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A Framework for Constructing Agent-based Models for Evaluating Emergency Evacuation Procedures; A Case Study Applied to Egaleo, Greece

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Abstract

Planning and preparing for evacuations of populations during emergencies requires a multifaceted approach covering the essential concerns of understanding hazard risk, preparing critical infrastructure for egress and shelter, determining the makeup of the population at risk, understanding how that population will respond in the event of an emergency, and developing robust evacuation procedures and policies. While tools and methods often exist for understanding these concerns separately, these do not allow decision-makers to systematically understand their interconnections and the implication of change in one dimension on the other. To address this challenge, we introduce a comprehensive framework designed to assist emergency management decision-makers in evaluating community evacuation plans. Central to our approach is the use of micro-simulations that model known human behaviors in emergencies for evacuating populations. Our framework, encompassing the five dimensions of Infrastructure, Population Demographics, Evacuation Policy, Hazard Model, and Human Behavior Model, allows users to systematically build "what-if" scenarios that introduce changes in different dimensions to test the robustness of evacuation policies. We present a case study of employing this framework in Egaleo, Greece, a seismic-prone region, as part of the European HORIZON project C2IMPRESS, in collaboration with local government. We showcase the effectiveness and relevance of our approach in enhancing emergency response strategies within dynamic and high-stakes environments.

Keywords: Agent-based modeling, Simulation, Emergency planning, Human behaviour modeling

1. Introduction

Emergency evacuation of populations to safety from natural hazards like fires, floods, and earthquakes is a multifaceted problem influenced by interconnected factors. From the layout of the environment to the efficiency of communication systems, each element plays a crucial role in ensuring a successful evacuation. However, comprehending the intricate interactions among these factors poses a significant challenge. Emergency management services (EMS) face the ongoing task of assessing and improving evacuation procedures and policies to adapt to changing populations, landscapes, etc. Yet, discerning the precise impact of changes in one factor on the overall outcome remains elusive, as the dynamics of emergency situations are often unpredictable and complex.

In addition, evacuating populations involves individuals with diverse behaviors and reactions to hazards. Human responses to emergencies vary significantly, influenced by social ties, prior experience, training, risk perception, cultural backgrounds, cognitive biases, and psychological states. This variability introduces an additional layer of complexity to evacuation planning and execution. Human responses can profoundly influence the effectiveness and safety of evacuation efforts, underscoring the importance of considering human behavior in emergency preparedness and response strategies.

As part of the Horizon EU project C2IMPRESS, a

collaborative initiative involving 16 partners, tailored agent-based models (ABM) to capture the effects of people's attitudes towards hazards. ABM is particularly well-suited for this task due to its ability to model the complex, heterogeneous behaviors of individuals and groups during emergencies through the integration of a human behavior model (HBM). By doing so, we aim to provide valuable insights into how individuals perceive and respond to various hazards and how their collective decisions influence the outcome of evacuations. This effort is tested in the Egaleo case study area (CSA) in Greece, where the project examines seismic hazards and simulates earthquake evacuation scenarios. This case study serves as a practical demonstration of the project's objectives, showcasing how insights derived from ABM simulations (coupled with HBM) can support more informed decision-making and enhance risk mitigation strategies.

We propose a comprehensive framework that provides a structured approach for defining and analyzing simulation scenarios in the context of evacuation procedures and policies. This framework is built around five key dimensions—Infrastructure, Population Demographics, Evacuation Policy, Hazard Model, and Human Behavior Model—which serve as the foundational elements for constructing detailed evacuation scenarios. The framework extends previous work by offering three major contributions: First, it enables decision-makers to better understand the interconnections between these dimensions, illustrating how changes in one area, such as infrastructure, impact the others, including human behavior or policy effectiveness. Second, it broadens the scope of evacuation analysis by incorporating a wider range of post-evacuation behaviors, providing a more comprehensive view of the evacuation lifecycle. Third, it offers clear guidelines for optimizing simulation capabilities, particularly through the use of scenario-specific metrics that guide the co-creation process with stakeholders, ensuring that new scenarios are both relevant and actionable. By systematically organizing these dimensions and metrics, the framework facilitates deeper discussions with stakeholders, enhances decision-making, and allows for the continuous improvement of evacuation strategies under varying conditions.

