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# Agent-based simulation of seismic crisis including human behavior: Application to the city of Beirut, Lebanon

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## Abstract

Earthquake simulations at the urban scale usually focus on estimating the damages to the built environment and the consequent losses without fully taking into account the human behavior in crisis. Yet, human behavior is a key element for improving crisis disaster management; therefore, it is important to include it in seismic crisis simulations. In this study, an agent-based model for the simulation of pedestrian evacuation during earthquakes at the city scale is developed following an interdisciplinary approach. The model recreates the urban conditions using Geographic Information System (GIS) and a synthetic population, in addition to the earthquake consequences on the urban fabric. Moreover, the model integrates realistic human behaviors calibrated using quantitative survey results. We simulate pedestrian outdoor mobility with the different constraints that affect it such as the topography and the presence of debris. The simulator is applied to the case of Beirut, Lebanon. A what-if approach is adopted to analyze the population's safety in case of earthquakes in Beirut, particularly the open spaces' capacity to provide shelters and the effect of debris and realistic human behaviors on people's safety. The simulation results show that less than 40% of the population is able to arrive to an open space within 15 minutes after an earthquake, this number is further reduced when some open spaces are locked. Debris and realistic human behaviors both significantly delay the arrivals to safe areas and therefore should not be neglected in earthquake simulations.

## Keywords

earthquake, pedestrian evacuation, human behavior, agent-based modeling and simulations, urban scale simulations, post-seismic survey

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## 1. Introduction

Simulations play an essential role in improving the preparedness for future disasters through the evaluation of the possible adverse consequences of hazards and the identification of the most effective response strategies. This is especially true for the case of sudden onset hazards, such as earthquakes, which require a prompt emergency response often with limited information on the extent and the severity of the damages in the affected area. Earthquake simulations in urban areas often focus on the physical consequences on the urban environment, such as the building damages and the generated debris. The estimation of the seismic damages requires a fine characterization of the earthquake hazard and the buildings' vulnerability and seismic response, which have been the topic of interest of numerous studies<sup>1-4</sup>. However, the simulation of the social consequences of earthquakes, and particularly the human behavior has received less attention. Nevertheless, simulating human behaviors in an earthquake, especially evacuation behavior, can help identify and anticipate the possible challenges for crisis disaster management<sup>5</sup>. Evacuation simulations can help determining the fastest routes, or the nearest safe areas for people to seek shelter, in order to make evacuations faster and safer. Therefore, effective earthquake simulations should simultaneously: capture the characteristics of the social and physical environments, recreate the responses of the buildings to earthquakes and consider the responses of individuals. Additionally, the interactions between the individuals and the post-seismic physical environments should be included in the analysis.

Earthquake simulations with realistic physical and social responses are possible with agent-based modeling and simulations (ABMS). ABMSs have been widely used in the simulation of emergency evacuations<sup>6-9</sup>. This is particularly due to the ABMSs' ability to represent the heterogeneity of social agents at the individual level and the emergent phenomena that result from the interactions among individuals, and between the individuals and their environment<sup>10</sup>. An important advantage of ABMS is also its capability to include individual-decision making and social behaviors of individuals and groups<sup>11</sup>. Most of the previous ABMSs of earthquake evacuation focused on the simulation of indoor room or building evacuations<sup>11-13</sup>. Only few studies have developed ABMSs of pedestrian earthquake evacuation at the urban scale (outdoor mobility). Most of these models do not integrate physics-based estimates of damages and debris<sup>14-17</sup> or they only include simplified human behaviors and assume that all agents evacuate towards safe areas<sup>18-23</sup>.

Nevertheless, it has been documented in post-seismic surveys that people who are in buildings during an earthquake do not always evacuate, and when they do, they do not necessarily go towards safe areas<sup>24-27</sup>. These surveys have identified that the most common behaviors adopted during an earthquake are evacuating, taking cover, freezing in place and reaching and protecting others. When the shaking ends, some people resume their previous activities, while others evacuate from buildings, return to their houses, or look for their relatives and reunite with them. The behavioral differences observed at the individual-level were found to be compelled by people's vulnerability, which is accentuated by structural and everyday constraints, that can be cultural (e.g. religion), social (e.g. demography), economic (e.g. poverty) and political (e.g. social protection)<sup>28,29</sup>. Additionally, the local physical environment and its interactions with the social environment can have a large influence on how people behave in crisis<sup>30</sup>. However, no universal rules can be defined, as some findings were contradictory between different studies. The differences in the observations could be related to the cultural context, which was found to influence risk perception and response<sup>31,32</sup>. Therefore, in order to model the human response to an earthquake in a society of interest, the best approach would be to analyze, within the same culture, behaviors adopted during events that are relatively similar to the event modeled.

In this paper, we present PEERS (Pedestrian Evacuation in Earthquake Risk Simulations) an ABM for the simulation of pedestrian evacuation and mobility in an urban area in the immediate aftermath of an earthquake. In this context, we define evacuation as the action of exiting a building, and mobility as the movement of a person outdoors from one location to another. The simulations in PEERS start at the time of occurrence of the earthquake, and last until 15 minutes after the earthquake (real time), since during this period the information about the nature of the event and its consequences are still unknown to both the individuals experiencing it, and to the decision-makers in charge of coordinating the emergency response. PEERS is adapted to the case of the city of Beirut, the capital of Lebanon. Although the seismic hazard in Lebanon is moderate to high<sup>33</sup>, no major earthquakes occurred in the country in the recent history. Nonetheless, Lebanon has been historically struck by several devastating M7+ earthquakes, such as the earthquakes of 551 AD and 1202<sup>34,35</sup>. The rapid urban growth of Beirut in the last couple of decades led to a decline in its open and green space<sup>36,37</sup>. Moreover, the seismic regulation on buildings being introduced in 2005 and only made mandatory since 2012, combined with the general lack of seismic provisions enforcement, make Beirut particularly vulnerable to earthquakes. In this study, we investigate the safety of Beirut's population in the immediate aftermath of an earthquake by asking the following research questions:

- Does Beirut's urban form, particularly its open spaces, have the capacity to provide shelters for the residents in the immediate aftermath of an earthquake?
- What is the impact of the physical and social environments on the population's safety following an earthquake?

To answer these questions, realistic human behaviors calibrated to the case of Lebanon were derived from an online survey on the individuals' responses to sudden onset disasters, presented in section 2. Section 3 presents PEERS and its underlying models, namely the city, earthquake damage and human behavior and mobility models. Section 4 focuses on the

implementation, calibration and experiments applied to the case of Beirut, the simulations and results are presented in section 5 and discussed in section 6.

## 2. Collection of human behaviors in response to sudden onset events in Lebanon through an online survey

Since behaviors are highly dependent on the social and physical local contexts, behavioral data had to be collected from previous events that happened in Lebanon. Although Lebanon did not experience any major earthquake in the recent past, the catastrophic August 4 2020 Beirut port explosion provided valuable observations on the Lebanese population's responses to a rapid onset disaster. Despite earthquakes and explosions being events of different origins, they may evoke similar human behaviors due to their similarities in terms of their rapid onset, their environmental signals (vibrations and noise) and the way they are perceived by the affected individuals. This assumption can further be justified by the scientific paradigm that considers that individuals' behaviors do not differ according to the type of disaster, but rather according to the social dimension of the disastrous event<sup>38</sup>. The social dimension includes the event's predictability, recurrence, and rapidity of onset; the social centrality of the affected population and the proportion of the population involved. Therefore, two events of different origins, such as explosions and earthquakes may evoke similar individual behaviors due to their shared aspect of rapid onset. Another justification could be related to the observation that in the immediate aftermath of a sudden onset event, the affected population may not have all the necessary information to accurately identify the nature of the event they witnessed, which leads them to make their own interpretation according to the environmental clues they have perceived. This has been observed in the case of the Teil earthquake in Ardèche, France (2019,  $M_w$  5.1), where in the opposite direction, the earthquake was thought to be an explosion by 21% of the respondents of the survey of the French Association of Paraseismic Engineering<sup>39</sup>, in comparison to only 14% of the respondents who thought it was an earthquake.

