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Enhancing Disaster Evacuation Planning with Cognitive Agent-Based Models and Co-Creation

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ABSTRACT:
Agent-based models (ABMs) are increasingly used in disaster evacuation simulation to capture system-level dynamics. While ABMs are often combined with human behavior models (HBMs), few approaches integrate these with infrastructure and demographic data that are carefully modeled using local knowledge, along with hazard-specific impacts and policy settings. Even fewer embed this integration within a co-creation loop that involves local stakeholders throughout the entire development lifecycle, from conception and design to implementation, testing, and beyond. This paper introduces the methodology that we developed to address this gap by combining a structured co-creation process with technical simulation development. The co-creation process engages local stakeholders, planners, and experts to iteratively shape evacuation scenarios, define assumptions, and validate outcomes, ensuring the model aligns with local realities. These inputs are translated into a multi-dimensional simulation framework built in MATSim, integrating network and infrastructure models, hazard effects, population, and behavior modeling enhanced through Belief-Desire-Intention cognitive architectures. We applied this methodology in different case study areas, demonstrating its capacity to simulate heterogeneous evacuation dynamics and provide diverse performance metrics. Finally, we explore how this methodology can be applied in other hazards, geographic regions, and evacuation scenarios, offering pathways for broader application and future development.

Keywords: Agent-Based Models, Human Behavior Models, Co-creation Processes, Disaster Evacuation Simulation, Disaster Preparedness

1. Introduction

Effective emergency evacuations after hazards such as earthquakes, floods, and wildfires are crucial for reducing casualties and ensuring public safety (Jiang, 2021). The success of evacuations depends on multiple interdependent factors, including hazard intensity, the resilience of critical infrastructure (roads, buildings, etc.), demographics of affected populations (age, gender, dependencies, disabilities, etc.), behavioral tendencies, and the effectiveness of evacuation policies (Bakhshian & Martinez-Pastor, 2023; Khan et al., 2020). To take these factors into account, and given the inherent uncertainty of hazard

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impacts, we must rely on computational models to simulate and evaluate how evacuations unfold in practice. One widely used approach is Agent-Based Modeling (ABM), which allows for representing individuals as autonomous entities with distinct characteristics and decision-making processes, and the ability to adapt to changing circumstances and conditions (An, 2012). While this approach has gained widespread attention, current models still struggle to capture the full complexity of real-life evacuations and remain limited in integrating behavior, infrastructure, and hazard-specific constraints into a cohesive framework (Moradi, Iskandar, Rodriguez, Singh, Dugdale, Tzempelikos, Sfetsos, et al., 2025).

Reviewing previous studies (Senanayake et al., 2024) shows that current ABM approaches designed to simulate evacuation processes face several critical limitations that compromise their accuracy, realism, and practical applicability in real-world settings. These limitations can be summarized as follows:

- **Limited Integration of Infrastructure, Hazard, and Policy Constraints**: Many existing models incorporate some aspects of hazard impact, demographic data, or infrastructure networks, but often in fragmented ways. They fail to systematically link infrastructure disruptions, transportation constraints, hazard effects, and policy settings into a cohesive simulation. This fragmented approach limits the ability to evaluate the dynamic interactions between physical systems, population movements, and emergency response measures, reducing the realism and usefulness of the simulations for practical evacuation planning.

- **Overly Simplistic Behavioral Assumptions:** Many simulations assume that individuals act primarily out of fear or self-interest during evacuations (Bracha, 2004), or they rely on simple rule-based or uniform behavioral models that overlook the variability of human behavior across social, cultural, and environmental contexts (Senanayake et al., 2024). However, research shows that evacuation decisions are shaped by a complex interplay of factors, including individual characteristics, social dependencies, cultural background, prior experience, and perceived risk, all of which significantly affect evacuation outcomes and must be explicitly represented in models (Wang et al., 2021).

- **Lack of Integration with a Co-Creation Process**: Many models are developed in isolation by technical teams, without systematically involving local stakeholders, practitioners, or experts throughout the model development cycle. This limits the relevance of simulation assumptions, weakens stakeholder buy-in, and makes it difficult to ensure that outputs align with local needs, constraints, and decision-making processes (Ramaswamy & Ozcan, 2018).