In Egaleo, as perceived by stakeholders, the application of our framework clearly demonstrated its effectiveness in addressing the contributions outlined above. Through guided discussions and ABM simulations, stakeholders gained a deeper understanding of how various factors interconnect and influence evacuation dynamics. The framework facilitated

the identification of critical issues that might have been overlooked, while also providing a detailed exploration of evacuation behaviors throughout the entire process. Its structured approach offered clear guidelines for defining relevant scenarios and improved communication and collaboration among stakeholders. As a result, decision-makers were equipped with a more comprehensive understanding of evacuation strategies, enabling them to identify areas for improvement. The validation of these outcomes by experts in EMS will be presented in future research.

The rest of this paper is organized as follows: Section 2 provides background information on agent-based models and human behavior simulations in emergency evacuation scenarios. In Section 3, we present the proposed framework, detailing the five key dimensions of Infrastructure, Population Demographics, Evacuation Policy, Hazard Model, and Human Behavior Model. Section 4 discusses the application of this framework to the Egaleo case study, including the evolution of the simulation scenarios and the insights gained from each. Finally, Section 5 concludes the paper by summarizing the results and suggesting future directions for research.

2. Background

In this section, we review the existing literature on ABM and simulators that study human behavior and evacuation dynamics during emergencies, especially earthquakes. Our focus is on studies that apply ABM to emergency evacuations, particularly those that integrate psychological, social, and environmental factors, which are essential for accurately capturing human behavior. We also assess the strengths and limitations of existing simulators in various disaster contexts, identifying areas where current models fall short. The review provides the context for understanding how our work addresses these gaps. Finally, we introduce the simulation platform used in this research, which integrates the Belief-Desire-Intention (BDI) framework to model decision-making during emergencies. This structure ensures a logical progression, starting from existing knowledge and challenges, and leading into the rationale behind our proposed framework and simulation platform.

2.1. Agent-based human behavior model and simulation

Significant contributions to simulating human behavior models have been made by researchers such as [Helbing and Molnar, 1995], who introduced the social force model to simulate pedestrian dynamics

by considering social interactions alongside physical forces. This model has been instrumental in understanding how physical environments influence individual movements during crises. Helbing's work, refined by many researchers to adapt to different environments and achieve more accurate results [Chen et al., 2018], demonstrated the role of psychological factors, such as the desire to escape and crowd density, in determining evacuation efficiency. While these models provide valuable insights, there is growing recognition of the need to shift toward individual-based modeling approaches like ABM, which offer enhanced capabilities in representing the heterogeneity of individuals who exhibit diverse behaviors and reactions when confronted with hazards [An, 2012].

ABM is a powerful simulation methodology extensively used to study complex systems, particularly human behavior in emergency scenarios [Zhuo and Han, 2020]. In these scenarios, the system is typically represented by interactions between agents, each possessing distinct attributes, behaviors, and decision-making capabilities. These agents interact within an artificial environment that models real-world aspects such as urban design, transport infrastructures, and hazards. This enables agents to adapt to changing conditions, thus better reflecting real-world evacuation dynamics [Bulumulla et al., 2017, Sharma et al., 2018, Bakhshian and Martinez-Pastor, 2023]. Several ABM-based simulators have been developed for various disaster scenarios, including floods [Taillandier et al., 2021], tsunamis [Mas et al., 2015], volcanic eruptions [Gillet et al., 2024], bushfires [Marquez et al., 2022], and earthquakes [Zhang et al., 2018].

In the earthquake context, the EPES agent-based simulator models human behaviors and environmental interactions for urban pedestrian evacuation [Quagliarini et al., 2014]. However, its human behavior model, expressed through rules within the ABM, can be oversimplified compared to the nuanced behaviors observed in real-world evacuations. Conversely, SOLACE [Bañgate et al., 2017] enhances realism by incorporating various behaviors, including social ties between family and friends, based on Mawson's theory of social attachment [Mawson, 2017]. Nonetheless, SOLACE lacks support for multi-trip evacuations, where family members regroup before moving to safety. PEERS, which models pedestrian evacuation after an earthquake [Iskandar et al., 2023], applies a BDI approach to simulate realistic behaviors such as leader-follower dynamics and social ties, while also incorporating physical debris

that affects movement and casualties. Despite its realism, PEERS is computationally demanding, with full-city simulations taking several days. IdealCity [Battezzorre et al., 2021] overcomes the computational challenges and can handle large-scale simulations but it falls short in addressing the diversity of human behaviors.

