Modeling Realistic Human Behavior in Disasters. A Rapid Literature Review of Agent-Based Models reviews

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Abstract. Agent-based models of human behaviors in emergencies are extremely important in prevention, preparedness, response and mitigation of crises. However, there is huge variation in the modeling of human cognitions and actions, with varying degrees of realism and even more diverse definitions of how realism should be implemented in the models. The aim of this Rapid Literature Review is to identify existing patterns in modelling realistic behaviours in simulation models of disasters and crises, but also to identify gaps in existing literature on the basis of a qualitative assessment of review papers on the topic. We analyze eight papers (identified through a search of 68 papers in the Scopus database) that review ABM models designed either to investigate general behaviors in emergencies (i.e., evacuations) or reactions to specific crises (i.e., Covid-19). Our analysis shows that while all the papers agree in advocating for more realism in modeling human behavior, very little has been done in terms of designing agents, interactions and environments that can be considered realistic.

Keywords: Agent-based Model · Crisis · Disaster · Human behaviour · Rapid Literature Review · Realism.

1 Introduction

In the last 20 years there has been a steep increase in the frequency and intensity of disasters worldwide. Such an increase originates in the growing global interconnectedness, the impacts of the climate crisis, the increasing geopolitical risks,

but also more local factors such as the expansion of urban development in areas prone to seismic, volcanic, and flooding hazards, combined with existing vulnerabilities to weather hazards (heatwaves, wildfires, heavy rains, rising sea levels, drought, and floods). If the current trends continue, the number of disasters per year globally may increase from around 400 in 2015 to 560 per year by 2030 -– a projected increase of 40% during the lifetime of the Sendai Framework [8]. A **disaster** is "a serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts" [9]. The consequences of disasters extend beyond the immediate time frame of the event, and they can trigger long-term **crises**, but the two terms are often used interchangeably [1].

The use of computer simulations in the field of disaster preparedness is not new [2, 21] and the opportunity to model and simulate past events, ongoing disasters, and to identify trajectories of new crises is essential for researchers, practitioners, and policy decision makers. There are several reasons to use Agent-Based Models (ABMs) to model disasters. First, disasters are complex events that involve the interaction of several psychological, social, organizational, and institutional processes. For instance, in the course of an evacuation, citizens can disregard the instructions of the first responders (e.g., by adopting dangerous behaviours to save loved ones) and this can jeopardize both their own safety and the safety of responders. At the same time, citizens' responses can be affected by their trust in institutional communication about risk, but also by the influence of their network or their own personal perception of risk [12]. Second, ABMs can help generating unimaginable trajectories and suggest emergent outcomes that cannot be linearly predicted on the basis of the input variables. These "artificial societies" [11] offer a powerful tool to recognize, understand, and model interacting physical and social processes triggered by crises and disasters. Third, ABMs allow to "experiment" with disasters that have not happened yet (prospective simulations), but also to use existing data and information to create retrospective models of past disasters.

There are several problems that limit the applicability and success of ABM in disaster situations. For instance, while a major crisis might lead to a "flourishing" of models of the crisis, each simulation study is different and hard to compare with the other studies. For instance, a search on Google Scholar with the keywords <agent-based model AND tsunami> returned 49 results between 2000-2003, but the number of papers published on the same topic increased to 269 in the three years after. This indicates that the occurrence of the 2004 Indian Ocean earthquake and tsunami was a turning point in the simulation of that kind of crisis, with a steep increase in the number of models of that specific event. A more recent case is the Covid-19 pandemic, which has triggered the development of several different pandemic models (e.g., [7, 23]), each of them designed with different parameters, rules, and outcomes. An additional variation comes from the fact that models of the same catastrophic event can also differ with regard to which of the four different phases of the emergency management cycle

is modelled. Mitigation (preventing future emergencies or minimising their effects), preparedness (preparing to handle an emergency), response (to minimise loss and damage), and recovery (to return to safety) require different agents, interactions, and environments, adding even more alternatives to the modelling possibilities. This diversity in objectives, features, and measures of ABMs can be a blessing (flexibility, richness), but it is often a curse (fragmentation, robustness), as attempts at distinguishing between modelling purposes [10] or at introducing standard protocols [13] show.