- **Limited Support for Collaborative Communication through Simulations:** Even when simulations are developed, they often lack the capacity to present the process, assumptions, and outputs (including videos) in ways that are accessible and understandable to diverse audiences, including technical experts, decision-makers, and local communities. This limits the use of simulations as tools for collaborative dialogue, shared learning, and informed decision-making, reducing their value as platforms for building mutual understanding and improving preparedness.

Having identified these gaps, this paper presents a consolidated synthesis of the methodological and empirical work carried out within the C2IMPRESS (Co-Creative Improved Understanding and Awareness of Multi-Hazard Risks for Disaster Resilient Society) project, building on the approaches and findings from our earlier studies (Moradi, Iskandar, Rodriguez, Singh, Dugdale, Tzempelikos, & Sfetsos, 2025; Moradi, Iskandar, Rodriguez, Singh, Dugdale, Tzempelikos, Sfetsos, et al., 2025). Here, we focus on demonstrating how the integrated application of agent-based simulations, human behavior modeling, co-creation processes, hazard modeling, and infrastructure and policy constraints can meaningfully address the limitations identified in existing evacuation studies. By drawing on lessons learned from real-world case studies, including earthquake scenarios in Egaleo and flood and wildfire scenarios in Mallorca, this work offers a comprehensive perspective on the practical value, challenges, and potential of using such combined approaches to support evacuation planning, stakeholder engagement, and disaster preparedness across diverse hazard contexts.

To test this approach, we applied our methodology to two case study areas: Egaleo, Greece, a seismically active urban area exposed to earthquake risk (Lekkas, 2001), and the municipalities of Sant Llorenç and Canyamel in Mallorca, Spain, which have a history of flash floods and wildfires. These locations were selected for their diverse hazard profiles, urban complexities, and available demographic and infrastructure data, providing a suitable setting to demonstrate how the proposed simulations capture the interaction between hazard effects, evacuation behaviors, and local policy settings, and how they can inform urban disaster preparedness.

The remainder of this paper is organized as follows. Section 2 reviews relevant research on agent-based evacuation modeling, human behavior modeling, and co-creation processes. Section 3 outlines the methodology for defining simulation scenarios, developing multi-dimensional models, and implementing the co-creation loop. Section 4 presents the results of applying the framework in Egaleo and Mallorca. Section 5 discusses the findings, implications, and directions for future research. Finally, Section 6 summarizes the key contributions and offers recommendations for practice.

2. Research Background

Early evacuation models focused primarily on physical dynamics and spatial constraints, particularly methods such as the *social force model* (Helbing & Molnar, 1995), which simulates movement based on how people interact with their environment. Even though such approaches are good at modeling aggregate movement patterns and, therefore, have been widely applied to analyze crowd flow (Chen et al., 2018; Zhang et al., 2018), they don't capture the complex individual and social behaviors observed during real-world emergencies (Zhao et al., 2021). As research increasingly highlights the influence of psychological, social, and contextual factors on evacuation dynamics (Zhao et al., 2021), there has been a growing shift towards ABMs (Senanayake et al., 2024). Under ABM, agents can behave in a variety of ways and make adaptive decisions in dynamic environments, making them particularly well-suited for simulating urban evacuations under different hazards, where behavioral variability, hazard impacts, and infrastructural disruptions interact in complex ways (Cimellaro et al., 2017). It should be noted, however, that in parallel with this shift, recent advances in machine learning have also shown potential for incorporating behavioral heterogeneity by predicting evacuation dynamics based on large-scale data sources (Sun et al., 2024). While these models offer strong predictive capabilities, they often require extensive training datasets and provide limited transparency into the underlying decision processes, making them less interpretable and harder to adapt across diverse local contexts (Kyrkou et al., 2022). Given these constraints, we adopt an agent-based approach to ensure interpretability and adaptability across different settings.