Despite these advances, the limitations discussed above highlight the need for a framework that defines what should or should not be included in a simulator. To address these challenges, we integrate the BDI model for human decision-making within our ABM platform, MATSim [Singh et al., 2016, Singh et al., 2020], which provides a flexible and scalable simulation environment. In the next section, we present a generic framework to guide modelers in determining what to include in their simulators.

2.2. Modeling rational behavior in emergency situations

The BDI computational model of rational decision-making stems from work in the psychology of mind on intentional systems [Dennett, 1989] and practical reasoning [Bratman, 1987]. The central premise is that agents hold beliefs about their world—factual or otherwise—that drive their choices, maintain internal desires for states of affairs they wish to bring about in the world through the proactive pursuit of goals, and have intentions or commitments to achieving some of these goals through deliberative reasoning and a course of action. The BDI model provides an intuitive way to describe the behavior of agents within a computer program using the constructs of beliefs, goals, and plans¹, and also acts as a convenient natural language bridge between domain experts and programmers. On the other hand, the observed behavior of a BDI agent can be easily explained by examining the context-aware reasoning that led to a particular choice of actions. This can be especially useful when modeling human behavior in emergencies like earthquakes and fires, where the rational actions of a person (based on knowledge at hand) may look like *panic* to other observers [Victoria Police, 2014].

Technically, a BDI program is described by a set of goals the agent will try to achieve and a related set of abstract recipes or plans relevant to achieving those goals. Typically the programmer provides several plan options for a given goal, each with a pre-condition that must hold at the time the plan is being considered, for a plan also to be *applicable* in that moment. This

¹This general programming paradigm is known as agent-oriented programming.

idea of providing multiple options for achieving a goal in agent-oriented programming is in stark contrast to traditional programming where a single function is coded for a given task. This difference arises from the underlying assumption in agent programming that the world the agent operates in is dynamic and unpredictable. This means that a complete plan of action constructed upfront, as is done in classical AI planning, before taking the first step, where steps take time to complete and in which time things can change, is often brittle. Instead, a wiser approach here may be to decide on a broad course of action but leave the minute details to a future time when those choices must be made. For example, an evacuating agent cannot preempt what challenges it will find on its way to a safe place. A BDI agent will instead start walking towards the destination, and only when faced with obstacles adapt its plan in-place, by considering other (programmed) options, to achieve its goal.

Finally, BDI goals and plans can be structured in a hierarchy. To achieve a goal, an agent must pick one of its available plan options at the time. Each plan is effectively a sequence of steps that should be performed, where each step could be an observable action that the agent takes in the environment, or alternatively, a complex action or sub-goal, with its own set of plan options. For instance, an agent's high-level goal to evacuate may consist of a plan to first assemble household members, and then leave together as a unit. Reuniting with family (sub-goal) may involve sending a phone message with a location, however, if the cellular system is down at the time, then a backup plan might dictate that all members assemble at a pre-determined spot (plan options). What options are coded is determined by behaviors to be expected, which can come from domain experts and learnings from past events.

2.3. Simulation Platform

The BDI-ABM framework [Singh et al., 2016] connects the rational BDI brain of an agent with its embodiment in an environment, such as the virtual world of an earthquake-affected area. The ABM captures the mechanics of the world including where the agents are, how they interact (directly via communication channels or indirectly via shared resources within the world), and how the decisions of the BDI agent affect change in the world. The BDI agent is forever in a sense-reason-act cycle: it perceives the world via the ABM, deliberates over new information in light of its goals, adapts its plan of action if needed, and performs actions towards its goals in the

world.