Human behaviors in response to the Beirut port explosion were collected through a questionnaire that was specifically built for designing an agent-based model for human behaviors in earthquakes<sup>40</sup>. After adapting the questionnaire to the case of the explosion, the survey was launched online on August 18, 2020, around two weeks after the explosion. The link to the survey was shared through our personal and professional networks, as well as social media platforms and websites of Lebanese and French institutions: Pacte (Grenoble), ISTerre (Grenoble) and O'LIFE (Beirut). It contained questions about the respondents' location at the time of the explosion (the district in Beirut they were in, or the city if outside Beirut), their social context (alone or with other people), their perception and reactions to the explosion and questions related to their profile (age, gender, education, etc.). The survey responses were anonymous and no data allowing the identification of individuals by cross-referencing social data or by geographical location (address, IP address...) were collected. The survey reached 571 responses when it was closed on 09/03/2021. The survey responses were filtered by removing the responses of individuals who did not experience the explosion and those who were from the under 18 age category (4 responses) to be in compliance with Article 8 of the General Data Protection Regulation (EU GDPR) about the use of personal data related to children. The final sample was composed of 481 observations ( $N=481$ ). In the final sample, the percentage of female participants was greater than males (65.1% vs 34.9%). The 25-39 age group was over-represented as almost half of the participants (46.2%) were from this age category. The educational level of the respondents was almost homogeneous, with 97.9% of the respondents having achieved higher-level education.

### 2.1. Evacuation behavior

In response to the question "Did you get out of the building you were in?" answered by the survey respondents who were indoor ( $N=387$ ), 24.8% responded "Yes". The bi-variate relationship between the responses to this question and variables that could explain the evacuation behavior was analyzed by performing the Chi-square test ( $\chi^2$ ). The explanatory variables were chosen as the gender and the age of the respondent, the presence of other people and the building's reported damage level. The results of the bi-variate analysis summarized in Table 1 reveal that males were slightly more inclined towards evacuating than females; however, there was low significance between gender and evacuation. Although people aged 25-39 were more likely to evacuate compared to other age groups, there was no clear statistical significance between age and evacuation ( $p = 0.33$ ). The presence of other people did not have a significant influence on the evacuation decision ( $p = 0.27$ ), despite people alone being more inclined to evacuate than people who were with other people. The relationship between the building's reported damage and the evacuation behavior was very significant, as people who did not witness any buildings damage were more likely to remain in the building. As the damage level increased, the percentage of the people who evacuated increased as well.

Table 1 : Results of the bi-variate analysis of the evacuation behavior. (\*) symbol next to p-value shows the variable is significant

Did you get out of the building you were in?	Yes	No	Chi2	p-value
	%	%		
<b>Gender</b>			2.38	0.12
Female	22.3	77.7		
Male	29.4	70.6		
<b>Age</b>			3.4	0.33

18-24	23.5	76.5		
25-39	28.4	71.6		
40-64	22.9	77.1		
65 and more	12.5	87.5		
<b>Presence of other people</b>			1.21	0.27
Alone	30.5	69.5		
With other people	23.8	76.2		
<b>Buildings damage</b>			70.86	<0.01*
No	9.0	91.0		
Yes, low damage	23.6	76.4		
Yes, moderate damage	40.6	59.4		
Yes, strong damage	57.1	42.9		
Yes, totally destroyed	85.7	14.3		

## 2.2. Outdoor behaviors and mobility

Regarding outdoor behaviors, the multiple-choice question “When you were outside, what did you do?” was asked to the respondents who were outdoors during the explosion and to the respondents who had answered “Yes” to the question “Did you get out of the building you were in?”. The most common response was “I tried to meet up with family” (50%), followed by “I went to a safe area” (30.2%). 15.6% of the respondents helped people around them, 5.2% followed someone and 4.2% went to hospitals (Table 2).

Table 2 : Distribution of the behaviors adopted outdoors. N denotes the number of respondents.

<b>When you were outside, what did you do?</b>		
	N	%
I tried to meet up with family	96	50.0%
I went to a safe area	58	30.2%
I helped people near me	30	15.6%
I followed someone	10	5.2%
I went to hospital	8	4.2%
I contacted relatives	5	2.6%
I stayed where I was	4	2.1%
Other	25	13.0%
Total number of respondents	192	

To determine the actual mobility destinations, the open-ended question “Where did you go?” was asked to the respondents who were outdoors in the immediate aftermath of the explosion. The question received 151 free responses, which were grouped into relevant categories according to the destination mentioned (Table 3). The most common mobility destination was going home (38.4%), followed by going to the streets (19.9%). 11.9% of the respondents went to a hospital, while 10.6% headed towards a relative’s home. Some people mentioned staying in place (8.6%) while only 4 respondents went to their workplace.

Table 3: Destination reached in the aftermath of the explosion. N denotes the number of respondents

<b>Where did you go?</b>		
	N	%
Home	58	38.4%
Street	30	19.9%
Hospital	18	11.9%
Relatives home	16	10.6%
Stayed in place	13	8.6%
Work	4	2.6%
Other	12	7.9%
Total number of respondents	151	

The respondents’ knowledge of safe areas was also evaluated by the question “Do you know where the safe area is near you ?” (N= 481). The answers to this question revealed that only 27.4% of the respondents know where a safe area is located near their home and/or their work (Table 4).

Table 4: Respondents' knowledge of the location of safe areas

<b>Do you know where the safe area is near you ? (Safe area : area away from buildings in which you are protected in the event of emergencies like fires, earthquakes, etc.)</b>	N	%
No I do not know	349	72.6%
Yes, I know the safe zone near my home and/or my work	132	27.4
Total number of respondents	481	

### 2.3. Summary on human behaviors in response to sudden onset events in Lebanon

The survey allowed identifying that in Lebanon, evacuation is highly correlated to the perceived level of building damage, as individuals are more likely to evacuate with increasing building damage severity. In case of mobility, the most common behavior is joining family members, as 50% of the respondents wanted to join someone, and the most chosen target destinations were home, hospital, safe space or an undefined location such as a relative's place. The population's knowledge of safe areas is limited and only 27.4% of the respondents knew where the safe areas are located. These results are used to design the agent-based model for the simulation of seismic crisis and to calibrate it to the case of Beirut.

### 3. PEERS: Multi-model of seismic crisis in urban area

PEERS, like any model, represents a simplification of reality<sup>41,42</sup>. PEERS is based on a multi-model framework, recreating the interaction of three simple, but empirically and theoretically grounded models (Figure 1). PEERS combines a city model representing the spatial environment and the population, along with an earthquake damage model that represents the consequences of an earthquake (damages, debris, casualties) in the urban environment. PEERS also integrates a human behavior and mobility model. This model recreates complex human behaviors, as well as pedestrian mobility and constraints in an urban environment.

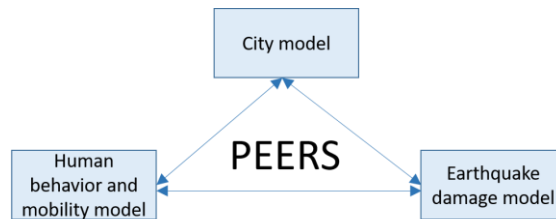


Figure 1: Multi-model framework in PEERS

#### 3.1. City Model

The city model in PEERS aims to recreate as closely as possible the spatial and social conditions in the urban area. It is composed of an urban environment model coupled with a model of the residents and their social ties (Figure 2). The urban environment model includes the features of the urban environment that are relevant for the simulation of human behaviors in response to an earthquake. It includes the boundary of the city that defines the spatial extent of the study area. The buildings are also included as they are urban assets that can be damaged when an earthquake occurs. Additionally, depending on the building's function (residential, work or hospital) it can serve for the population's distribution at different times of the day and it can also be a mobility destination in case of evacuation. Finally, buildings also represent obstacles for the mobility of pedestrians as people should avoid buildings and move around them when navigating in the urban area. The urban model also includes the open spaces in the city, which can provide a safe refuge space for taking shelter in the event of an earthquake<sup>43,44</sup>. However, in Beirut, open spaces may be secured by gates and barriers. When the gates are locked these open spaces become inaccessible to the population, thus morphing from what should be considered a safe space into an obstacle for pedestrian mobility. The possibility of an open space being locked is also taken into consideration in PEERS. Additionally, we have considered that depending on its surface, each open space has a maximum number of people that it can accommodate in safe conditions. Moreover, barriers that obstruct pedestrians' mobility are included. Barriers can be natural features of the terrain, such as cliffs or water bodies (rivers, lakes, etc.) or features of anthropic origins such as highways, bridges and tunnels. Finally, the slope of the terrain is included as it affects pedestrian movements: people exert an increased effort to travel an uphill slope and should move slowly to ensure their safety in steep downhill slopes, resulting in the reduction of their speed in both directions<sup>45</sup>. The model of the residents and their social ties recreates the size and spatial distribution of the exposed population. Additionally, PEERS' population is characterized by social attributes related to the population's age, gender and household composition. These attributes are included due to their relevance for the decision-making (presented in section 3.3). Each person is characterized by an age (from 0 to 100) and a gender (Male or Female). Additionally, the social ties between the residents are represented by organizing the population into households. A household is composed of members who share the same living space and who have social

ties. Each person is considered to belong to a household (one household only). Households may have different sizes; however, only one household member is designated as the head of the household, i.e., the person who has more decision-making power than others in the household and more control over the household's resources<sup>46</sup>. The notion of the head of the household was introduced in PEERS due its prevalent use in household surveys in Lebanon<sup>47</sup>. As the building stock in Beirut is composed mostly of apartment buildings and not individual houses, each household (and therefore its members) is considered to live in an apartment (one apartment only) in a residential building (one building only). The dynamic spatial distribution of the residential population is accounted for by locating the population in residential units during the night. This is because we make the assumption that people do not have any work or outdoors activities at night-time. During the day, people may have different activities: work/ school/ leisure activities, and therefore some people will be at home whilst others will be in non-residential buildings or outdoors. A probabilistic approach was therefore used to distribute the population during the day.

