the literature, the discussion between collaboration and competition shifts toward coordination, understood as one of the main tasks of humanitarian organizations, and a key requirement for the efficiency and effectiveness of humanitarian action (Xu *et al.*, 2023; Wagner *et al.*, 2024). Despite its importance, coordination continues to be a field of both scientific and practical development, since several authors urges the formulation of coordination mechanisms to reduce organizational discrepancies from a strategical approach to disaster preparedness (Kamyabniya *et al.*, 2019; Corbett *et al.*, 2022; Dhingra, 2022; Stumpf *et al.*, 2023). To fulfill the purpose, qualitative interviews were conducted to local actors involved in disaster management operations in the city of Manizales, Colombia. Then, the agent-based simulation model was designed and coded to represent the conditions, relationships and decisions of the local preparedness system, based on three strategic coordination mechanisms, and evaluated the overall performance of the system from three different dimensions. Study findings indicate that the best coordination occurs in scenarios where ordered schemes are established based on centralization mechanisms and the cluster approach. The decentralized configuration has shown more difficulties in achieving higher performance, in efficiency (measured in overall use of resources), effectiveness (measured in overall level of compliance) and flexibility (measured in number of teams conformed for each process on average). In this sense, Stumpf *et al.* (2023) similarly conclude that a decentralized scheme tends to be vulnerable to contingencies; therefore, this structure demands more academic analysis regarding humanitarian preparedness. Kamyabniya *et al.* (2019) point out the difficulties inherent in decentralization, given its highly challenging condition for planning decisions. On the other hand, Shalash *et al.* (2022) recognize the need for some head to take the leadership of humanitarian action, especially when the lack of coordination is generated by the lack of an actor in charge. Likewise, main findings are consistent with contributions given by Jahre and Jensen (2021) and Anjomshoae *et al.* (2023), who accept the current trend toward the cluster approach in humanitarian sector and the potential in logistics performance, although its development has been largely dominated by international organizations.

Given the specific features of this work, there was difficulty establishing concrete comparative frameworks to establish quantitative parallels with previously published studies. However, as stated before, alignment was found regarding the behavior of the simulated scenarios based on coordination mechanisms. According to Wang and Zhang (2019), the systematic impact generated by simply having an interest in coordinating and sharing resources is crucial, as the performance of humanitarian systems can be significantly improved. Aros and Gibbons (2018) address centralized schemes in communications between humanitarian agencies; their results highlight the positive impacts of centralization on response times. Kunz *et al.* (2014) focus on logistical preparedness management and recognize the positive impact of centralizing aid distribution decisions through relief warehouses. Hashemipour *et al.* (2018) study the search and rescue processes under a task auction scheme. They conclude that the number of clusters formed is an important factor that has a great effect on the overall performance of the system, and that the assignment of agents to tasks should be done based on the skills and experiences of the agents. Therefore, the correspondence of this work with the cited authors, who have addressed coordination mechanisms in HL, supports the strategical advantages of applying structured schemes focused on the centralization of the local actors involved in the disaster management processes.

It is important to highlight the critical and innovative aspects of this work. The singularities of the study have focused on the problem of interorganizational coordination, the key phase of disaster preparation, the focus on location as a decisional framework, the case study addressed in a Latin American context, the type of disaster based on events of hydrometeorological origin (which are exacerbated by climate change phenomena) and the diversity of dimensions for performance measurement. This conjunction of multiple aspects makes this work unique, although not isolated from what has been discussed in specialized literature in recent times. Among others, harmony is maintained with Shokr *et al.* (2022) who call for incorporating coordination schemes where a local leader facilitates the participation and flow of resources for humanitarian development and sustainability; Jahre and Jensen (2021) state that the study of coordination mechanisms is relevant for both practical and empirical studies on this topic; and there is also an alignment with Rodríguez-Espíndola (2023), who exhorts the incorporation of multidimensional performance schemes in disaster operations management. Thus, this work emerges as an interesting proposal to establish opportunities for new research, under the methodological proposal developed, to be implemented in contexts other than those of Latin America.