For this work, we use the MATSim mobility simulator as the model of the world, i.e., the ABM, and connect BDI reasoning to the mobile agents within MATSim [Singh et al., 2020]. In this worldview, the movements of the physical agent are constrained by the road network and its flow capacity. MATSim's mobile agents know how to navigate this world, such as how to find a route from their current location to a chosen destination, and travel that route via a chosen mode such as a private vehicle or on foot. Their travel time is governed by their maximum travel speed (the lesser value of speed limit and maximum speed for the chosen mode) and whether any road links reach maximum flow capacity due to high demand and become congested.

MATSim agents, however, are unaware of a higher context of evacuation during an earthquake. This high-level reasoning around evacuation is captured within the BDI counterpart of each MATSim agent. The BDI brain deliberates and makes evacuation decisions, such as assembling at location X within the context of a higher-level goal. The MATSim body simply sees the outcome of the deliberation, which is a directive to "go to location X now." When the MATSim agent eventually arrives at X, the BDI agent senses that it is now at X, and resumes its evacuation-related planning. If, on the other hand, the MATSim agent had failed to reach X because of a blocked road, the BDI agent senses the failure and deliberates on how else it could reach X from where it was stuck.

3. Framework Overview

To address the complexity of understanding emergency evacuation scenarios, we propose a framework that analyzes them using five key dimensions: Infrastructure, Population Demographics, Evacuation Policy, Hazard Model, and Human Behavior Model. Each dimension allows experts and stakeholders to focus on specific factors critical to the evacuation process. Early stakeholder involvement is crucial for ensuring relevance and acceptance of the simulation tool, and we advocate using an iterative co-design approach.

This approach begins with establishing a *baseline scenario* by defining the core data for each dimension. For example, the population demographics should include characteristics (such as age and gender). The team then follows an interactive, incremental process to refine and enhance the data for each dimension. This process is illustrated in Fig. 1. We now present a concise overview of each framework dimension and explain how each contributes to defining evacuation scenarios.

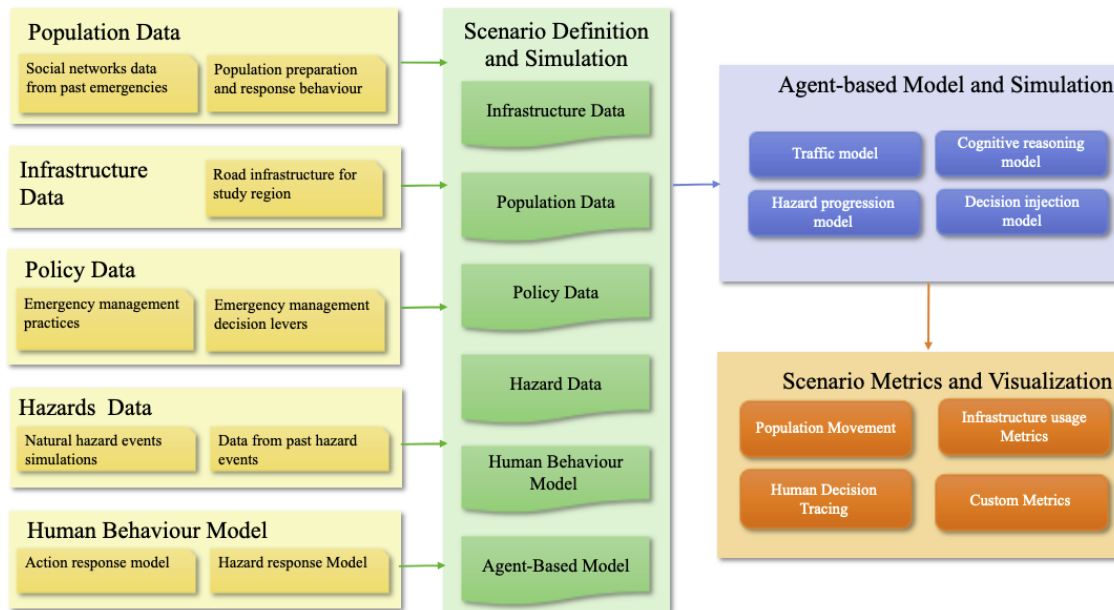


Figure 1: Framework for Emergency Evacuation Scenario Definition

3.1. Infrastructure

This dimension focuses on the physical structures and facilities within the area of interest. Its primary function is to extract, process, and customize infrastructure attributes from datasets, such as OpenStreetMap, to create precise test environments for our simulations. Collaborating with local experts ensures that attributes such as road types, capacities, and speed limits reflect real-world conditions. Furthermore, the infrastructure dimension considers cultural and social practices, such as parking on sidewalks, that may impact mobility.