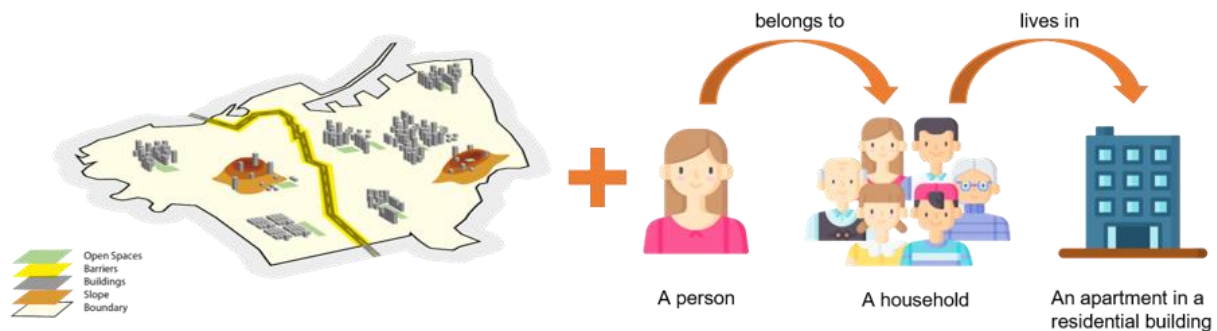


Figure 2: Illustration of the city model in PEERS composed of an urban environment model (to the left) and model of the residents and their social ties (to the right)

### 3.2. Earthquake damage model

The model can be adapted to several seismic scenarios, defined by the strength of the shaking and the duration of the earthquake. The strength of the shaking is represented by the Peak Ground Acceleration (PGA) at outcropping rock, the maximum recorded acceleration during an earthquake, a commonly used metric in earthquake engineering for the design of earthquake-resistant buildings<sup>48</sup>. The duration of the earthquake is especially relevant for the estimation of the casualties, as in the model, casualties occur due to falling objects and debris, assumed to only happen while the ground is shaking. The building damage assessment related to the simulated seismic scenario is based on Artificial Neural Networks trained to estimate the building damage according to the seismic scenario, the soil and building vibrational properties. However, the damage assessment is performed in a separate module, and not directly in PEERS. In this module, the damage state of each building is estimated and it ranges from no damage, to slight, moderate, extensive and complete damage. The extent and height of debris deposited around damaged buildings are also estimated based on a geometrical approach taking into account the building's typology and its level of damage. Similarly, the debris assessment is performed in a separate module, and the resulting results are integrated in PEERS as debris zones, defined by their heights and extent. Additional information on the building damage and debris assessment can be found in<sup>49</sup>.

To estimate the casualties (injury and death), we consider that during ground shaking, an agent that is in a building or in a debris zone might become injured with a probability (casualty rate) that depends on the building's typology and its damage state. The casualty rates are based on the HAZUS loss estimation manual of the FEMA<sup>50</sup> and are assigned to the buildings and debris zones accordingly. Although casualties from earthquakes are classified by HAZUS into 4 main severity levels, only three injury severity levels are considered in PEERS:

- Injury severity 2, which refers to an agent having a moderate injury, requiring going to hospital in order to be treated. Although in a crisis, some people with this level of injury may continue their activities instead of going to a hospital, for the sake of simplicity, we consider that they seek medical attention.
- Injury severity 3, which refers to an agent having a severe injury and consequently immobile, which would impose on the agent to stay in place and wait for emergency medical assistance.
- Injury severity 4 (fatal injury) refers to an agent being killed, and consequently the agent is considered dead.

Injury severity 1, related to injuries that require basic medical aid was not included in PEERS since it does not result in any behavioral changes such as severe mobility constraints nor an urgent need to go to a hospital.

### 3.3. Human behavior and mobility model

In PEERS, we can simulate “ideal” behaviors, i.e. how policy makers think individuals should behave, in which all agents adopt the official guidelines and evacuate towards the nearest open space with a minimal delay. In this scenario, agents

have perfect knowledge of where the open spaces are located and they behave autonomously regardless of their age. If an agent is indoors when the earthquake occurs, it evacuates from the building. However, a delay in the evacuation can occur because the agent may take time to perceive the shaking or take additional time to go down the stairs and arrive to the building's exit door. Consequently, we assume that agents might have a random delay between 0 to 100 s from the time of occurrence of the earthquake before leaving the building they are in.

We can also simulate "realistic" behaviors, i.e. how individuals have been observed to respond to previous events, in which agents can decide on the behaviors they want to adopt in the aftermath of an earthquake. These behaviors are derived from a targeted literature review on human behaviors in earthquakes and are adjusted to the local context using detailed survey results.

### Indoor behaviors

Since the model focuses on pedestrian mobility, evacuation is the only behavior modeled for indoor agents. Although other commonly observed indoor behaviors such as collecting belongings and looking for information are not directly modeled, they are considered as pre-evacuation behaviors and are accounted for by the time delay before evacuation. Therefore, agents that are indoor during the earthquake, decide to evacuate or not according to their evacuation probability, and in case of evacuation, the maximum evacuation delay is increased to 180 s (3 minutes) (compared to 100 s in the ideal case).

A binary logistic regression with multivariate categorical variables was performed on the survey data to derive the individual evacuation probability of each agent. The explanatory variables were chosen as the damage level of the building and the gender and age of the agent. Although gender and age had little significance on evacuation behavior, they were included in the logistic regression model to incorporate the difference in the behavioral choice across agents of different genders and age groups. The results of the regression analysis are displayed in Table 5. The probability of evacuation can be calculated for each agent by multiplying each variable by its corresponding coefficient (coef. in Table 5) as follows:

$$p_{i, \text{evac}} = 1 / (1 + e^{\left( - \left( 0.893104 - 4.584032 \times D_N - 3.427137 \times D_S - 2.405917 \times D_M - 1.707436 \times D_E + 1.825227 \times A_{24} + 1.910626 \times A_{39} + 1.208290 \times A_{64} - 0.543178 \times S_F \right) \right)}) \quad (1)$$

where  $D_N$ ,  $D_S$ ,  $D_M$  and  $D_E$  are binary variables corresponding to the damage level of the building, representing respectively none, slight, moderate and extensive damages. The binary variables  $A_{24}$ ,  $A_{39}$  and  $A_{64}$  are variables related to the age of the agent, representing respectively being aged less than 24, between 25 and 39, and over 64. Finally, the variable  $S_F$  refers to the agent's gender, being a female in this case.

Table 5: Results of the multivariate binary logistic regression analysis between the evacuation behavior and the building damage, age and gender

Variable	Reference category	Coef.	Odds ratio
<b>Constant</b>		0.893	
<b>Building damage</b>	<i>Totally destroyed</i>		
No damage		-4.584	0.010
Low damage		-3.427	0.032
Moderate damage		-2.406	0.090
Strong damage		-1.707	0.181
<b>Age</b>	<i>65 and more</i>		
24 and less		1.825	6.204
25-39		1.911	6.757
40-64		1.208	3.348
<b>Gender</b>	<i>Male</i>		
Female		-0.543	0.581

### Outdoor behaviors

Agents that are outdoor (during the earthquake and those that evacuated) have a target destination, representing the first destination the agent heads to after experiencing the earthquake, which depends on the agent's motivations and other contextual factors. The survey revealed that in outdoor situations, the most common behaviors in the immediate aftermath of a sudden onset event in Lebanon are meeting up with family members usually at home, going to a safe area, going to a hospital and going to an undefined location (such as the street or a friend's place). However, the factors that influence the choice of target destination could not be directly inferred from the survey since it did not contain a close-ended question asking the respondents to choose among one of these options when specifying their mobility destination. In order to fill this gap in the data, it was assumed that the target destination of each agent depends on its characteristics, namely: whether or not the agent knows where the open spaces are located, whether or not the agent wants to join a family member and



whether or not the agent is injured. The probabilities of knowing the location of open spaces and joining someone are derived from the survey results (27% and 50% respectively). The probability of having a moderate injury depends on the agent's location during the earthquake, whether the agent is in a building or a debris zone during the earthquake, and therefore is computed during the simulation.