In this paper, we focus on one specific limitation that we argue to be especially relevant when modeling disasters and crisis: the lack of psychological, behavioural, and social realism. We argue that models should be able to display relevant behavioural diversity and be suitable for a particular disaster context, rather than using a default model of human behaviour. The importance of realistic models has been advocated by several authors indicating that we need to argue and question for our decision model fit [25], specifically in the context of modelling human behaviour in, for example, fisheries management [24, 16] or human migration [15]. We will not address the conceptualisation of realism in agent-based modelling as such, but we are interested in assessing what is considered "realistic" in ABMs of human behaviours in disasters. This means that the models should contain and report on a set of theoretically grounded and empirically plausible (if not validated) assumptions about the way in which agents (individuals, households, organisations, or communities) perceive the situation (Is it dangerous? What are the risks?), make decisions (Do I trust warning messages? Do I follow emergency responders' instructions?), behave (What are the escape routes? Do I wait for others or do I evacuate the area?), and communicate with other agents (Am I informing others about the risks?).

The aim of this Rapid Literature Review is to identify existing patterns in modelling realistic behaviours and their underpinnings in models of disasters and crises, but also to point out gaps in existing literature on the basis of a qualitative assessment of review papers using ABMs of disasters/crisis. The research question is: "What do we model when we model realistic human behaviour in simulations focusing on disaster resilience?". We refer to resilience because we are not interested in one specific phase of the disaster cycle, but rather on the use of models to address any challenge related to disasters and crises.

We decided to focus on reviews of existing models, because we are interested in knowledge mapping and consolidation. We aim to offer ABM modellers an overview of consolidated knowledge they can tap into, but also to highlight frontiers, challenges, and opportunities for collaborations. Scholars in disaster studies might benefit from this review to get a glimpse of the possibilities offered by modelling and simulation, in the hope that new and fruitful collaborations will blossom.

2 Method

A Rapid Literature Review (RLR) was employed to answer the research questions. A RLR is a structured, transparent, and reproducible process to identify, select, critically appraise, and synthesize documents meeting pre-specified eligibility criteria in a timely manner [4]. In this study we have used the RLR phases described in [4]. As mechanisms to expedite the review, we have limited the search strategy and have paralleled review tasks such as eligibility screening, data extraction, and data synthesis.

The search was performed on 21.04.2023, using one single database, i.e., Scopus, which is an abstract and citation database of peer-reviewed scientific literature produced by Elsevier Co. The search was limited to reviews and to English language documents. No other restrictions were used. We did not limit our search to journal articles because in several disciplines conference papers are as important as journal publications. Three inclusion criteria were used: the document should be a review of ABMs, the ABMs should be of crisis or disaster, and the ABMs should include human behaviour.

Based on this search strategy (summarised in Figure 1), the search query was the following:

TITLE-ABS-KEY ((disaster OR crisis) AND (abm OR agent-based AND model*) AND review)

The broad screening of titles and abstracts was performed by only one of the co-authors. All of the co-authors participated in the paralleled strict screening of full-text articles passing the broad screen. All of them participated in data extraction, which was performed following a coding scheme developed based on the research questions, and in data synthesis. The coding scheme included codes related to the type of crisis/disaster, disaster cycle, realism, and modelled human behaviour. In order to ensure intercoder reliability, the coders checked each other's coding and discussed it.

3 Results and discussion

3.1 Metadata

As explained above, eight papers have been included in the in-depth analysis and synthesis phase. These papers are listed in Table 1. Five of these papers are published after 2020, the year of the most recent worldwide crisis, i.e., the Covid-19 pandemic. On average, there are three authors per publication, with all but one paper having two or more authors, something that is expected both in the case of reviews and of multi/inter/trans-disciplinary research (which we assume disaster-related research to be). One third of these publications are journal articles, while two thirds are conference papers. Three of the analysed papers were published in venues from the geosciences and physics domain; two in engineering; two in computer sciences; one in a social simulation outlet; and one in a venue focused on crisis response and management. This variety might reflect