3.2. Population Demographics

This dimension defines the number of individuals and their locations at the onset of a disaster or evacuation alert, which is critical for designing various evacuation scenarios, such as day or nighttime evacuations. It also maps demographic characteristics such as age, gender, household size, and socio-economic status, which can later be combined with human behavior models for more realistic simulations.

3.3. Evacuation Policy

This dimension incorporates current or anticipated evacuation protocols and disaster response strategies as defined by stakeholders. Such policies have a

direct impact on population dynamics and governmental responses to emergencies. Understanding how changes in policies affect evacuation processes is essential for optimizing emergency response plans and improving decision-making.

3.4. Hazard Model

The hazard model dimension is crucial for accurately representing natural hazards that may impact both infrastructure and evacuation dynamics. This involves developing and integrating models for hazards such as earthquakes and floods into our simulations. These models dynamically adjust infrastructure attributes, such as capacities and speed limits, based on hazard severity. By incorporating realistic hazard models, such as earthquake debris distribution or flood progression, our simulations can reflect the complexities of managing evacuation routes during disasters.

3.5. Human Behavior Model

This dimension focuses on capturing and modeling human reactions and behaviors during disasters. Accurately modeling human behavior is crucial for the realism and effectiveness of evacuation simulations. However, obtaining reliable data and simulating human behavior in emergencies is a complex challenge. In this work, we use the BDI approach in the HBM, but other techniques [Fuchs et al., 2023] could be applied for this

dimension.

3.6. Agent-based Model and Simulation

Note finally that in our framework, the five dimensions provide critical inputs that shape the *ABM* model and simulation environment and agent decision-making (i.e., *HBM*). For instance, infrastructure data such as road capacities influence route selection, while the hazard model updates environmental conditions (e.g., debris or road blockages), prompting agents to adjust their plans based on their beliefs (e.g., hazard perception), desires (e.g., evacuation goals), and intentions (e.g., planned actions).

4. Case Study: Egaleo Earthquake Evacuation Assessment

Building on the generic framework outlined above, this section explores how each dimension was applied to the Egaleo earthquake evacuation simulations. We demonstrate the practical implementation and iterative refinement of these dimensions, emphasizing their collective impact on the relevance and effectiveness of both the simulations and the resulting evacuation policies.

4.1. Egaleo City Case Overview

The pilot implementation of the C2IMPRESS earthquake case study is based on the 7th September 1999 event, which occurred near Mount Parnitha, Greece, at 14:56:51 EET, with a magnitude of 6.0. Due to its proximity to the Athens metropolitan area, the earthquake caused widespread structural damage: over 100 buildings (including three major factories) fully collapsed, and approximately 70,000 more were damaged. The death toll was 143, and around 1,600 individuals sustained injuries, while the estimated economic damages exceeded 3 billion euros [Lekkas, 2001]. According to the European Seismic Risk Model (ESRM20), this area remains a high-risk earthquake zone. This underscores the importance of developing robust evacuation planning to improve disaster management and minimize loss of life and injury.

The case study focuses on the Egaleo Municipality, which spans an area of 6.4 km² and has a population of 65,000, according to the 2021 Greek Census data. The simulation models targeted the central part of the city, incorporating data from the municipal emergency response plan, including the locations of designated evacuation centers.

4.2. Applying the Framework to Egaleo

Following our iterative approach, we describe below the evolution of the simulations as the team analyzed the Egaleo case study using the framework. Before that, a snapshot of the evacuation process, illustrating the dynamic movement of agents towards safety is shown in Figure 2.

