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Disaster management performance under behavior changes: exploring scenarios using agent-based modeling

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Natural disasters have highlighted the importance of humanitarian logistics, which involves systematized processes for managing emergencies such as the location of assistance centers and temporary shelters. These processes are often challenging, especially in situations where infrastructure is affected by flooding. To address this, a hybrid approach combining a mathematical multicriteria decision model and an agent-based simulation model is proposed to manage emergency strategies for urban flooding risks. The focus is on the principles of humanitarian logistics to prioritize the spatial location of temporary shelters. The use of multicriteria methods recognizes the subjective nature of decision-making and four criteria were established to evaluate the order of prioritization for temporary emergency shelters. Agent-based models can simulate complex and heterogeneous systems, such as the logistics of managing floods over large areas. Through this approach, an order of locations for community or collective temporary shelters was established, including the necessary computational and logistic operations needed to save lives. This approach provides a decision support tool that can assist in the construction of an Emergency Plan in response to floods, at the strategic or operational level of logistical decisions. The proposed hybrid approach is effective in risk management and can help address the challenges associated with implementing humanitarian logistics in disaster situations.

Keywords: Disaster management; Disaster risk management; Natural Disasters; Temporary Shelters. MCDM; MAUT; Agent Based Simulation

1. Introduction

The intensification of extreme weather events has been one of the main consequences of climate change, resulting in an increase in the frequency and severity of natural disasters worldwide (IPCC, 2018). In addition, growing urbanization and concentration of people in high-risk areas increase communities' vulnerability to these events, making risk management strategies even more critical.

Among natural disasters, floods are one of the most common and impactful events. According to the Global Climate Risk Index (CRI), floods account for 43% of deaths caused by natural disasters worldwide, in addition to generating significant financial losses. In the last ten years, approximately 1.7 billion people have been affected by floods, resulting in over 170,000 deaths and an economic loss of over US$ 600 billion (EM-DAT, 2021). In this context, the need to develop effective risk management strategies and emergency response becomes even more pressing. In this regard, the combination of multi-criteria decision-making models based on MAUT with agent-based simulation models has been identified as a useful approach to address the complex challenges of flood disaster management (De Almeida et al., 2015). Multi-criteria decision-making models based on MAUT are a decision-making tool that allows for a holistic evaluation of alternatives, taking into account multiple criteria and decision-makers' preferences (De Almeida et al., 2015). In turn, agent-based simulation models allow for simulating and evaluating different emergency response scenarios, considering the dynamic interactions between the agents involved (e.g., government authorities, rescue teams, local communities, among others) (Chen et al., 2020).

It is possible to evaluate and compare emergency response alternatives by combining models, taking into account both immediate and long-term implications for community sustainability and resilience. Moreover, this approach allows decisions to be based on solid and transparent scientific evidence, promoting more efficient and effective disaster risk management.

2. A theoretical background on emergency planning for Disaster management

Natural disasters have been one of the greatest challenges that humanity has faced globally. In addition to causing significant economic losses in recent decades, their incidence has been on the rise, posing serious challenges to sustainable development across social, economic, and environmental dimensions (ZHOU & GUO., 2014). Natural disasters can be defined as the consequence of human vulnerability to natural risks, taking into account natural vulnerability as well (Ming et al., 2022). As a result, they can cause both material and economic losses, while also having interconnected environmental impacts and effects on public health (EM-DAT, 2021).

Despite their natural origins, these disasters are often caused and/or exacerbated by human activities, such as unplanned urbanization and the risks associated with climate change effects. When combined, these factors increase the likelihood of natural disasters occurring, potentially resulting in severe damages (DA SILVA; ALENCAR; DE ALMEIDA, 2020). According to EM-DAT (2021), this combination has affected approximately four billion people worldwide over the past 20 years, with 1.7 billion people impacted by hydrological natural disasters, including floods and tsunamis, followed by other disasters that also have climate change and meteorological uncertainties as aggravating factors.

Mathematical modelling of environments often synthesizes the behavior of real-life situations and therefore requires significant effort to characterize the particularities and corresponding attributes of the problem's parameters and variables (Wu et al., 2020), especially when dealing with hazardous and uncertain situations that involve behavioral variables of a group of people, different levels of vulnerability, intensity of being affected by the consequences of disasters, as well as meteorological and climatological uncertainties.