The probabilities of choosing each target destination according to the agent's characteristics are summarized in Table 6. We assumed that if an agent knows the location of open spaces, the target destination is the nearest open space. If an agent is not at home and wants to join someone, the target destination is the home building and if an agent has a moderate injury (severity 2), the target destination is the nearest hospital. If an agent does not know the location of open spaces, does not want to join a family member, and is not injured, the agent would go an undefined location. However, if an agent has more than one of these characteristics, the probability of following the recommended behavior (going to open space) decreases in the favor of altruistic (going home to check-up on family members) and self-preservation behaviors (going to a hospital to treat injuries). Altruistic and self-preservation behaviors were given the same level of priority whenever an agent had to choose between these two options. These parameters were based on assumptions due to the lack of data; nevertheless, if in the future more data become available they can be easily changed depending on the new findings.

Table 6: Target destination choice in PEERS according to the agent's characteristics

Agent's characteristics			Probability of choosing each target destination			
K.	WJS	HMI	OS	HOM	HOS	UL
OS						
Yes	No	No	100%	0	0	0
No	Yes	No	0	100%	0	0
No	No	Yes	0	0	100%	0
Yes	Yes	No	30%	70%	0	0
Yes	No	Yes	30%	0	70%	0
No	Yes	Yes	0	50%	50%	0
Yes	Yes	Yes	20%	40%	40%	0
No	No	No	0	0	0	100%

**K.**OS: knows the location of open space; **WJS**: Wants to Join Someone; **HMI**: Has a Moderate Injury; **OS**: Open Space; **HOM**: Home; **HOS**: Hospital; **UL**: Undefined Location.

### Group behaviors

Additionally, as several observations have reported, in emergencies families tend to group and evacuate together<sup>51</sup>, PEERS integrates group behaviors driven by the social bonds between the household members. A group is formed indoors whenever agents from the same household are in the same building. In outdoor scenarios, agents from the same household group together whenever they are within 50 meters from each other; this is the perception distance between family members<sup>16</sup>. As found in the literature, each group is characterized by a leader, a person who is in charge of the decision-making and is followed by the other group members<sup>52</sup>. Therefore, in PEERS, each group has a leader, evaluated when the group is formed and every time the group members change. The group's leader is assigned as the head of the household, if the head is in the group, otherwise, the agent with the highest leadership score, a metric introduced to classify agents according to their level of influence on others during emergencies, is assigned as the group leader. The leadership score is calculated as the average of the open space knowledge (1 if the agent knows the location of open spaces, 0 otherwise), and the agent's age normalized over 100, the maximum age that an agent can have in PEERS (equation 2).

$$leadership\ score = \frac{open\ space\ knowledge + \left(\frac{age}{100}\right)}{2} \quad (2)$$

The open space knowledge was considered as a leadership indicator as it has been found in previous emergencies that people with a better knowledge of emergency egress routes often lead other evacuees towards safe destinations<sup>53</sup>. The choice of the age as a leadership indicator come from observations that in Lebanese families, the relational structure is mostly vertical<sup>54</sup>. Older members, such as parents or older siblings often assume leading roles with respect to other family members. The leader is followed by the other group members in both the evacuation decision and the choice of mobility destination. Hence, if the group is indoors during the earthquake, the group's decision to evacuate will be the same as the leader's. In the case where a group evacuates, all group members evacuate at the same time<sup>55</sup>, they wait for the group member who has the longest evacuation delay. Similarly, the individual target destinations of the group members are changed to the target destination of the group's leader. To ensure the group navigates in a cohesive manner towards the leader's target destination the leader is set to navigate towards its target destination while the other group members follow the leader by navigating towards the leader's position at each step. Additionally, the group's cohesion is also maintained by imposing the same speed for all group members, set to the speed of the slowest group member<sup>56</sup>.

### Safety conditions

An agent that arrives to a home, a hospital or an undefined location, is not considered safe, as the agent's exposure to threats from aftershocks is high if it is close to buildings. An agent is only considered safe when it arrives to an unlocked and unsaturated open space. If an agent arrives to a locked open space, we assume that communication will happen between the agents, and those that know which open spaces are unlocked will inform the others. Therefore, the agent changes destination and goes to the nearest unlocked open space. If an agent arrives to a saturated open space, we assume that this agent will prefer to stay around the crowd gathered in the open space rather than traveling again towards another open space. Therefore, the agent stays outside the saturated open space. This hypothesis is based on the theory of social attachment<sup>57</sup>, which claims that in response to threats and disasters, people seek the proximity of familiar people and places for the calming effect it brings them, even if this results in approaching or remaining in an unsafe situation.

## Mobility

To model the mobility of individuals in the aftermath of an earthquake, we assume that all mobility behaviors take place on foot, but for simplification purposes, we consider that pedestrian mobility is not restricted to the sidewalks. Agents can move freely in the urban space, however, several constraints affect their route options and speed. The agents' motion is based on the social force model (SFM)<sup>58</sup>. Each agent has an attraction force towards its target. The agent avoids collisions with other agents, and keeps a safe distance from buildings and debris zones. The avoidance of agents, obstacles and debris zones are modeled as repulsive forces on the agent. The sum of these forces determines the direction at which the agent will move. The agent's step size, determined by its speed, depends on its age as defined in<sup>16,59</sup>. Agents are classified into three age categories: children, adults and elderly, each category being characterized by a minimum and maximum preferred speed (Table 7). Each agent's preferred speed is assigned following a normal distribution according to the minimum and maximum speeds of its age category.

Table 7: Preferred speed for agents in the child, adult and elderly categories as defined in Bañgate et al., 2018, 2019

Category	Age	Preferred speed (m/s)
Child	<14	0.56 - 2.23
Adult	15-59	0.9 - 3.83
Elderly	60+	0.7 - 1.11

$$\gamma = e^{-3.5 (|\tan \theta + 0.05| - 0.05)} \quad (3)$$

Moreover, the speed of an agent can be affected by the slope of the terrain, as when an agent is moving uphill or downhill, its speed is reduced by a factor  $\gamma$  that depends on the slope's value.  $\gamma$  is calculated using equation (3) given by<sup>60,61</sup>, where  $\theta$  is the slope angle relative to the horizontal plane (in degrees). In addition to the slope, the presence of debris further constrains the agent's mobility: when an agent is in a debris zone, it is moving on unsteady objects and therefore the agent needs to adjust its speed to manage this instability. As suggested by Osaragi and Oki<sup>62</sup>, the effect of the debris on the agent's speed depends on the debris height, as if the debris height is less or equal to 1 m, the agent's speed is reduced by 50%. For higher debris zones, the agent's speed is reduced to 0.16 m/s to simulate that the agent has to climb over the piles of debris.

After defining the three sub-models of PEERS (city, earthquake damage, human behavior and mobility) as well as their interactions, PEERS was formalized in a UML (Unified Modelling Language) class diagram and the activity diagram of person agents was defined as well. Both the class and activity diagrams can be found in the Appendix. Although PEERS could not be validated by stakeholders in Beirut due to unstable political and institutional contexts in Lebanon during our study, the development of the model benefited from a strong collaboration with researchers in social sciences and earthquake engineering in Lebanon in the framework of a funded by the AUF-PCSI<sup>2</sup>. The model and the first simulations were presented in international conferences and received encouraging feedback from different research communities<sup>63,64</sup>.

## 4. Implementation, calibration and experiments: Application to Beirut, Lebanon

### 4.1. Implementation

PEERS was implemented in a simulation platform to perform dynamic simulations of pedestrian evacuation and mobility in a seismic event. The GAMA Platform<sup>3</sup><sup>65</sup> was chosen for the implementation of PEERS due to its (1) ability of integrating and manipulating geospatial data, (2) capacity to handle large-scale simulations, needed to run simulations at the city scale (3) intuitive modeling language (GAML), which makes it accessible to non-computer scientists and (4) open source framework, which facilitates the reproduction and the communication of the model.