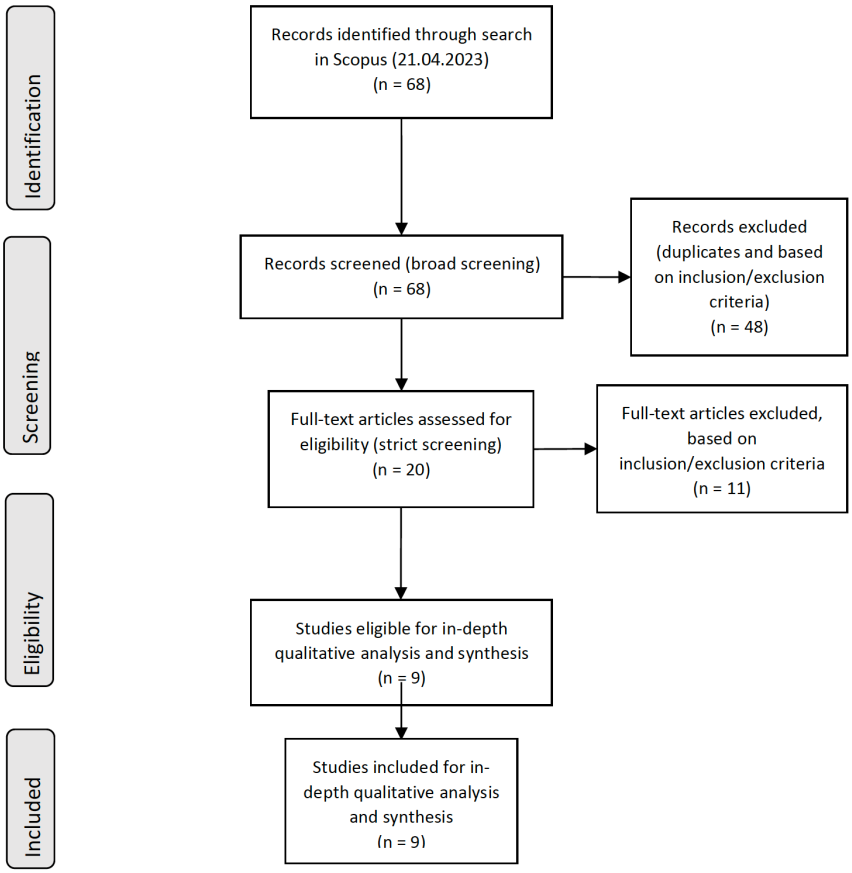

Fig. 1. Prisma Diagram, adapted from [20], describing the process of selecting the publications suitable for this analysis.

the multi- and inter-disciplinarity of the literature on disasters and crises, but also the diversity of the simulation community.

3.2 Summaries of and reflections on the review papers

The coding schemes were independently applied by the four co-authors, who then compared and discussed their notes. Our main question was:"how is human behavior modelled and what do the models consider realistic human behavior?" More generally, when analyzing the papers we observed two general trends regarding what is modelled. Either these papers reviewed existing models of human reactions to a specific hazard (tsunami, earthquake, floods), or they focused on a specific response (such as evacuation) regardless of the hazard, .

Zhou [26] reviews the development of diverse applications of agent-based pedestrian modeling and simulation, with specific attention for: (1) transporta-

Year	Reference	Publication venue
2008	[26]	Geoinformatics 2008 and Joint Conference on GIS and Built Environment: Geo-Simulation and Virtual GIS Environments
2015	[18]	Pure and Applied Geophysics
2017	[3]	International ISCRAM Conference
2021	[6]	Journal of Physics: Conference Series
2021	[17]	Journal of Artificial Societies and Social Simulation (JASSS)
2021	[22]	Lecture Notes in Computer Science
2022	[5]	IGARSS - International Geoscience and Remote Sensing Symposium
2022	[14]	Archives of Computational Methods in Engineering

Table 1. Overview of the publications included in the in-depth analysis and synthesis

tion planning in pedestrian facilities, (2) planning and design of urban space, (3) crowding, evacuation, and disaster management, and (4) commercial activity organisation and shopping behaviour. Their main take away is that the proposed models and simulation systems are still immature (in conceptual stages) and not suitable for practical decision making. A few years later, **Mas [19]** published a review on the topic of response in case of tsunami evacuation. The ABMs included in this review focus on path-finding or route-planning behaviour for evacuation. Behavioral *realism*, according to the authors, manifests as follows: "increases in computational power have enabled the analysis of large amounts of data and have made it possible (...) to improve realism in pedestrian dynamics and collision avoidance behavior".