It is possible to mimic the behavior of a real system of interest using models and simulation to create scenarios that involve the planning, management, and evaluation of public policies, such as emergency situations of flood disasters, require a detailed analysis based on experiences and considering various perspectives and dimensions (Raikes et al., 2021).

According to Zhuo & Han (2020) and Koc & Işık (2020), computational simulation seeks to perform analyses of the behavior of the system under specific conditions, seeking the solution to a given problem of the real world, through the simplification of the problem in a safe environment from the risks of the real world. The author also highlights Simulation predicts the future state of a system based on assumptions about its current and future behavior.

However, it is important to analyze and understand how the Individual attributes, such as physical capabilities and perceptional judgment, are used to differentiate ability and decision-making for evacuation route selection, to incorporate the quality of flood warnings, the heterogeneous nature of human behavior in response to flood warnings, and thus build more efficient emergency plans, as well as more effective flood warnings and flood warning response systems. (IRSYAD & HITOSHI, 2022).

3. Materials and methods: a MCDM/A model based on Utility and Agent based model

3.1. *MCDM/A Model based on Utility*

The MCDM model aims to assess utility taking into account four dimensions of repercussions, based on performance indicators of the process of mass resident queuing up to seek refuge along roadways not affected by the flooding. more particularly, the project's budget for temporary housing in terms of the financial aspect. Four factors were taken into account in flood catastrophe management in order to rank and evaluate the best outcomes in terms of ability to respond to extreme disasters.

The model aims to evaluate utilities taking into account four dimensions of repercussions, based on performance indicators of the process of citizens mass queuing up and taking the flood-unaffected roadways to the shelters. the project's budget for temporary housing, more specifically, on the financial aspect. These dimensions were taken into account and are discussed below (fig. 1), in order to evaluate and rank the best flood disaster management outcomes in terms of capacity for responding to catastrophic disasters.

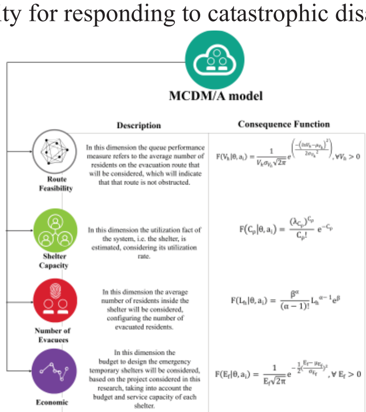

Fig. 1. Attributes and consequence function of the MCDA model.

According to Keeney and Raiffa (1993), the utility function "U" of a person or a group of people whose values are of interest is what is intended using this approach. The strategy is to break the "U" into smaller pieces, deal with them individually, and then combine them.

The scale constants for aggregating the utility functions from which the criteria can be derived can be obtained through this extremely well-structured elicitation technique. In this sense, the utility function elicitation procedure took place, initially, in a scale interval between [0,1] where "0" means the worst consequence and "1" the best consequence for the attributes of the route feasibility dimension ($\boldsymbol{V_h}$), the shelter capacity dimension ($\boldsymbol{C_\rho}$), the number of evacuees dimension ($\boldsymbol{L_h}$) and the economic dimension ($\boldsymbol{E_f}$), in order to evaluate the values of the utilities with the estimated consequences.

Therefore, analysts and experts support the decision maker by seeking to estimate $\boldsymbol{F(c|\theta, a_i)}$, with Probability Distribution Functions (PDF). By the way, this equation represents the probability of occurrence of a consequence $\boldsymbol{c}$, in a hazard scenario ($\boldsymbol{\theta}$) for each alternative ($\boldsymbol{a_i}$) that are potential candidates for emergency temporary shelter. Probabilistic modeling adds the aspect of uncertainty in a coherent way. Uncertainty is inherent to decision making in disaster risk-prone environments, and, the PDFs, in turn, are representative estimates of these probabilities. In view of the above, the PDFs were obtained, based on statistical analyses, choosing the function according to the best fit of the p-value obtained. Thus, for the dimensions of route feasibility, economy, capacity and number of evacuees, the defined PDFs below, which follow the distributions: Lognormal, Poisson, Gamma and Normal.