### 4.2. Calibration to the case of Beirut

Due to the lack of complete and accessible data in Lebanon, we relied on heterogeneous data sets from various sources,

<sup>2</sup> Agence Universitaire de la Francophonie- Projets de Coopération Scientifique Inter-universitaire

<sup>3</sup> <http://gama-platform.org/>

such as OpenStreetMap and high-resolution satellite images to prepare the GIS shapefiles related to the urban features in Beirut (buildings, open spaces, etc.) as displayed in Figure 3. In total, 15 089 buildings were identified (13 930 residential, 1 073 work and 86 hospitals) as well as 268 open spaces (total surface area of 4 028 220 m<sup>2</sup>). The capacity of each open space was calculated on the basis of 2 m<sup>2</sup> per person<sup>66</sup>. Moreover, the open spaces that can be locked were identified; they consist of the Sanayeh Garden, Horsh Beirut, the Hippodrome, the Sioufi Garden and the port of Beirut (Figure 3). A synthetic population of 819 717 individuals was generated in GAMA using Gen\* plugin<sup>67</sup> with attributes of age and gender according to the distributions provided by the Central Administration of Statistics in Lebanon (CAS)<sup>47</sup>. These individuals were then fitted into households following ad-hoc rules based on the distributions of the household sizes in Beirut, the age and gender of the head of the household and the relations of the other household members to the head of the household. This has resulted into the generation of 246 325 households, each assigned to a residential building as a home building.

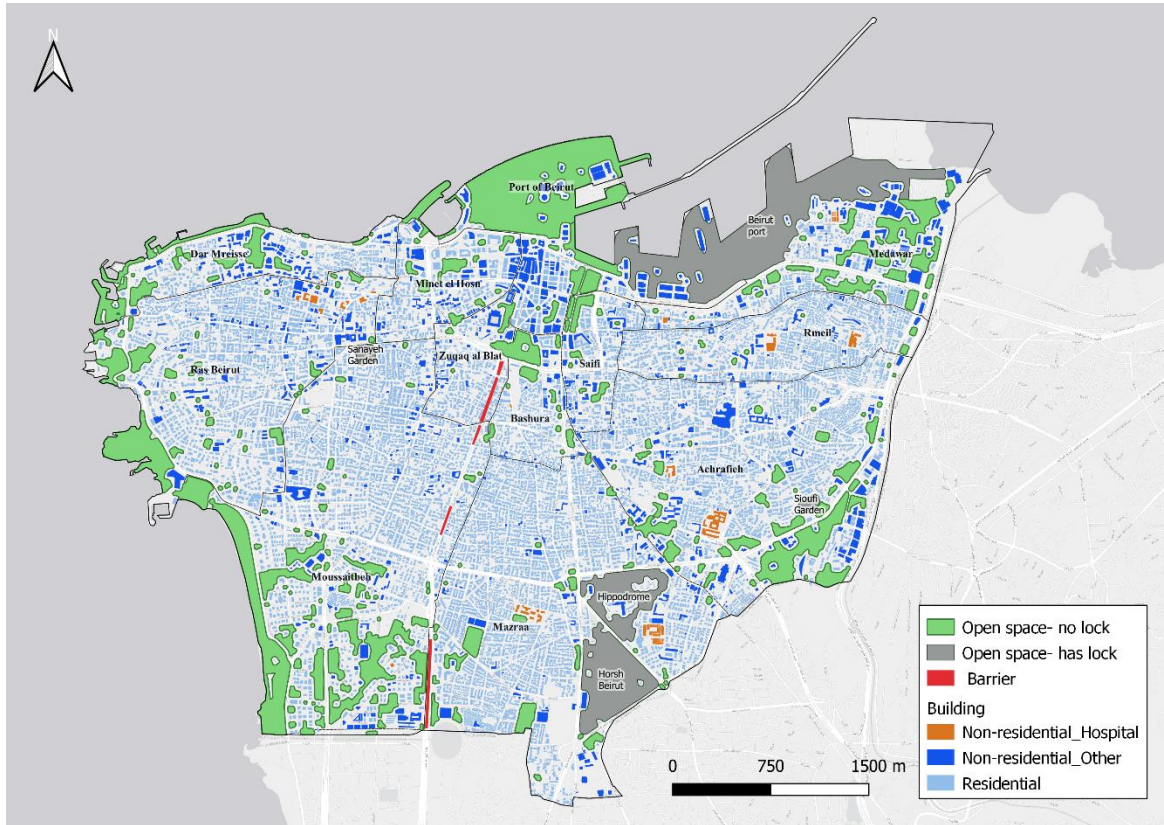


Figure 3: Map of the urban features in Beirut, Lebanon

### 4.3. Experiments

The experiments with PEERS were designed to answer the two research questions related to the safety of Beirut's population in the immediate aftermath of an earthquake. The research questions, simulated scenarios and their corresponding parameters are summarized in Table 8 and further detailed hereafter. The first research question is related to Beirut's urban form, and particularly to the open spaces and their capacity of providing shelters for the residents in the immediate aftermath of an earthquake. This question was investigated by two experiments that represent ideal (or near ideal) conditions, however with varying complexity levels. We defined a first scenario (Scenario 1) that represents a baseline scenario. An earthquake with a PGA of 0.3 g, which is the recommended acceleration for the design of earthquake-resistant buildings in Beirut, all the open spaces are unlocked, all the individuals go to the open spaces with a minimal delay (ideal behavior) and the residents are all located in their homes (night scenario). A night scenario is considered in the "ideal" case, as it contains less uncertainty about the spatial distribution of the population compared to a day scenario. In the second scenario (Scenario 2), we add to the previous scenario an additional complexity factor by defining a scenario that represents the realistic access conditions to the open spaces in Beirut. In this scenario, all the open spaces in Beirut that have gates are considered locked. The earthquake's PGA is 0.3 g, the population adopts ideal behaviors, and the scenario occurs at nighttime.

The second research question is centered around the impact of the physical and social environments on the population's safety following an earthquake. To answer this question, we examine the increasing challenges on population's safety that are imposed by a stronger earthquake and realistic human behaviors. Scenario 3 is defined as a scenario with a stronger earthquake. In this scenario, we consider an earthquake with a PGA of 0.5 g. The other parameters related to the open

spaces and the population’s distribution and behaviors remain ideal. The objective behind this scenario is to analyze the impact of the increased debris in the environment on the population’s safety. In Scenario 4, we introduce more complex realistic human behaviors by considering group behaviors and the possibility of adopting different behavioral choices. The other parameters are considered ideal: the earthquake’s PGA is of 0.3 g, the open spaces are unlocked, the scenario takes place at night-time. The goal of this scenario is to analyze the effects of the realistic behaviors on population’s arrival to safe areas.

Table 8: Research questions and parameters of the experiments in PEERS. The cell indicating the parameter of interest in each scenario is highlighted in green. All scenarios are night-time scenarios

Research question	Scenario number	Earthquake PGA	Open spaces locked	Behaviors
Does Beirut’s urban form, particularly its open spaces, have the capacity to provide shelters for the residents in the immediate aftermath of an earthquake?	1	0.3 g	True	Ideal
	2	0.3 g	False	Ideal
What is the impact of the physical and social environments on the population’s safety following an earthquake?	3	0.5 g	True	Ideal
	4	0.3 g	True	Realistic

## 5. Simulations and results

In PEERS, each simulation step (or cycle) represents 1 s. Therefore, 900 cycles were executed to simulate 15 minutes from the occurrence of the earthquakes. These simulations allow to follow the evolution of the states of the population and the open spaces in the city by capturing at each simulated step, the location of the agents, whether they are safe, in a debris zone, indoor, or outside a saturated open space. PEERS also captures the arrivals of people to open spaces, and monitors for each open space the number of occupants and its occupancy rate, as well as the time required for the agents to reach the open space. Although PEERS can estimate the number of casualties and their severity, in the application to Beirut we did not focus on this aspect, the purpose of the experiments being the analysis of the population’s safety and arrivals to open spaces.

The simulations were executed in the headless mode (without graphical interface) on the cluster of the ISTerre laboratory. All the nodes on this cluster are configured with a Debian Linux operating system and are equipped with Intel(R) Xeon(R) processors with frequencies ranging between 2.2 and 3 GHz, and with a RAM capacity of 192 GB per node. Each scenario was run for 5 times to take into account the stochasticity of the model and the outputs of the different runs of the same scenario were averaged before analyzing them. For scenario 1, the simulation took 360 h (around 15 days) including 15 h for the initialization, with an average cycle duration of 23 min. The duration of each cycle increased with increasing number of active agents (Figure 4). For scenarios 2, 3 and 4 the average cycle durations were of 20 min, 23.7 min and 12.5 min respectively. The decrease of the cycle duration in scenario 4 can be explained by the difference in the number of active agents between simulations with ideal behaviors (i.e. scenarios 1, 2 and 3) in which all agents have mobility behaviors, and simulations with realistic behavior (i.e. scenario 4), where only a percentage of the agents is active.