Building on these advantages, several ABM-based simulators have been developed to capture evacuation dynamics under specific hazards. For example, EPES (Quagliarini et al., 2014) incorporated earthquake-specific behavioral rules into traditional pedestrian movement models, but its reliance on static, predefined behaviors limits its ability to reflect the dynamic and complex decision-making observed during real evacuations. Addressing these behavioral limitations, SOLACE (Bañgate, Dugdale, Beck, et al., 2017) and PEERS (Iskandar et al., 2024) advance realism by integrating social attachment theory and leader-follower dynamics through the BDI framework, alongside hazard-related mobility disruptions. However, PEERS, in particular, is computationally demanding, restricting its scalability for large urban areas. Prioritizing computational efficiency, IdealCity (Battegazzorre et al., 2021) focuses on infrastructural and mobility system performance in city-wide simulations but underrepresents behavioral diversity and social interactions. For instance, frequently observed behaviors such as returning to locate dependents before seeking safety together (Bañgate, Dugdale, Adam, et al., 2017) are absent from IdealCity. Collectively, these models provide valuable insights into specific aspects of evacuation under individual hazards. However, such platforms still face challenges in simultaneously capturing realistic human behaviors, infrastructure constraints, hazard-specific impacts, and policy settings, while ensuring the computational efficiency needed to support multi-scenario analyses for preparedness and response across different hazard types.

To efficiently represent the heterogeneous decision-making processes observed during evacuations, the authors in (Singh et al., 2016; Singh et al., 2019) integrated the BDI framework into the MATSim agent-based simulation platform. This integration empowers agents with a cognitive layer, allowing them to reason dynamically, adjust plans as conditions change, and pursue complex goals, such as coordinating with dependents and seeking safety (Bulumulla et al., 2017). While this approach led to the development of the Emergency Evacuation Simulator (EES) (Singh & Padgham, 2017), advancing behavioral realism and decision-making flexibility, prior implementations still lack comprehensive representations of several critical factors. These include the specific needs of vulnerable populations, the integration of multi-hazard impacts (such as earthquake, flood, and wildfire), the influence of local policy settings, and the collaborative involvement of stakeholders throughout the simulation process. This study aims to address these limitations by advancing a unified evacuation modeling framework that better captures the interaction between human behavior, hazard impacts, infrastructure constraints, and co-created policy assumptions across diverse hazard contexts.

3. Methodology

To address the limitations identified in previous studies and implement our proposed approach, we developed a three-part methodology consisting of: (1) a co-creation process that grounds simulation development in stakeholder knowledge; (2) a structured simulation framework that translates participatory inputs into model components; and (3) an implementation layer that operationalizes the models using a cognitive agent-based platform. Before detailing each of these components, we first provide a high-level overview of how they interact to form a coherent simulation development cycle.

3.1. Overview

As introduced earlier and visualized in Figure 1, the methodology is composed of three coupled components (i.e., co-creation, simulation design, and simulation execution) that operate in synchrony. Each component plays a distinct role, yet they are designed to drive one another forward through iterative cycles of development, feedback, and refinement. This configuration enables the methodology to respond flexibly to new data, stakeholder insights, or contextual constraints without requiring fundamental redesign. The resulting structure supports both tailored scenario development and generalizable modeling across diverse hazard settings.

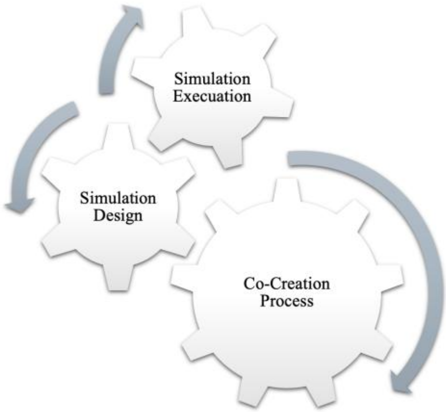


Figure 1. Overview of the Core components of the simulation methodology.

In this mechanism, the co-creation component involves the structured engagement of local stakeholders to define assumptions, constraints, and evaluation priorities. These insights inform the simulation framework, which organizes input data and behavioral models into formal structures representing hazards, infrastructure, policy settings, and population demographics and characteristics. The simulation execution component operationalizes this framework using agent-based and cognitive modeling tools, whose outputs can also serve as new inputs for subsequent iterations.