Disaster preparedness and interorganizational coordination in the frame of HL continue to be topics of interest that demand more research efforts. The ABM designed for the local context of disaster preparedness is presented as an intentional contribution toward strengthening the knowledge on issues related to local disaster management, as well as the measurement of the performance of the preparedness stage. These contributions are based on the study of strategical coordination mechanisms. However, the proposed ABM has some limitations. First, the results applied to only one real case limit the model scope. In this regard, future works will be formulated to take advantage of this simulation model to study different situations, with other geographical contexts. Second, this work has focused on a particular typology of disaster: hydrometeorological events, such as flash floods, torrential rains and landslides. In this regard, future research could develop studies to adjust the model to the conditions of preparedness for different types of disasters. Third, the decision-making scope has been strictly limited to the key actors that participate on the local level of disaster management (for a municipality level). This implies a new possibility of proposing future lines to work focused on the participation of other agents of different and wider regional levels. The proposed model, with proper adaptations, could be used to study other types of geographical scenarios (other real cases), different types of disaster (e.g. seismic, or anthropogenic events), as well as other disaster management phases, with the aim of assessing other performance indicators and even consider other types of actors, based on local, regional, national or international levels, even at latitudes different from those studied here.

The ABM replicability will be subordinated to the geographical context and the types of disaster (i.e. geomorphology of the territory, risk factors and actors involved, must be recognized) to quantify agent attributes. The research instrument proposed (Appendix 1) can be adjusted to gather the information from humanitarian agencies in the territory. Thus, the possibility of replicating the study shown in this paper is postulated through the methodological proposal, as described in section 2. More than a standardization of the decision tool, the aim is to provide guidelines for the analysis of other contexts. An adaptation of the conceptual and computational design of ABM is envisioned as a methodological strategy based on the principles of ABM aligned to humanitarian environments. In this way, a possibility of replication of the methodological proposal is conceived, based on field studies and development of agent-based simulation models to analyze the coordination problem in the disaster preparedness phase, to any context in the world where there is the possibility of applying the precepts addressed here. The contribution to the theoretical and practical fields is aimed at providing elements of discussion that strengthen the field of knowledge of humanitarian logistics, through the edges that demarcate the research interests. This seeks to generate academic interest in geographical environments, through the technical development of local strategic processes. Likewise, the proposed ABM is a key product of this research. The proposed model has the potential as a decision-making tool for policies and local coordination schemes for future disasters. In prospective terms, further research will be aimed at establishing guidelines for the application and implementation of the model, while increasing the social impact of humanitarian work in the territory based on the protection of communities in greater vulnerability. Such claims may be materialized with alternative research methodologies, such as action research, or social appropriation of knowledge. The transfer of management models will favor the correct assignment of responsibilities in environments of high uncertainty, as defined by Hooshangi and Alesheikh (2018), while advancing in the support of social processes, with the adaptation of academic language that allows integration with organizations from the real sector (Shrivastav and Bag, 2023). Future research is encouraged to address key points of HL, increasing relationships with the empirical sector and strengthening academic collaborative networks. Based on the technical-based tools developed, the use of the ABM can be enhanced and exploited to other disaster typologies, even to other geographic latitudes. Thus, simulation tools will be able to demonstrate their versatility and applicability for additional findings and key contributions in the development of the humanitarian sector in the world.

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Appendix 1. Research instrument applied in the case study

Instrument consolidation process

With the need to recognize the capacities, available resources and particularities of the actors that participate within the local preparedness system, the design of the research instrument considered different sections to obtain adequate information and data to feed the ABM. An initial version of the instrument was tested as a pilot to obtain convenience, clarity and effectiveness in its final application. The pilot was carried out with two of the local actors: the office of Risk Management Unit (local government), and local Red Cross.

Final design of the instrument

After the consolidation of the instrument, it was obtained an outline of the questionnaire, as shown in Table A1.

Application of the instrument

The interviews were conducted in the main offices of each local organization. 8 key local actors in the city participated in the field work. Table A2 summarizes general features of the interviews conducted.

The data provided by the interviewees facilitated the identification of which actors are related to the different preparedness processes within the local disaster management system. A second finding is related to the types of resources involved in the preparedness phase, that possess the humanitarian agencies in the local context. A total of 39 types of resources were obtained. This level of specificity was achieved thanks to the information provided by the officials interviewed.

Appendix 2. Sensitivity analysis of the ABM

Description of the sensitivity analysis for the ABM designed

The purpose of the analysis was to identify how the simulation results are affected from the variation of the key inputs, such as:

- the functional capabilities of the local actors;
- the individual resources available of the actors; and
- the initial coordination probability of the actors.

The analysis was addressed to the three ABM outputs:

1. the overall level of compliance;
2. the overall use of resources; and
3. the average number of teams conformed for each process.