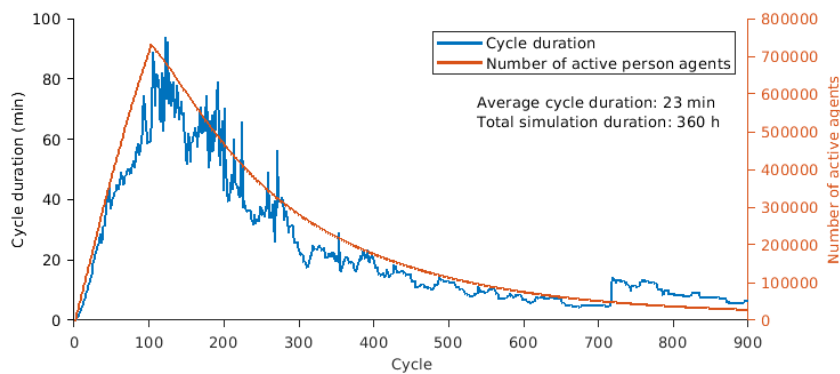


Figure 4: Time taken (in min) to execute each cycle of the simulation of scenario 1 on the ISTerre cluster. The number of active agents is also plotted for reference

### 5.1. Open space capacity in Beirut

To investigate the open space capacity in Beirut, we analyze first the simulation results of Scenario 1. After 15 minutes, i.e. at the end of the simulation, only 38% of the population was safe in an open space, while 59% arrived to a saturated

open space and 4% have not arrived (Figure 5). In Figure 6 displaying the agents' arrival times to unsaturated open spaces; it appears that the first arrival to an open space was recorded after 8 s from the start of the simulation. Such a fast arrival time could represent the arrival of a person who lives at the ground floor of a building located just next to an open space. Overall, 50% of those who arrived to an unsaturated open space did so in the first 150 s. The average arrival time to an open space is 198 s with a standard deviation of 146 s. The maximum arrival time of 900 s, suggests that people were still arriving to unsaturated open spaces at the end of the simulation. In total, with 38% of the agents (311 492 agents) in open spaces and a total open space surface in Beirut of 4 028 220 m<sup>2</sup>, only 15% of the open spaces surface could be used by the population. While 50% of the open spaces in Beirut had an occupancy rate higher than 80%, 29% of the open spaces received less than 20% of their maximum capacity. The spatial distribution of the open spaces' occupancy rates (Figure 7) shows a large contrast between the large open spaces on the outskirts of the city that are barely occupied and the smaller open spaces within the city that are highly saturated. It is not only the capacity of the open spaces that determines the population's safety, but also the distribution of the open spaces' sizes and distance from populated areas. Therefore, from the simulation results, we can conclude that although in theory the open spaces in Beirut have enough capacity to provide safe shelters, the distribution of these open spaces in terms of size and location does not match the population's need even in ideal conditions when all the open spaces are unlocked.

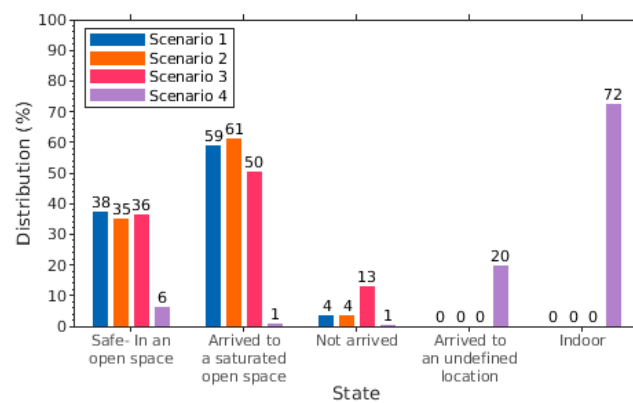


Figure 5: Distribution of the agents' states at the end of the simulation in Scenarios 1 to 4

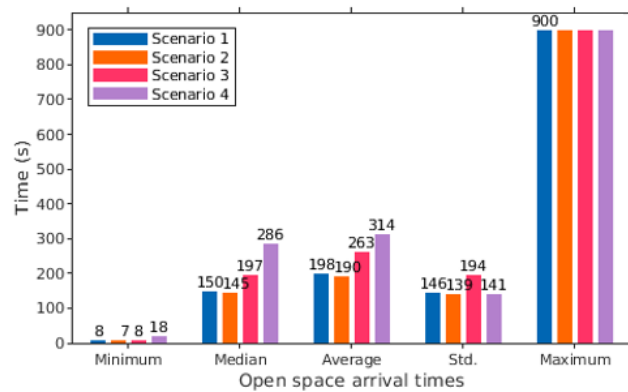


Figure 6: Distribution of arrival times to open spaces in Scenarios 1 to 4: minimum, median, average (and standard deviation), and maximum arrival times

### Case of an earthquake of PGA 0.3 g with some open spaces locked

When some of the open spaces were locked (Scenario 2), less agents (35% compared to 38% in Scenario 1) were able to arrive to open spaces, whereas more agents arrived to saturated open spaces (61% compared to 59% in Scenario 1) (Figure 5). Although locking some open spaces (5 out of 268) did not have a major impact at a macro-scale; at a local level, it resulted in an increase of the population's influx towards the open spaces around the locked open spaces as displayed in Figure 8. When we analyze the individual situation of each open space, locking the Sanayeh Garden resulted in an increase of the influx towards the two already saturated open spaces nearby, which showed an increase of 6 762 and 1 214 agents outside each open space. 100% of the agents that were coming to the Sanayeh Garden ended up outside a saturated open space, and therefore could not find another shelter Figure 8(a). Similarly, for Horsh Beirut and the Hippodrome displayed in Figure 8(b), although around 2 225 agents could go to the unsaturated open spaces in the south of Horsh Beirut and the west of Hippodrome, more than 10 000 agents arrived to saturated open spaces that do not guarantee their safety. If we look at the case of Sioufi Garden displayed in Figure 8(c), the open spaces around it gave shelter to around 1 600 agents,

while 823 agents were found in a saturated open space at the northwest of the locked open space. Finally, for the port of Beirut displayed in Figure 8(d) we observe that most of the agents could find a safe space in the unsaturated open spaces nearby, while only 246 agents went to a saturated open space. We can conclude that locking some open spaces in Beirut does not have a major impact on a global level. However, at a micro-scale the effect on the population's safety is important, especially for open spaces that are surrounded by saturated open spaces.

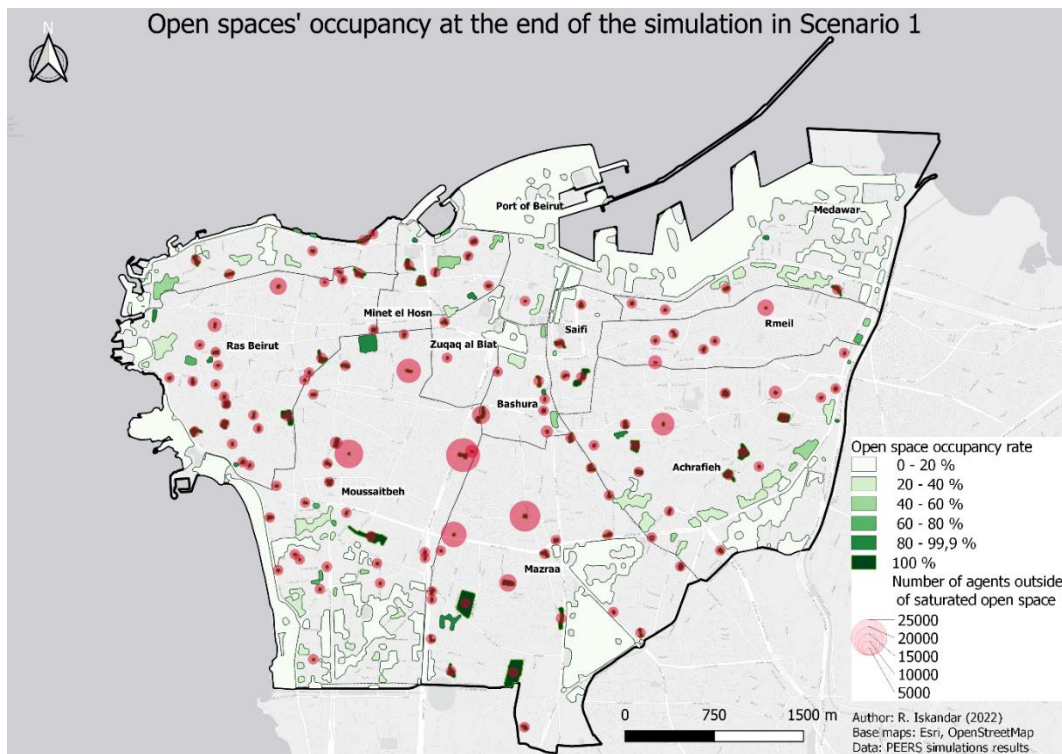


Figure 7: Occupancy rates of the open spaces in Beirut at the end of the simulation in Scenario 1