With respect to the latter point, it should be noted that what distinguishes this methodology is its emphasis on bidirectional translation: stakeholder feedback informs technical implementation, while simulation outputs return as communicative tools for stakeholder reflection and refinement. This dual movement enables the simulation to evolve through successive iterations, maintaining fidelity to real-world conditions while expanding its analytical utility. The methodology thus functions not as a linear pipeline, but as a coordinated reasoning system in which each component actively supports, adjusts, and refines the others within a unified simulation environment.

3.2. Co-creation process

Co-creation is a structured participatory method through which stakeholders are actively involved in the development and refinement of systems, policies, or tools (Frow et al., 2015). It allows for capturing local knowledge, operational constraints, and lived experiences that might otherwise be missed in top-down or expert-only approaches (Ramaswamy & Ozcan, 2020; Trischler & Charles, 2019). In the context of evacuation modeling, co-creation ensures that simulation scenarios are not only technically valid but also context-specific and grounded in the practices and priorities of those responsible for managing real-world emergencies (Voinov et al., 2016; Whybark, 2015). It supports the alignment of simulation assumptions with both expert understanding and community-based insight, which is essential for applicable multi-hazard evacuation planning.

In this study, as shown in Figure 2, the co-creation process is used to iteratively design and validate simulation scenarios. It functions as both the entry point and return loop within a continuous, iterative development cycle, ensuring that stakeholder insights inform each stage of the modeling process and are continuously integrated as the simulation evolves. It guides the design of the simulation framework by transforming stakeholder input into validated scenario components and design requirements. These requirements then inform the structure of simulation elements, including behavioral logic, hazard settings, infrastructure disruptions, and policy constraints, which are implemented in the simulation platform.

Once implemented, the simulation produces outputs that are returned to stakeholders in the form of visualizations and performance indicators. These results serve not only as a basis for technical refinement but also as boundary objects that facilitate structured dialogue, shared understanding, and collaborative evaluation among stakeholders. Through these interactions, co-creation enhances the transparency and credibility of the simulation, promotes stakeholder ownership of the scenarios, and supports informed decision-making. In this way, co-creation is not limited to scenario generation but becomes a sustained mechanism for aligning the simulation framework with domain expertise, local priorities, and evolving operational needs.

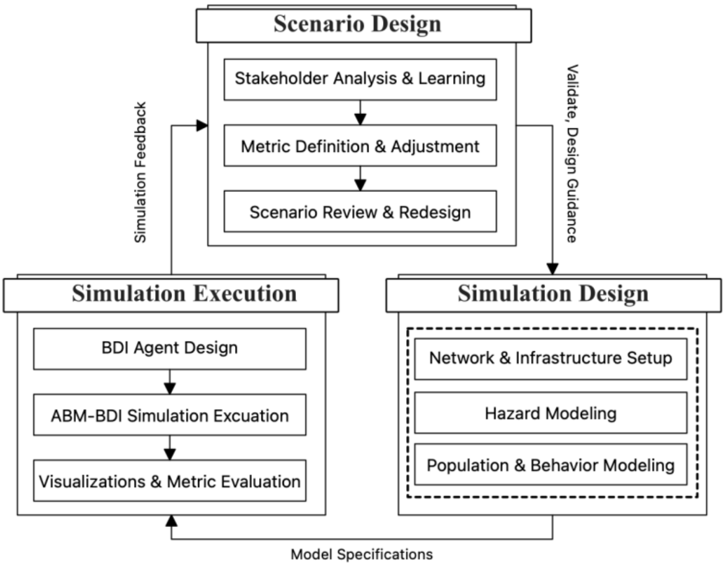


Figure 2. Overview of the co-creation process in different simulation steps.

Note here that, in practice, the co-creation process occasionally surfaced diverging stakeholder views. Such differences were addressed through follow-up workshops in which inputs were collaboratively revisited, prioritizing inputs that were supported by multiple participants and feasible within the simulation constraints. Although no formal conflict-resolution mechanism was adopted, this iterative and transparent process proved effective in building consensus and credibility among participants. That said, balancing subjective stakeholder insights with empirical evidence (especially in politically sensitive or contested contexts) remains a methodological challenge. We therefore highlight this as a key area for future refinement, particularly when replicating or scaling the framework across more complex governance settings.