The quantity of model runs for each scenario was 30 replicates, while the simulation period was four years (or 1440 days).

Effect of the processes assigned to the actors

The functional capabilities represent if an actor can participate in the execution of the preparedness processes. This binary variable is one of the main inputs and hence it is needed to identify its effect on the outputs of the simulation model.

The functional capabilities of the actors were modified in percentage terms. Scenarios were designed ranging from 10% of the functions assigned to the actors (i.e. where each actor is assigned only 10% of the processes, on average), to the scenario of 100% of the functions assigned (i.e. each actor has the possibility of participating in all processes). The scenarios

Table A1 Structure of the research instrument

Section	Questions
Initial section: Includes personal questions for the interviewee, as well as introductory and contextual readings of the study	Personal data of the interviewed official Introductory reading of the study Reading of the study objective Gratitude for participating in the study
Second section: This section includes questions about the preparedness logistical processes	In what preparedness processes has your organization participated? What types of resources does the organization own? What resources are required in each preparedness process? What duration and frequency of execution have the preparedness processes?
Third section: This section has questions that characterize inter-organizational relationships	With which organizations have you participated in the execution of the preparedness processes? What mechanisms of communication and coordination have you used with other organizations? What frequency, category and importance do you assign to relationships with other organizations?
Final section: Closing questions	How has the inter-organizational coordination been in the execution of the preparedness processes? What factors have limited your organization's ability to work collaboratively with other organizations? How could relationships and inter-organizational coordination be improved during preparedness processes that take place at the local level?

Source: Created by authors

Table A2 Representative data from the interviews carried out

Organization	Interviewee's position	Interview date	Interview duration
Local government	Director	10/28/2019	1 h
Red cross	Sectional director	10/4/2019	1.5 h
Civil defense	Operational coordinator	10/15/2019	1.5 h
COBM	COBM commander	11/1/2019	2 h
CBVM	CBVM commander	10/29/2019	1.5 h
GER	Director	11/7/2019	1.5 h
BYR	Director	10/15/2019	2 h
UTAC	Director	10/24/2019	1 h

Source: Created by authors

were designed in 10% intervals. The general results of the runs for each defined scenario are shown in Table A3.

Regarding the overall compliance of the processes, the indicator increases with the increase in functional capabilities. A similar effect occurs with the actors which are favored by reaching better use levels of their resources, when the assigned functions increase. Regarding the number of alternatives obtained per process, an increase is observed in the different possible configurations of teams conformed to execute the preparedness processes. Thus, the effectiveness improves when the actors have more functions within the preparedness system; this is complemented by a better use of the available resources of the actors, as well as a greater flexibility of the system.

Analysis of the variation of the available resources

An important input of the ABM is the possession of different types of resources by local actors. In this sense, 10 scenarios were generated corresponding to different resources available. The scenarios represent the conditions in which the actors possess from 10% of the whole possible resources, on average, to 100% of the different types of resources. These ranges increase by 10%. Table A4 summarizes the data obtained by running the Model 30 times per scenario.

The performance of the system improves as the resources of the actors increase. However, it is striking that, upon reaching 100% of the possible resources, local actors generate a drastic decrease in the global performance. This occurs in the proposed indicators for effectiveness and flexibility. The unexpected condition arises because the actors, with the intention of participating actively in the system, focus all possible efforts and resources to the processes that remain with the highest priority, and this produces an abandonment of the other pending processes. This is the global result manifested, even though, from a purely individual perspective, the actors seem to be making better use of their individual resources. It is evident that there is a strong influence of

Table A3. Global results of 30 runs executed for the scenarios designed according to the functions assigned to the actors

	Overall level of compliance (%)		Overall use of resources (%)		Alternatives (TOA) conformed per process	
Scenarios (%)	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Functions at 10	0.00	0.00	0.00	0.00	0.00	0.00
Functions at 20	15.05	0.67	13.69	0.25	0.23	0.00
Functions at 30	17.30	0.75	17.46	0.64	0.46	0.00
Functions at 40	13.20	0.05	14.76	0.67	0.45	0.02
Functions at 50	41.07	0.18	29.63	1.07	1.86	0.13
Functions at 60	41.24	0.60	31.56	1.40	2.16	0.15
Functions at 70	47.22	0.86	36.62	1.47	3.43	0.22
Functions at 80	85.71	3.58	43.64	1.39	7.01	0.55
Functions at 90	88.38	1.05	43.52	1.36	6.91	0.26
Functions at 100	86.61	3.29	48.56	1.24	7.96	0.50

Source: Created by authors

resources on the execution of the preparedness processes, from 70% to 90% of availability of the resources. A similar effect is found with the overall use of resources since the indicator has an increasing trend in the scenarios as the local actors have more available resources, while a sustained improvement in flexibility is also achieved by increasing the resources to the actors in the whole system.