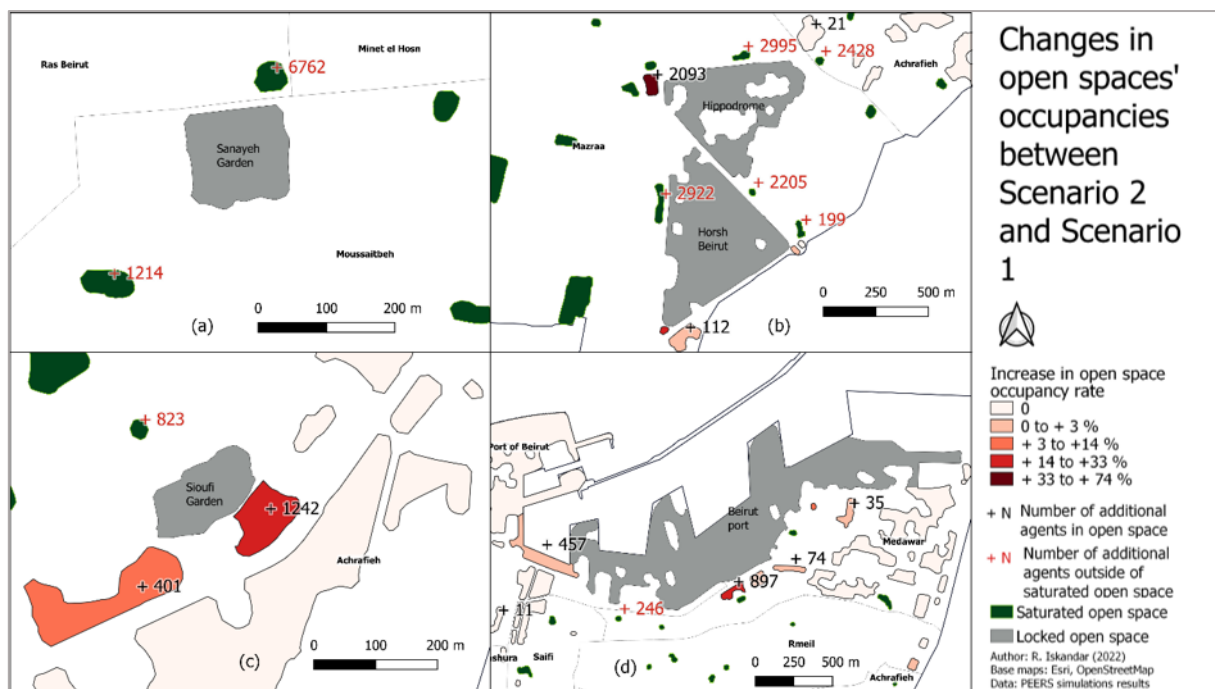


Figure 8: Changes in the occupancy of the open spaces between Scenario 2 and Scenario 1. Close up on locked open spaces: (a) Sanayeh Garden, (b) Horsh Beirut and Hippodrome, (c) Sioufi Garden, (d) Beirut port

## 5.2. Impact of the physical and social environments on population's safety following an earthquake

### Case of a stronger earthquake

In this section, we analyze the effects of considering an earthquake of  $PGA = 0.5$  g (Scenario 3), compared to a more conservative earthquake of  $PGA = 0.3$  g (Scenario 1) on the agents' arrival to safe areas. At the end of the simulation, the percentage of arrival to safe areas decreased by 2% in Scenario 3 (from 38% in Scenario 2 to 36% in Scenario 3) (Figure 5). The most significant changes are the decrease of the percentage of agents outside of saturated open spaces, from 59% in Scenario 1 to 50% in Scenario 3, and the increase of the percentage of agents that were still moving towards open spaces from 4% in Scenario 1 to 13% in Scenario 3. The increase of the percentage of agents that were still moving at the end of the simulation can be explained by the effect the debris have on the speed of the individuals. With an earthquake of  $PGA = 0.5$  g the debris are higher and wider than in an earthquake of 0.3 g. Therefore, agents take longer to travel in the environment and at 15 minutes, a higher percentage of agents was still moving. The effect of the debris can also be seen on the time agents took to arrive to a safe area, as the average time to reach an open space increased from 198 s in Scenario 1 to 263 s in Scenario 3, which corresponds to a relative increase of 33% (Figure 6). On the map in Figure 9 showing the changes in both the number of agents in open spaces and the number of agents outside of saturated open spaces between Scenario 3 and Scenario 1, we can see that the highest changes occur in the southern part of the city. This is correlated with the distribution of the debris having heights exceeding 1 m. The number of people in open space may show a decrease reaching - 2 500 arrivals after an earthquake of  $PGA$  of 0.5 g compared to a scenario of  $PGA$  of 0.3 g. Similarly, the number of agents outside saturated open spaces can be reduced by as far as -12 000 agents.

### **Case of realistic behaviors**

When realistic behaviors were considered (Scenario 4), the number of safe agents at the end of the simulation was significantly reduced (6% compared to 38% in Scenario 1) (Figure 5). This observation is mainly because 72% of the agents remained indoor and did not evacuate when realistic behaviors were considered. In addition, most of the agents that evacuated went to an undefined location (20% of the agents) rather than going to an open space (6% of the agents). As the influx towards open spaces was reduced, the percentage of agents arriving to saturated open spaces also decreased (1% compared to 59% in Scenario 1). The arrival times to open spaces were significantly higher in Scenario 4 than in Scenario 1 (Figure 6). The minimum arrival time increased from 8 s in Scenario 1 to 18 s in Scenario 4, while the average arrival time increased from 198 s to 314 s in Scenario 4, representing a 59% increase in the average time taken by a person to reach a safe area when realistic behaviors were considered. The longer arrival times observed in Scenario 4 can be explained by two factors. Firstly, when realistic behaviors are considered, the evacuation delay is longer due to pre-evacuation activities, which results in a longer time taken by the agents to start moving towards the open space. Secondly, in Scenario 4, as all the agents are located at home, all agents behave in groups (except agents in households composed of only one member). In total, 207 198 groups were formed in Scenario 4. As agents behave in groups, their evacuation delay is increased to match the delay of the group member with the longest delay, and their speed is reduced to the speed of the slowest group member, resulting in a two-fold effect of the group behavior on the time taken to arrive to an open space.

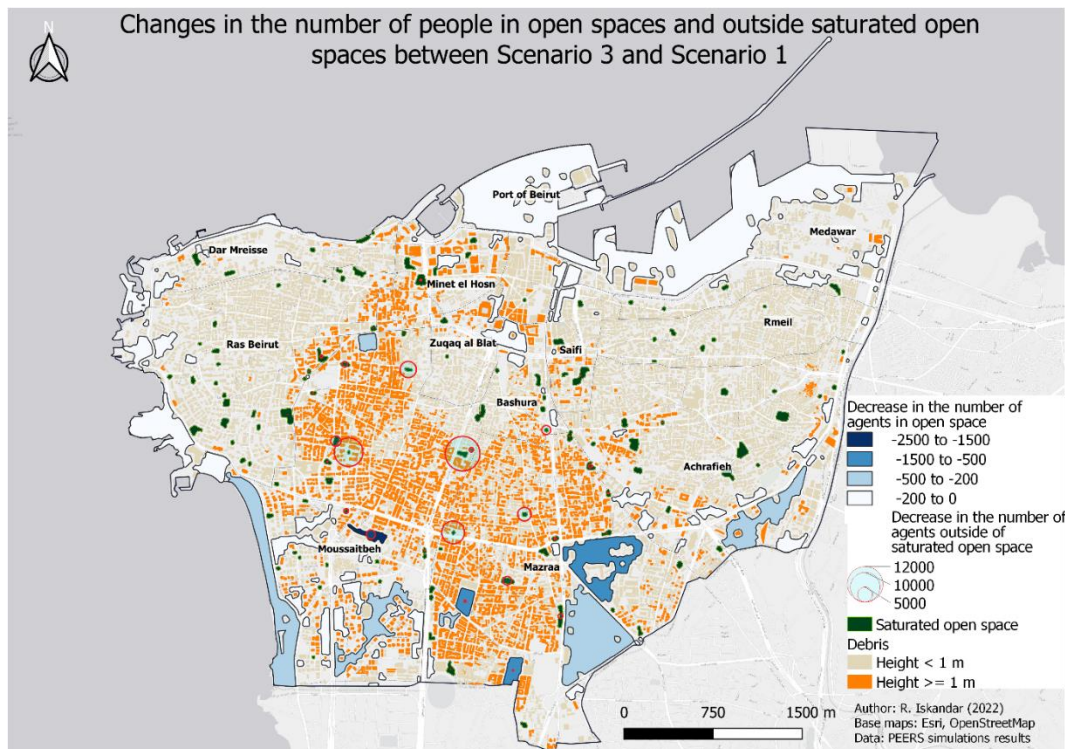


Figure 9: Changes in the number of agents in open spaces and outside saturated open spaces between Scenario 3 and Scenario 1