The benefits of selecting shelters for disaster management are analyzed in this study in a

probabilistic and independent approach, taking into account the ramifications in terms of human, economic, and operational factors. For example, it is reasonable to assume that the impacts of a period of severe rainfall in an area where riverbank regions are densely populated would have a substantial social impact since they will almost certainly result in the relocation of people as a result of geohydrological catastrophes (flooding and landslides). It is critical to have a flood warning system in place, as well as emergency rescue teams and shelters, in order to assist the afflicted people.
Given the probability of the outcomes and the utility functions for each dimension in hand, the expected utility can be determined using the following function:

$$U_{(c|\theta,a_i)} = \int F(c|\theta, a_i)\, u(c)\, dc \tag{1}$$

Whereas $\boldsymbol{c}$ is the consequence of each attribute, and $\boldsymbol{u(c)}$ is the utility estimated, used to infer the decision maker's preferences based on utility theory. The model implies that the consequence functions on the dimensions under consideration have no substantial association and can thus be calculated independently. In general, the condition of nature has a random and independent effect on the dimensions. When additive independence in the attributes is confirmed, the multi-attribute utility function might take the form of an additive function or a multilinear function. Nevertheless, the additive utility function may be expressed by Equation 2, which shows the decision maker's preferences' independence with regard to the dimensions considered:

The additive utility function can be represented by:

$$Uglobal(a_i) = K_{V_h}\,U(V_h) + K_{C_\rho}U(C_\rho) + K_{L_h}\,U(L_h) + K_{E_f}\,U(E_f) \tag{2}$$

Where $\boldsymbol{U}$ ($\boldsymbol{Eh}$,$\boldsymbol{Vh}$,$\boldsymbol{C\rho}$,$\boldsymbol{Lh}$) are the one-dimensional utility functions [0,1] and the "K's" are scaling constants that indicate the value of the tradeoff. The sum of the K's must equal 1 ($\Sigma\boldsymbol{K}=\mathbf{1}$).

3.2. *Agent Based Model Evacuation*

Evacuation decision-making is complex due to the influence of various factors on human cognition during catastrophic events.
The study aimed to comprehend the complex behavior of individuals during an evacuation in the case of a sudden flood. To achieve this, the area with shelters having the highest expected utility indexes was considered, using the MAUT-based model to measure evacuation strategy times necessary under stochastic assumptions.
The Agent-based model utilizes Anylogic Software's Georeferenced Information System (GIS) map layer, which provides real-time map data from sources such as OpenStreetMap. The agent is a key component of the model, acting as an atomic component of a generative theory that can operate independently, receive information, and conduct actions on itself and other agents. The model simulates a sudden flood along the GIS route of the river and the resulting movement of citizens to selected shelters. It integrates the GIS map, an output graph tracking the number of people warned, evacuating, and evacuated over time, as well as various variables, parameters, agents, and functions.

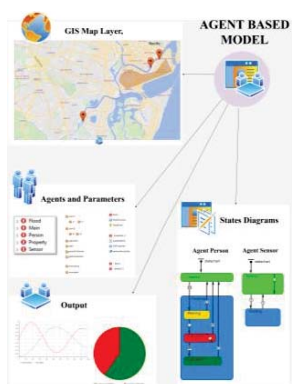

Fig. 2. Agent-based model structure

The agents in the model are Main, Flood, Person, Property, and Sensor. The Flood agent represents the behavior of the flood that will happen, in a simplified way, from the elevation of the water level of the river. Therefore, the flood will follow the route created in the GIS map and having an initial default speed, included as a property in Main. The agent was designed in order to follow the *floodFunction*, to define the movement of the flood water in the river using the variables that were defined. The agent Person - represents the people involved in the evacuation dynamics.