Even if these two review papers focus on evacuation, their interpretation of realism is quite narrow: [26] offers no detailing of nor reflection on human behavioral realism, but rather suggests that ABM has the potential to represent human behaviors in a more realistic way. They do see an opportunity in the increasing availability of individual-level tracking data, in particular for GIS to complement the agent-based modeling and simulation of pedestrian movements. The author seems to hold the assumptions that more individual level data will enable to understand more of how humans behave and to better approximate behaviors. However, what is missing in the conclusions is that distinctly different situations may arise, and that very low frequency disasters may need to rely on some realistic core mechanisms in simulations to be able to develop and engage in contextually new situations. Similarly, in [19], the authors advocate the use of real and virtual big data (cloud gaming) to create a library of human behavior in evacuation scenarios, but also to complement that with big data collected in real time.

A different approach to realism in modeling evacuation behaviors in emergency situations is proposed by **Rollan et al. [22]**, who reflect on crowd cognitive models for disaster management. The authors describe models that formalise emotions and/or personality: *Among the aspects of a realistic crowd evacuation simulation are the involvement of the influences of emotions and personality*

traits [3–8], knowledge, and roles [9, 10] to behavior and decision-making. A main conclusion of this paper is the need for an integrated, comprehensive, and standard emergency management system regardless of disaster type, incorporating human cognitive aspects to improve realism. Realism in this work is related to the influence of emotions and personality traits, knowledge, and roles on behavior and they even propose a framework of a cognitive model for disaster management, bringing together the different insights on behavioral realism.

Kaur and Kaur [14] in their systematic review of various types of models for evacuation management in disaster situations distinguish between models at the macroscopic (evacuation as a continuous flow), microscopic (evacuation as a bottom-up process of interacting individuals and their environment), and mesoscopic level. Here, ABMs are described as part of the microscopic level and the authors believe that the influence of psychological, physiological, and behavioral characteristics can be studied using ABMs. This review does not define nor reflect on human behavioral realism, not even in the limitations suggested by the authors. They identify three main shortcomings of current models of evacuation management:

- the small number of subjects involved in experiments to find optimal strategies for evacuation and limited coverage of large data sets to test evacuation strategies,
- limited testing of different models within one study, and
- limited number of events per disaster - no single model can cover all possible events accurately.

A similar lack of attention for realism in modeling human behavior is also present in **Chiew** [6], who offers a short overview illustrating how ABM can be used in different emergency scenarios, from preparededness and adaptation to floods to the management of Covid 19. A more in-depth analysis of agents' behaviors is offered by [5], which concerns models of flood risk management, considering different aspects of it (Participatory Simulations; Evacuation Simulation Model; Flood event simulation; Specific perspective on flood risk), but mainly focusing on evacuation. The authors argue for more flexibility and adaptability in ABM models by including flood events, realistic representations of the environment, simulation of resident behaviour, various evacuation strategies, and control of infrastructure degradation in order to contribute to a better Integrated Flood Management system. However, realism in human behaviour is not explicitly mentioned, and the authors instead suggest to focus on realistic modeling of the environment, including social networks and communities.

Among these reviews on evacuation, there is one paper that stands out in terms of the attention devoted to psychological realism in disaster modeling. **Bangate et al. [3]** review existing ABMs in evacuation with the goal of identifying two main shortcomings in the literature: the lack of realism in modeling social and psychological factors in evacuation models, and the unrealistic assumptions about mobility characteristics of the agents: *Most evacuation research is based on the mobility of able-bodied adults (Larusdottir and Dederichs, 2011). Therefore the developed plans are unrealistic, as they do not include the*

mobility of physical disabled persons, children etc., which comprise substantial portions of the population. The paper presents a review of different ABMs of social attachment during crises with the aim of developing a strong foundation to build ABMs for crisis scenarios. The authors conclude that group dynamics and strong ties are two missing elements in current models, and they propose to apply existing psychological theories to ABMs of evacuation behaviour.