4.2.1. Scenario 1: Baseline The baseline scenario incorporated essential information for each dimension. Infrastructure data were drawn from publicly available information from OpenStreetMap, which in addition to the road network also provided facilities and open spaces. Population demographics were found from data from the 2011 census², where the number of residents at each location reflected population density and distribution patterns.

Our framework advocates for the continual enhancement of scenarios by focusing on the dimensions as guiding principles. During one of the iterations, the team delved into the 'Infrastructure' dimension and how the local infrastructure in Egaleo could influence evacuation. Members of the Egaleo local government highlighted the practice of parking cars on sidewalks. In the event of an earthquake, these parked cars would impede the flow of people on the roads, resulting in reduced network capacity. As a result, we reduced the capacity of some roads in the model. This corrected network capacity was incorporated into our baseline scenario.

Concerning the policy dimension, the Egaleo evacuation policy was that everyone should immediately head to the nearest evacuation center. For the human behavior dimension, agents were given homogenous behaviors, with each agent strictly adhering to the evacuation policy. Concerning the hazard dimension, the local government representatives wanted to make the assumption that the earthquake caused minimal impact

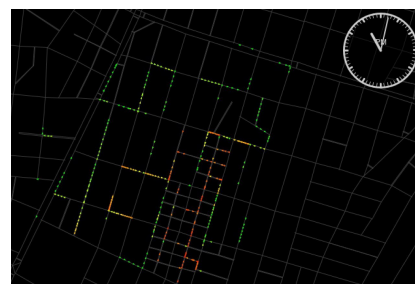
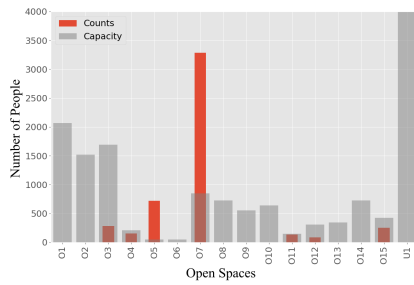
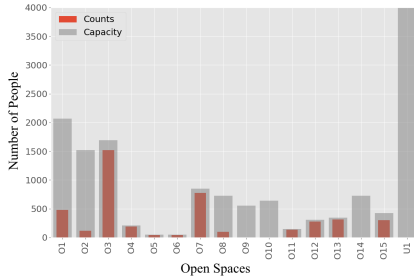


Figure 2: Snapshot of the Evacuation Simulation

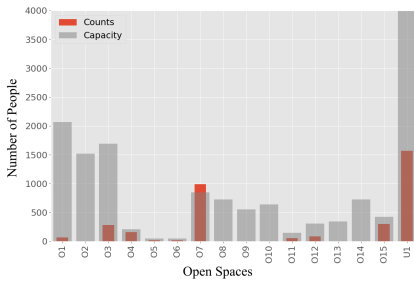
²<https://www.statistics.gr/en/2011-census-pop-hous>



(a) Scenario 1



(b) Scenario 2



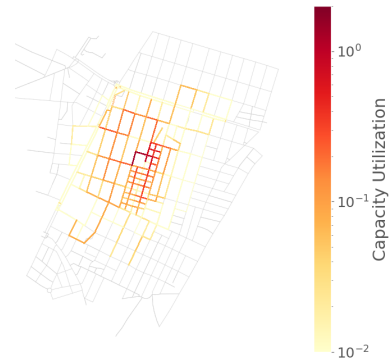
(c) Scenario 3

Figure 3: Distribution of People in Different Evacuation Centers per Scenario

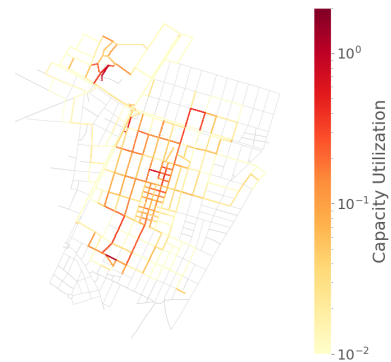
on agent mobility in order to focus on the core aspects of evacuation planning.