3.3. Simulation design

The simulation framework provides a structured approach for translating co-created evacuation scenarios into executable models within the agent-based simulation environment. It serves as the intermediate layer between participatory scenario development and simulation execution, ensuring that local context, stakeholder priorities, and system dynamics are captured through formal representations. The framework is organized into three core components (see Figure 2): Network and Infrastructure Setup, Hazard Modeling, and Population and Behavior Modeling , each corresponding to key dimensions defined during the co-creation process, and together they translate participatory inputs into a structured, simulation-ready model.

The Network and Infrastructure Setup component defines the spatial environment and mobility pathways within the simulation. It involves extracting topological and geometric data from sources such as OpenStreetMap to construct a routable transportation network, including road segments, intersections, and access points to safe places. This base network is refined in collaboration with local stakeholders to reflect real-world constraints, including local parking behaviors, and road-specific conditions such as one-way restrictions or partial access. Road attributes (such as speed limits, capacities, and functional classifications) are encoded into the network graph and used to support routing, congestion modeling, and capacity analysis. In addition to physical mobility infrastructure, this component also incorporates the spatial configuration of Early Warning System (EWS) zones, which define where and when alerts (e.g., Advice, Watch and Act, Evacuate Now, etc.) are activated. These zones should be specified based on the current capabilities and protocols of each case study area, allowing the simulation to reflect heterogeneity in EWS deployment and coverage.

The Hazard Modeling component integrates disaster impacts into the simulation environment by modifying the capacity, accessibility, and functionality of pathways across different hazard types. This includes modeling physical disruptions such as blocked or partially obstructed roads due to earthquake debris, floodwater, or wildfire spread. In each case, road segments are assigned varying levels of disruption or capacity loss, enabling the simulation to represent a continuum of road and network functionality instead of relying on binary open-or-closed assumptions. These physical disruptions are further shaped by policy interventions, such as EWS, evacuation schedules, or safe zone assignments. In the simulation, such policies influence agent decisions by altering their perceived risk, available destinations, or departure timing, rather than imposing fixed routing rules. Because agents follow diverse decision-making styles based on their archetypes and context-specific beliefs, not all respond uniformly to policy signals. This enables the simulation to explore how regulatory measures interact with infrastructure disruptions, and whether certain policies alleviate or exacerbate congestion and delays in real-world scenarios.

The Population and Behavior Modeling component defines the agents and integrates behavior logic in accordance with what individuals are expected to do during evacuation, based on local policies, social norms, and prior experiences. Population data, including household composition, age, mobility status, and dependency relationships, is drawn from local demographic sources and used to generate a synthetic population that reflects the structure of the real community. To incorporate decision-making processes and behavioral diversity, we adopt the archetypes approach proposed by (Strahan et al., 2018), which models shared behavior patterns based on demographic, social, and psychological characteristics. Each archetype represents a distinct decision-making profile, allowing the simulation to account for variations in behavior across different groups. To obtain the archetypes in our case study areas, we collected data on local behavior during past hazard events through a structured questionnaire.

3.4. Simulation execution

Building on the structured scenarios and simulation components defined in the previous sections, this section explains the operationalization of the model within an integrated cognitive agent-based simulation system based on the simulation scenarios derived from the co-creation process. The architecture of our simulation execution brings together three critical elements: the cognitive reasoning layer, the environmental simulation configuration, and the agent-embodiment integration architecture. These components are developed in parallel, but converge at runtime to produce an emergent, interactive evacuation model grounded in stakeholder-defined conditions.

The cognitive reasoning system operationalizes the HBM through the Belief–Desire–Intention (BDI) framework. The HBM is rooted in empirical data gathered via a tailored questionnaire administered in each case study area, capturing evacuation experiences, preparedness levels, and decision-making processes across diverse socio-demographic groups. Responses are analyzed using hierarchical clustering to identify behavioral archetypes, i.e., distinct profiles of individuals sharing similar attitudes, motivations, and behavioral tendencies related to evacuation decision-making. These archetypes were then encoded as BDI agents, each defined by a structured set of beliefs (about self, others, and the environment), desires (evacuation or coordination goals), and intentions (adaptive plans for achieving those goals). BDI goal-plan hierarchies were constructed to reflect these archetypes, embedding fallback strategies and context-sensitive responses that evolve as the simulation unfolds.