Analysis of the variation of the coordination probability

To identify the effect of the propensity of local actors to coordinate, it was decided to generate scenarios by the variation of the coordination probability. From the value 0.0, it was increased, with a range of 0.1, to the value of 1.0 for all actors in the system. Thirty iterations per scenario were run and the information of the performance indicators was collected. Table A5 summarizes the general results.

It can be noticed the low performance shown by the scenarios with both very low and very high values of coordination probability. In the extreme case where the actors have no vocation for coordination (i.e. a value of 0.0), it is not possible to comply with any of the process requirements considered. That is, under the parameters worked on in the model, the coordination of the actors is required to carry out the preparedness processes. It is also observed that high values of coordination probability are not required to obtain good results. Just having an interest in coordinating shows that the performance of humanitarian systems can be significantly improved.

It is pertinent to highlight the negative effects when the coordination probability is near or equal to 1. This situation implies that the actors have full willingness to collaborate, and each organization deploys its resources in compliance with the processes that are most relevant in the system. This behavior has an impact on performance at the system level since it is not possible to cover the requirements of all preparedness processes. In other words: when there is a high coordination probability, maximum use of resources can be achieved in individualistic terms. But it only seeks to satisfy a local optimum, since at a global level a very low performance is manifested regarding compliance with the requirements demanded, as well as the system flexibility. Consequently, the designed model is also sensitive to the coordination

Table A4. Global results of 30 runs executed for the scenarios designed according to the available resources of the actors

	Overall level of compliance (%)		Overall use of resources (%)		Alternatives (TOA) conformed per process	
Scenarios (%)	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Resources at 10	0.00	0.00	0.00	0.00	0.00	0.00
Resources at 20	25.97	2.61	37.63	1.14	3.06	0.28
Resources at 30	29.71	1.98	41.89	1.48	3.68	0.32
Resources at 40	51.42	2.06	41.56	1.30	5.06	0.35
Resources at 50	54.42	1.40	39.75	1.20	5.76	0.37
Resources at 60	54.94	0.88	38.19	1.67	5.83	0.31
Resources at 70	91.69	1.15	40.04	1.56	7.51	0.43
Resources at 80	92.78	0.74	37.95	2.00	7.60	0.45
Resources at 90	93.49	0.88	38.70	1.72	7.58	0.41
Resources at 100	60.86	7.29	49.67	0.71	0.92	0.08

Source: Table created by authors

Table A5. Global results of 30 runs executed for the scenarios designed according to the coordination probability of local actors

	Overall level of compliance (%)		Overall use of resources (%)		Alternatives (TOA) conformed per process	
Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
C.P. at 0.0	0.00	0.00	0.00	0.00	0.00	0.00
C.P. at 0.1	55.09	7.25	22.60	1.20	4.43	0.30
C.P. at 0.2	83.38	3.51	30.23	1.64	7.10	0.43
C.P. at 0.3	86.60	1.87	33.33	1.36	8.09	0.28
C.P. at 0.4	86.72	1.87	36.62	1.26	8.51	0.33
C.P. at 0.5	87.80	1.64	39.81	1.73	8.53	0.27
C.P. at 0.6	87.07	2.15	42.80	1.36	8.17	0.26
C.P. at 0.7	82.95	4.10	46.32	1.42	7.22	0.44
C.P. at 0.8	79.17	4.97	49.36	1.45	5.94	0.40
C.P. at 0.9	65.68	8.89	52.57	1.32	3.73	0.46
C.P. at 1.0	50.40	5.68	57.33	1.02	0.94	0.14

Source: Created by authors

probability. Thus, it can be intuited that it is significantly not enough for organizations to just want to coordinate, since the integration and coordination procedures modeled are not enough to obtain a global improvement of the preparedness system. This condition does not imply a good global performance in the system. The notion that emerges at this point focuses on the need to seek coordination in the processes in accordance based on what is required. Different integration alternatives and other coordination mechanisms must be assumed to achieve sustainable improvements in performance, and under a holistic-strategic perspective. Those are the purposes of the scenarios that reflect strategic coordination mechanisms in the main body of the article.

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