The simulator was run with the baseline scenario and the results were analyzed according to the jointly defined metrics, one of which was the custom metric on the capacity of evacuation centers/open spaces. The results showed that one particular evacuation center/open space was well over capacity, as illustrated in Figure 3(a). Therefore, the team reassessed the *evacuation policy dimension*.

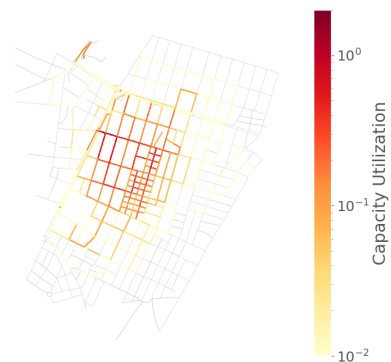
4.2.2. Scenario 2: Preassigned Evacuation Centers Revisiting the *policy dimension* resulted in experimenting with changing the evacuation policy



(a) Scenario 1



(b) Scenario 2



(c) Scenario 3

Figure 4: Heat Map of Network Capacity Utilization

in order to test what would happen if agents were pre-assigned evacuation centers. Each agent was allocated an evacuation center based on its distance to it and its maximum capacity. This adjustment, integrated into scenario 2, aimed to address the shortcomings identified in the baseline scenario.

Practically, we introduced a constraint by enforcing

capacity limits at each evacuation center. This was calculated by using 3.5 square meters per person, based on guidelines from the Sphere Handbook [Association et al., 2018]. Agents received their preassigned evacuation center based on its capacity. This scenario helps in understanding the impact of capacity constraints on the distribution of evacuees across different centers and prevents the overcrowding observed in Scenario 1 (see Figure 3 (b)).

In Figure 4 we observe how changes in different dimensions may impact the evacuation dynamics. Figure 4 (a) shows the road network capacity utilization with the baseline scenario using a heat map. Figure 4 (b) shows how that utilization is modified by changing only people’s allocated evacuation center. This highlights how the *evacuation policy* influences the *infrastructure* dimension.

4.2.3. Scenario 3: Human Behavioral Archetypes for Earthquakes

For scenario 3 we concentrated on the *Human behavior model dimension*. This centers on people’s reactions when faced with a hazard. In order to establish realistic human behaviors we carried out an online survey gathering data from Egaleo residents who have previously experienced earthquakes.³ The survey received 137 responses, which were narrowed down to 121 after excluding 7 samples from outside Egaleo and 10 from individuals who had not experienced earthquakes in Egaleo. The survey responses were cleaned and filtered to remove inconsistencies, and open-ended answers were categorized into predefined closed-ended options. The responses were then analyzed using hierarchical clustering analysis in the Treensight software⁴.

We adopted the evacuation archetypes approach, as proposed in [Strahan et al., 2018, Singh et al., 2023], to distinguish between different behavioral patterns and decision-making processes. An archetype represents a group’s shared behavioral patterns and decision-making tendencies, drawing on universal human traits and social constructs [Jung, 2014].

From the cluster analysis we identified seven distinct behavioral archetypes among Egaleo’s residents, as shown in Figure 5. These archetypes encompass a broad spectrum of evacuation preferences, from the *Prepared Stay-at-Home* archetype, representing individuals who prioritize the safety of their homes, to a variety of evacuating behaviors. Among those who evacuate, we observe the *Social Proactive Evacuator*, engaging with family or friends to collectively move to official open spaces. This is contrasted with