In parallel, the simulation environment is configured using MATSim, an open-source, agent-based transportation simulation framework designed to model individual travel behavior and network dynamics at scale. This includes defining the infrastructure network, generating synthetic populations, and modeling hazard-induced disruptions. Spatial data from OpenStreetMap and local sources is processed to build a routable transportation network, which is then refined based on stakeholder input regarding road conditions, accessibility, and emergency routing constraints. Demographic data is used to generate agent populations with characteristics such as age, household structure, mobility limitations, and dependencies. Hazard scenarios (e.g., flood, fire, earthquake) modify the accessibility and functionality of specific network segments, allowing the environment to reflect the physical impacts of disasters in real time.

At the core of the execution system is a three-tier integration architecture that synchronizes reasoning (BDI) and embodiment (ABM) at each simulation timestep. As shown in Figure 3, the system operates in synchronized cycles: the MATSim layer perceives environmental conditions (e.g., congestion, blocked roads) and passes a list of percepts to the BDI system. The BDI agents process these inputs using their goal-plan hierarchies and return a set of actions and action status updates. These actions are then executed in MATSim, allowing agents to navigate the network in accordance with their cognitive decisions.

The architecture comprises three interconnected layers. The generic layer defines the shared data structures and synchronization mechanisms that standardize communication between the cognitive and physical subsystems. This includes the exchange of percepts, actions, and queries, as well as the coordination of control flow at each simulation timestep. The system layer provides platform-specific integration code, enabling coupling between a variety of BDI programming platforms (such as JACK, Jadex, JASON, and JILL) and the MATSim agent-based simulation environment. Finally, the application layer encodes domain-specific logic (such as behavioral archetypes, evacuation heuristics, and agent interaction patterns) and maps cognitive decisions into MATSim activity chains. This layered architecture allows cognitive reasoning and physical embodiment to operate independently while remaining tightly synchronized throughout the simulation lifecycle. This runtime loop supports bidirectional feedback between agent cognition and the simulated environment. If, for instance, an evacuation route becomes impassable due to hazard conditions or congestion, agents perceive these changes, reevaluate their goals or intentions, and select alternative strategies.

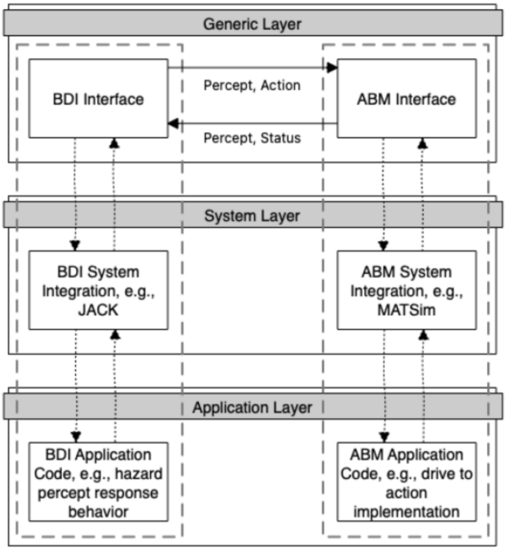


Figure 3. The architecture of ABM-BDI integration used to execute simulations.

4. Results and discussion

Having applied the proposed methodology across the case study areas of Egaleo (earthquake), Sant Llorenç (flood), and Canyamel (wildfire), we present here the main findings grouped into three thematic domains aligned with the framework: the co-creation process, the simulation framework, and the simulation implementation. Rather than detailing simulation outputs, which are also accessible online, this section focuses on illustrating how the methodology itself contributed to the development of credible, context-sensitive evacuation simulations. Selected examples highlight where the integration of technical modeling and stakeholder input shaped scenario design, improved assumptions, and refined system evaluations.