The speed of people will follow a Poisson distribution, with arrival rate values (λ) in a range that can be configured before starting the simulation. The behavior of this agent has states and transitions structured in a state diagram (see Fig 2), with basically the use of a warning to evacuate due to flooding. So, it is assumed that the warning is given to everyone in the community, but not everyone receives it at the same time. In addition, a resistance to evacuating has been implemented, which means that a certain portion of people evacuate while another portion decides not to, but as things get worse the number of people who decide to evacuate increases. Agent Sensor - Ideally during the occurrence of an extreme event people will receive the flood warning, which in our model will be issued by the sensor, and react to it by moving to the evacuation zone if their houses are located in the flood zone. For this, the agent will be located as a georeferenced point on the map (GIS point) (see figure 2) and its behavior is structured by a state diagram (see figure 2) to define different states of the agent. This agent is assumed to have two main states: (1) normal: when the water level is below a certain level (no flooding); and, (2) Flooding: when the water level is above the normal level and the flood warning is issued.

Once people receive the warning and their homes are located in the flood zone, they begin to prepare and then move to the pre-designated evacuation zone. They will remain there until the flood warning is lifted. When the flood warning is lifted by the sensor, the people who have taken shelter in the evacuation zone return to their homes. Agent Properties - This agent population represents the inhabited buildings in the area. The centroid coordinates of such buildings were extracted by a dataset provided by the Open Street Map GIS platform, extracting some data into a final .csv file consisting of three columns, representing the properties ID, Latitude and Longitude. The agent is started by the following initProperties function in the Main agent, then the .csv file starts the buildings in the model GIS Map.

4. Empirical Application: Results and Discussion

This model was tested against a true scenario in Recife, a Brazilian city commonly impacted by the effects of floods during the rainy season, causing significant discomfort and harm to the inhabitants. Consequently, in figure 3, the ordering of the options that offered the highest performances in terms of predicted utility were A1, A9, A4, A5, and A7, which may be regarded the evacuation region (See Fig 4)

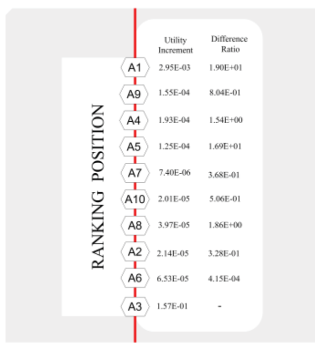

Fig. 3. Ranking of emergency temporary shelters

The region where citizens should seek refuge and protection during the flood disaster's emergency phase. The predicted utilities aid in catastrophe risk management by rating the expected utilities of temporary shelter solutions. The utility functions' interval scale (Keeney and Raiffa, 1976) permits comparisons of utility increments relative to shelters at the bottom of the hierarchy (ratio). Since the utility values are near, it is difficult to determine if the utility performance of the shelters is of extremely different or equal magnitude. Using the risk ratio, you may compare risk increments across alternatives based on the interval scale of the utility function to determine an alternative's percentage performance.

To determine if one choice is significantly superior to the others in the ranking. The risk increment is the difference in utilities between shelters at neighboring positions in the ranking, and the ratio shows the rate of perceived danger increase as the ranking rises. Because the utility function is an interval function, they are not absolute numbers, but rather rates of rise in the magnitude of utility to inform prioritizing (De Almeida et al. 2015; De Brito et al., 2016).

Figure 3 shows that when all risk dimensions are examined, A1 has the greatest risk value of the alternatives studied. As a result, the increase in risk values from option A1 to option A9 is 19 times more than the increase from option A5 to option A7.

Moreover, the results can be seen in Figure 4, spatially presented on the GIS-based map, which will be used as an input for the agent-based simulation model shown below.

Fig. 4. Geospatial distribution of MCDA model results

4. 2 Evacuation Simulation Model

For the purpose of evacuation simulation, three scenarios were established for evacuation simulation in order to explore the possibility of pre-adjusting the parameters listed in the tables below (Table 1). Due to computational effort and time required by the model, the approach of studying three different scenarios has been considered the most appropriate. The scenarios vary by the population size, according to the same distribution of arrival at shelters used in the multicriteria model dimensions (section 4.1), the resistance of the agents to evacuate, and the locomotion speed of the agents. The flood velocity parameter was kept constant to analyze only human behavior.

Table 1. Parameters of the scenarios.