³<https://enquetes.univ-grenoble-alpes.fr/SurveyServer/s/jnnjdo>

⁴<https://www.treensight.com>

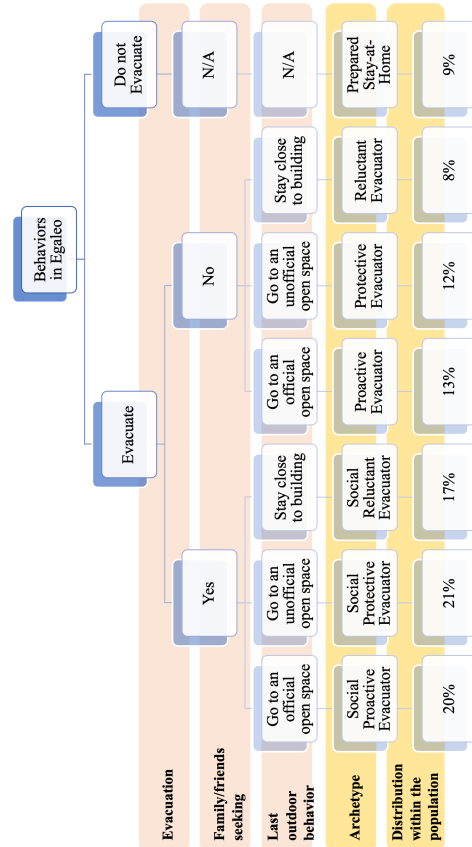


Figure 5: Classification of Archetypes Identified Within the Study Area

the *Reluctant Evacuator*, who individually limits their evacuation to the immediate surroundings of their building. Further nuances include the *Social Protective Evacuator*, who reunites with family to move to unofficial open spaces, and the *Social Reluctant Evacuator*, who stays just outside their home with their family. Moreover, some individuals directly seek refuge in either official (*Proactive Evacuator*) or unofficial (*Protective Evacuator*) open spaces, bypassing social connections. This range of identified archetypes reflects the diversity of personal, social, and spatial preferences.

Scenario 3 was designed to assess how diverse behaviors impact the evacuation process, highlighting the complexity of managing evacuations under realistic conditions. The impacts of including human archetypes in the simulation are illustrated in Figure 3(c). In this final scenario, agents follow the archetypes’ reactions, generating a heterogeneous set of actions that may differ from the standard evacuation policy defined by the city of Egaleo (see section 4.2.2).

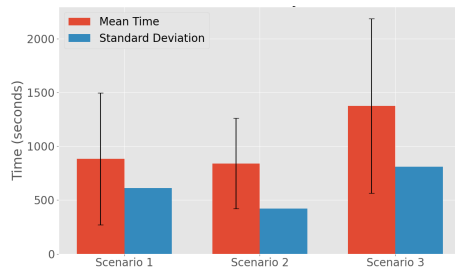


Figure 6: Comparisons of Evacuation Times in Different Scenarios

Moreover, Figure 4(c) demonstrates the tangible effects of integrating a more realistic human behavior model on network capacity utilization. This underscores the significance of agent-based simulation as a tool to elucidate the interconnected effects of various dimensions on evacuation dynamics.

These results highlight the critical effect of incorporating a human behavior model into the simulation. From another perspective, this inclusion could lead to an increase in both the average evacuation duration and the standard deviation of evacuation times, as shown in Figure 6. This means that, while some evacuees may evacuate more quickly, others may take significantly longer, resulting in a broader range of evacuation times overall.

5. Conclusion

Grasping the complex interactions of the multiple factors that impact an emergency evacuation is a challenging task. Furthermore, evaluating how (even minimal) changes may alter how an evacuation unfolds has proven to be strenuous. To facilitate this task, we have proposed (a) a framework consisting of five dimensions for analyzing and defining evacuation scenarios; and (b) the use of agent-based modeling and simulation as a means to integrate and evaluate those scenarios. We have then applied our framework to an earthquake case study in the city of Egaleo, Greece. We illustrated the benefits of the approach in systematically evolving the scenarios in close collaboration with key stakeholders.

From the stakeholders' perspective, the use of evacuation simulations with precisely defined model assumptions is crucial for enhancing emergency planning in the Egaleo municipality. These simulations have identified overcrowded evacuation spaces, consistent with patterns observed in previous earthquakes in Greece, and have mapped key evacuation routes and congested segments, guiding

potential improvements in municipal parking and street signage. Notably, the proposed framework, even from its development stage, has enabled stakeholders to effectively collaborate in characterizing Egaleo's emergency management process and define suitable scenarios for modeling inputs. Following this assessment, we believe the evacuation simulation framework could improve communication among different stakeholders, especially through enhanced visualization capabilities and effective communication strategies.

Future directions include expanding the systematic process of using the framework for scenario refinement; defining standardized metrics for evacuation management; and improving our agent-based simulation platform to seamlessly integrate with the framework.

Acknowledgements

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