4.1. Co-creation process findings

The co-creation process was critical not only for generating stakeholder buy-in but for surfacing local knowledge that fundamentally improved the realism and validity of the simulations. A particularly illustrative example emerged in Egaleo, where initial simulation assumptions identified a local park as a potential safe evacuation zone. Stakeholder consultations revealed that this area was heavily forested, making it inaccessible in an emergency and unsuitable as a congregation point. Figure 4 (a) and 4 (b) illustrate the comparison between including and excluding this site, showing how accounting for these local insights reshaped evacuation flows and improved scenario plausibility. This example highlights that co-creation is not merely a participatory add-on;

it is an essential mechanism for aligning technical models with real-world conditions, ultimately resulting in more credible and actionable outputs.

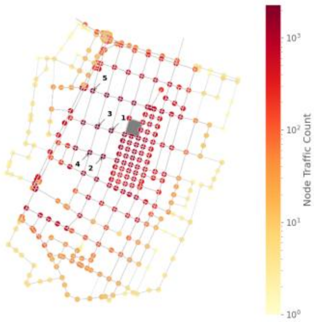
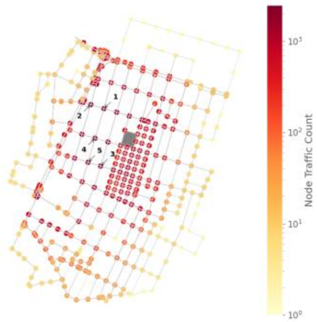


Figure 4. (a) Congested links and intersections when the highlighted area is used as a safe place



(b) Congested links and intersections when the highlighted area is not used as a safe place

4.2. Simulation framework findings

The simulation framework's multi-dimensional design allows for a systematic exploration of how interacting components such as infrastructure, demographics, hazard dynamics, human behavior, and policy shape evacuation performance. By considering these factors together, the framework demonstrates that even small adjustments in one area can lead to significant and often nonlinear effects across the entire system. To highlight these insights, we present case study examples that show how specific interventions, including policy changes, early warning systems, and more realistic behavioral modeling, can meaningfully alter evacuation outcomes.

In Egaleo, two contrasting policy scenarios were tested: one where agents headed to the nearest available safe point, and another where they were pre-assigned to specific evacuation centers based on co-created plans. While both scenarios operated under identical infrastructure disruption conditions, the introduction of pre-assigned destinations led to a noticeable reduction in congestion at critical intersections and improved overall evacuation performance (see Figure 5 (a) and 5 (b)). Similarly, the addition of EWS in Mallorca flood scenarios (Figure 6 (a) and 6 (b)) significantly decreased the number of stranded individuals, underscoring the life-saving potential of timely alerts. In wildfire simulations, incorporating HBM) (Figure 7 (a) and 7 (b)) produced markedly different movement patterns compared to uniform behavior assumptions, revealing how heterogeneity in behavior affects system dynamics.

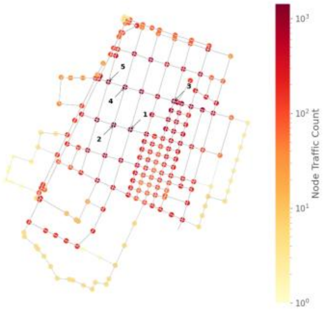
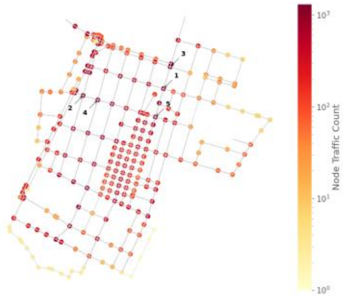


Figure 5. (a) Congested links and intersections resulting from agents seeking the nearest safe place



(b) Congested links and intersections when the agents are pre-informed of their evacuation destination

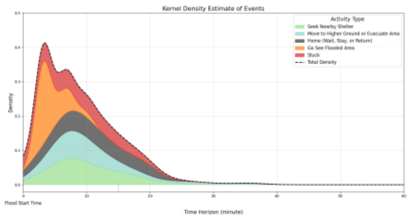
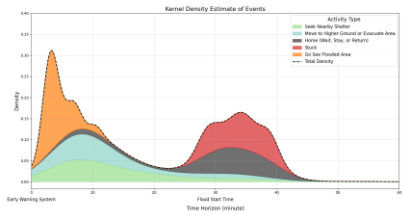