We can conclude that these review papers of evacuation models, either related to a specific disaster or in general, tend to agree on the need for further improvements of behavioral realism in existing models. Some authors (e.g. [26, 18]) seem to believe that the availability of larger and more diverse kinds of data will by definition improve the realism of existing evacuation models. Others (e.g. [6, 5, 14]) hint at the need for a more fine grained modeling of agents' cognitive models, actions, and interactions with the environment. The only paper in our sample that explicitly addresses not only what is missing, but also what can be added to models of evacuation to increase realism is [3]. They highlight what the state of the art in agent-based models of evacuation is in terms of integrating social and psychological aspects of human behavior and they add an interesting discussion on the psychological foundations of group dynamics and strong ties.

Regarding reviews of human behaviors in the context of a specific hazard, the recent Covid-19 pandemic has inspired many scholars to develop ABM of behaviors during the pandemic. Probably because of the diversity in the kind of hazard modeled, the review on models developed in response to the Covid-19 pandemic offers a very different perspective. **Lorig et al. [17]** provide a Systematic Literature Review focused on the response to the Covid-19 pandemic in the period 2020-2022. This study reviewed 126 articles that describe ABMs of Covid-19 transmission processes and it points out that existing models are very heterogeneous in multiple respects. The fact that most of the models were developed while the pandemic was still ongoing and some of them also aimed for providing suggestions to policy decision makers resulted in huge variation in modelling purpose, number of simulated individuals, and granularity of location, as well as transmission dynamics, disease states, human behavior, and interventions. The authors stress the importance of realistic modeling of human characteristics (psychological, social, physical), but they also remark in their conclusions that: *Most models 90.5% include simplistic models of human behavior, where decisions and actions are mainly random with predefined spatial or social networks. Some models, however, include more sophisticated models of human decision-making that make use of individual schedules, needs, or utility functions.* The authors conclude their review with a selection of challenges, from the need for real-world data to the lack of expert knowledge to verify model assumptions and results to the trade-off between complexity of the individuals and the number of individuals that are simulated.

4 Conclusion

The heterogeneity of review methods, models, contexts, types of disasters, and purposes of the reviews we analyzed makes it difficult to draw general conclusions. However, there are a few trends emerging from our analysis of these eight articles. First, most models that were reviewed include rather simplistic models of human behavior, even if there is consensus that ABMs of human behaviour in disasters and crises can benefit from more realism concerning psychological, social, and interactional characteristics of the agents and of the context. Agents have limited behavioural repertoires, often lack any cognitive mechanisms and they are rule-based, with a general lack of attention to agents' diversity in individual characteristics that may matter during an evacuation, for instance mobility, psychological traits, age, and gender, or to their social relationships. A second conclusion mentioned by most of the authors is the need for more real data, either to inspire the models or to calibrate them. Data about real mobility patterns, individuals' preferences and behaviours in emergencies, or the efficacy of Non-Pharmaceutical Interventions (NPIs) during a pandemic are advocated as essential to increase realism and to make the models more reliable. Although reasonable, this conclusion is more problematic than it might seem for many reasons. First, it is not enough to ask for more data, but it is important to gather data that are better suited for a specific purpose, ideally in line with the simulation purpose. Second, having more data is not the same as having good behavioural rules, but more importantly, it does not allow for anticipating different situations that have not occurred in the past. This results in a limitation of what behaviours the agents can display, which renders a simulation useless as soon as the people in the real word really start behaving differently. In addition, models based on large-scale real world data require a trade-off between complexity of the agents and the number of agents that are simulated. This is not only due to technical or computational limitations, but also to the mere fact that a model with too many parameters makes understanding of the underlying processes and of the results extremely difficult (and potentially fallacious). Third, many articles lament the lack of connections between modellers, practitioners, and decision makers. Practitioners can provide expert knowledge on the disasters and people's reactions that can be modelled in a more realistic manner which makes models more relatable and usable by decision makers.

This rapid review of modelling human behaviour in disasters and crises is obviously limited because of our focus on reviews of ABMs, which implies that we are relying on others' assessment of existing models rather than assessing these models ourselves. Our selection is also limited because only one paper was published in a venue read by people in disaster studies, which means that we might have missed many reviews of ABMs of human behavior published in the disaster literature. We plan to conduct a systematic review in the future in which a larger number of academic databases will be included, controlling for the representation of relevant research areas, but also using different search strategies (e.g., snowballing) with the goal of providing a grounded overview of

current knowledge and open questions about the modelling of human behaviors in emergencies, an endeavour that is becoming more and more urgent.

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