Parameter	Scenarios 1	2	3
Random generation of the population	Poisson (18)	Poisson (60)	Poisson (80)
Resistance to evacuation	10 min	30 min	45 min
Flood speed	10 m/s	10 m/s	10 m/s
Person Speed	10 m/s	6 m/s	2 m/s

As a first step, a standard scenario was analyzed with a medium level of "resistance" to receive the evacuation order (Warning) and a lower resistance time rate to start the evacuation phase. The evacuation process lasts approximately 69 minutes after the warning. In this scenario, the average number of evacuees is around 20% of the non-evacuees. (Table 2).

Table 2. Results of the evacuation simulation for scenario 1

Nº	Evacuation time (min)	Evacuees	Not evacuees
1	38,93	152	722
2	49,73	150	720
3	44,66	133	728
4	43,02	140	769
5	79,59	146	810
6	53,46	163	850
7	93,26	171	880
8	102,84	175	913
9	97,10	183	951
10	88,76	189	990

In the second scenario, the probabilistic generation distribution parameter increases to 60, the resistance to evacuation warning increases to a rate of 45 min, and also the average speed of residents decreases. With this, the results showed an average of 16% over the non-evacuated population (table 3). Also, the average evacuation time also increased compared to scenario 1.

Table 3. Results of the evacuation simulation for scenario 2

Nº	Evacuation time (min)	Evacuees	Not evacuees
1	54,13	710	3408
2	52,62	542	3768
3	55,11	623	3532
4	85,88	435	3430
5	55,71	567	3731
6	103,42	564	3498
7	72,16	657	3282
8	107,73	564	3598
9	108,32	762	3684
10	107,95	435	3602

Following the same logic of increasing population parameters and resistance to evacuation while decreasing pedestrian speed, the evacuation occurred at an average rate of 17%, with not much sensitivity in relation to the previous scenario (Table 4).

Table 4. Results of the evacuation simulation for scenario 3

Nº	Evacuation time (min)	Evacuees	Not evacuees
1	89,58	910	4368
2	117,76	765	4140
3	124,17	954	4288
4	98,02	689	5159
5	101,34	904	4313
6	95,26	457	4089
7	88,84	456	4848
8	101,55	985	4501
9	113,43	654	4361
10	109,62	975	4672

It is possible to observe the sensitivity associated with evacuation time, given the heterogeneity of individual behavior when faced with a dangerous scenario (see fig 5)

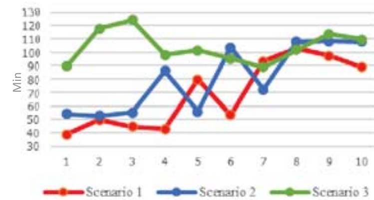

Fig. 5. Evacuation time in each scenario

Thees characteristics related to individuals' biomechanics, including their locomotion ability and vulnerability, contribute to an increased resistance rate to evacuate. When developing emergency plans to combat natural disasters, it is crucial to consider these factors to ensure successful execution. This involves taking into account not only deterministic variables such as weather and climate, but also probabilistic variables, which often play a decisive role in the success or failure of flood response operations.

So, it is noteworthy that the importance of simulating extreme events to assist public managers in analyzing the complexity of agent behavior in a given scenario, and consequently, providing a basis for constructing public policies that mitigate risks, as well as preparing, in terms of measures, to respond to disasters.

5. Remarks

This paper proposed a hybrid method, with adaptable models capable of aiding in disaster-related decision-making. Planning is required in severe scenarios to give more operational agility to adapt swiftly to the fast changes in demand and supply caused by the catastrophe scenario. When combined with agent-based modeling, the multicriteria method appears to be even more appropriate in emergency scenarios induced by geohydrological events, since it takes into account the varied effects of floods on the operation of urban environments.

In practice, modeling helps to reduce the risk and magnitude of disaster impacts while also sharing benefits with all stakeholders in the urban area by providing coherent recommendations based on more robust results, as well as other uses for the decision model, such as evacuation policy analysis and the creation of training scenarios.

As a consequence, the decision maker may conduct an in-depth examination of the range of options, from which solutions to undertake preventative and planned activities benefiting the urban community can be chosen.

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