Figure 6. (a) Kernel Density Estimates (KDE) of Different Events, illustrating the distribution of different events in case of no EWS



(b) Kernel Density Estimates (KDE) of Different Events, illustrating the distribution of different events in case of 30-min EWS

4.3. Simulation implementation findings

Beyond the technical execution of the models, integrating detailed hazard, infrastructure, and behavioral layers within a co-creation-driven process provided important methodological lessons. Successful implementation was not only a matter of software integration or simulation performance but also of ensuring that results were interpretable, meaningful, and usable for diverse audiences. The simulation system was built upon the EES a robust and extensible platform for agent-based evacuation modeling that provides the core architecture for simulating movements, infrastructure interactions, and hazard dynamics. Building on this foundation, MEES delivers a customized implementation specifically adapted for the C2IMPRESS project, integrating ABM, HBM, BDI-ABM cognitive reasoning, and social network diffusion tailored to the unique characteristics of the selected case study areas and hazards. The C2IMPRESS repository provides access to this tailored system, allowing researchers and practitioners to explore real and hypothetical evacuation scenarios, including earthquakes in Egaleo, wildfires in Mallorca, and flash floods in Mallorca, within a unified, reproducible simulation environment designed to capture the specific complexities of these contexts.

Working within this integrated simulation environment revealed several findings. First, the use of simulation outputs as boundary objects significantly enhanced stakeholder engagement. When presented in the form of visualizations, animations, or comparative metrics, these outputs facilitated structured dialogues between technical teams and community actors, bridging the gap between modeling assumptions and lived realities. Second, we found that stakeholder input during implementation often challenged default assumptions, such as the location of safe zones or expected departure times, highlighting the importance of retaining flexibility for late-stage model revisions. Third, the dynamic integration of cognitive reasoning and hazard-informed infrastructure layers enabled agents to adapt to disruptions in real-time, revealing emergent bottlenecks and coordination failures that static models typically overlook.

These findings underscore that the value of simulation lies not only in predictive accuracy but also in its capacity to surface decision-relevant insights through stakeholder reflection and feedback. Technical robustness alone is insufficient; effective implementation demands a methodological bridge connecting the rigor of agent-based modeling with the social, institutional, and policy contexts where these insights are applied. Future work should continue to enhance the usability, transparency, and collaborative value of simulations, ensuring that advanced modeling tools not only serve technical exploration but also contribute meaningfully to multi-hazard preparedness, local capacity-building, and evidence-based decision-making.

5. Conclusion

This paper presented a comprehensive framework for enhancing disaster evacuation planning through the integration of agent-based modeling, human behavior modeling, hazard-specific impacts, infrastructure constraints, and policy settings within a structured co-creation process. By combining technical modeling with stakeholder engagement, the proposed methodology addresses key limitations found in existing evacuation simulation approaches, including fragmented system representations, oversimplified behavioral assumptions, and limited stakeholder involvement. Through applications in diverse case study areas, including earthquake scenarios in Egaleo and flood and wildfire scenarios in Mallorca, we demonstrated the framework's capacity to generate context-sensitive, actionable evacuation simulations capable of supporting decision-making and preparedness planning.

Looking ahead, several avenues for future research stand out. First, enhancing the explainability of simulation outcomes will be crucial for helping diverse stakeholders understand and trust the complex behaviors and system-level dynamics produced by the model. Second, although the current framework incorporates archetypes to represent behavioral diversity, further work is needed to capture intersectional demographic complexity in a scalable and systematic way. Third, while the co-creation process effectively aligned local knowledge with simulation design, our approach to resolving conflicting stakeholder inputs was largely informal; future efforts should explore more structured and transparent methods, particularly in politically sensitive or contested contexts. Fourth, the behavioral effects of EWS are modeled through agent-level parameterization, yet the broader variation in EWS infrastructure across regions, in terms of delivery technologies, trust levels, and digital accessibility, remains an important limitation to address. Lastly, to move toward operational readiness, the framework should be scaled to support real-time data integration, cascading hazards, and geographically broader applications.

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