## 6. Discussion

The simulation results have highlighted that in Beirut, the distribution of open spaces in terms of size and location cannot ensure the safety of all of the population, even in ideal conditions where the behavioral component is reduced to reaching the closest safe area only. Indeed, in this case, only 38% of the population reached a safe area within 15 minutes after the onset of ground shaking even though the theoretical capacity of open spaces should shelter all of the city's residents. This can be explained by the distribution of the open spaces in terms of size and location within the city, as large open spaces are on the outskirts of the city. This is an important finding on Beirut's urban form that was highlighted through the simulations in PEERS. It further proves that the city's dense urbanization and lack of planned open spaces have a detrimental effect on the population's safety in case of seismic crisis. From this perspective, running evacuation simulations with realistic spatial data can contribute to the assessment of the current capacities of the urban area. Such simulations can help improve the urban planning and the city's earthquake preparedness by testing what-if scenarios, such as: what-if we demolish this old building and transform this area into an open space? These simulations can have a high positive impact if taken into account by the local stakeholders in charge of decision-making.

Moreover, both the physical and social environments significantly impact the population's safety post-earthquake. The consideration of a stronger earthquake affects the population's safety by increasing the time taken to reach an open space. This is mainly caused by the environmental modifications due to the earthquake, as the debris are higher and wider and cause more mobility constraints. When considering realistic human behaviors, the percentage of the population in open spaces is lower than when ideal behaviors are assumed. This is mainly because a high percentage of the population would remain indoor, and the majority of those who evacuate would go to an undefined location. Furthermore, the average time taken for a person to reach an open space is significantly increased compared to the same scenario with ideal behaviors. This increase in time is due to an increase in the evacuation delay and an increase in the travel time to reach an open space, which are both affected by social interactions and group behaviors. These results further validate the importance of considering realistic human behaviors when simulating earthquake evacuation.

Nonetheless, these results must be interpreted with caution and a number of limitations should be kept in mind. One of the limitations is related to the calibration of realistic human behaviors using survey data based on the particular case of the Beirut port explosion. The behavioral responses should be compared to observations in earthquakes in Beirut to validate that the same trends would be observed. Moreover, in the future the survey should be improved to include close-ended questions about the individual mobility in the aftermath of an earthquake, in which the respondent picks the first destination he/she went to. By defining the possible answers and limiting the options to one choice only, a multivariate statistical analysis can be done to identify the motivations depending on the choice of target destinations. Additionally, questions related to the injury level of the respondent could be added, which would allow correlating behaviors with different injury levels. Additional limitations can be highlighted in the modeling choices taken in the human behavior and mobility model.



For instance, all agents are given the ability to decide on their behavior and move towards their destination. This does not reflect reality, as young children and people with psychological or mobility disabilities might have limited capability for decision-making and autonomous mobility. A more realistic approach could be achieved by considering a percentage of agents that have disabilities. These agents would have a very low probability of moving or deciding autonomously. Moreover, other agents could be given the role of “caregiver”, and assist disabled agents and young children in evacuation. Another limitation comes from the assignment of the leadership score as a function of the group members’ age in an absolute manner. This might not represent reality in which adults with senior parents often assume leadership positions. Ideally, in future simulations we plan on including an age where the “leadership” moves to the younger household members. However, this would need a deeper investigation about household structures, which was not possible given the limited data available on Beirut’s population. Furthermore, PEERS only includes social groups formed by household members, disregarding other social ties such as friends and coworkers, and spontaneous groups that form during a crisis between strangers. These social groups will be included in future works to diversify the composition of groups. Another limitation that can be noted in the earthquake consequence model, particularly the estimation of casualties using HAZUS models, originally targeted for studies in the US, which might not be realistic when used in different geographical areas. Future work should focus on the analysis of casualty rates across different geographic and cultural contexts. In the absence of sufficient data, this can be done by comparing the study area to other countries with similar contexts. Finally, the results of this study could not be adequately validated, as no actual measures exist for counting the number of people in open spaces in the aftermath of a seismic event, or for the time taken for the population to reach an open space. In future works, possible approaches could be the use of videos and photos available through social media or on-line after an earthquake and/or the use of dark fiber optics data to monitor the population flow and count the number of individuals grouping in a safe area.

Despite these limitations, the simulations of earthquake evacuation in Beirut gave a first estimation of the importance of the distribution of open spaces and human behaviors and debris on pedestrians’ evacuation in the aftermath of an earthquake.

## 7. Conclusion

In this paper, we presented PEERS, an agent-based model for the simulation of pedestrian evacuation in an urban area in the immediate aftermath of an earthquake. The multi-model framework of PEERS is based on three underlying models representing the city, the earthquake damage and the human behavior and mobility. High levels of realism are achieved with PEERS through the integration of GIS data to represent the urban features and a synthetic population that replicates the demographics of the study area. Moreover, the earthquake damages, debris and casualties are based on established models for the estimation of earthquake consequences depending on the seismic scenario. The simulated human behaviors can represent ideal behaviors, in which the population follows the official recommendations, or realistic behaviors based on observations from previous events that are calibrated by survey results. PEERS was applied to the case of the city of Beirut in Lebanon and simulations of four different scenarios were performed to answer two research questions related to the population’s safety in case of earthquakes. Through these simulations, we found that even in ideal conditions, the distribution of open spaces in Beirut does not allow for more than 40% of the population to be safe in the event of an earthquake. Moreover, the population’s safety is further constrained by the debris and the human behavior. Although PEERS was developed and applied to the case of the city of Beirut, it can be adapted to other study areas given that the relevant data are available. Particularly, the calibration of the realistic human behavior model would require the acquisition of data on behaviors in previous events, possibly through post-seismic surveys.

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# Appendix

## 1. UML Diagram of PEERS

Figure 10 shows the UML class diagram of PEERS. PEERS has a multi-level architecture, represented by a world class that contains 4 high-level classes: *person*, *obstacle*, *debris\_zone* and *open\_space*. The classes *building* and *barrier* represent different types of obstacles. Finally, the *people\_in\_group* class represents a special type of person: a person who belongs to a group; and the *group* class represents a group of people. A brief presentation of each class with its attributes and methods is given in the following:

- The class *world*, defines the environment that contains the other classes of the model. The *world*'s attribute *shape* represents the extent of the environment, and therefore the limits of Beirut. The *world* also defines the *free\_space* geometry, which represents the space in the environment that is free from obstacles. Additionally, the topography of the environment is represented by the attribute *slope* that indicates the slope of the terrain.

In addition to its spatial attributes, the *world* defines the scenario considerations of the simulation. The earthquake scenario is defined by specifying the duration of the earthquake, its PGA and the time of day when it occurs. The *world* also defines considerations related to the behaviors of the individuals: whether the individuals follow the ideal guidelines or behave realistically, whether the open spaces that have locked gates or not.

- The *person* class represents the residents of the city, each characterized by an age and a gender. Each *person* has a *home\_building* and a *household\_ID*. The *household\_ID* defines the household to which each person belongs, therefore, people from the same household share the same *household\_ID*.

A boolean *is\_head\_household* is added to the *person* class, to represent if a person is the head of the household. Additionally, the booleans *wants\_to\_join\_someone* and *knows\_open\_space\_location* represent respectively if a person wants to join a household member and if the person knows the location of open spaces.

The *person*'s attribute *target\_destination* designates the type of the destination the person wants to go to, which can be an open space, a building (hospital or home), or an undefined location. On the other hand, the precise location that a person wants to go to is designated by the point attribute *target\_loc*.

The *person* class also has attributes related to the situation of the person, such as the *is\_in\_danger* boolean that takes a *true* value when the person is in a debris zone, and the *is\_safe* boolean that takes a *true* value when a person is in an open space. Additionally, the injury level of the person is indicated by booleans that represent if the person has a moderate, severe or a fatal injury.

The *person* class has methods that represent the actions taken by a person, such as evacuating, evaluating a target destination, going to a target, changing target open space, waiting near an open space and arriving to a destination.

- The *obstacle* class represents the obstacles that block the mobility of pedestrians and that should be avoided when he/she is moving. The obstacle can be either a *barrier* or a *building*. The *building* class has a *function* attribute that defines the use of the building. For implementation purposes, we have added a point attribute *door* to designate a location on the building's façade that serves as an exit point for people who evacuate from buildings, and a target location for the people whose target destination is a building. Finally, buildings also have attributes related to their damage level: their *damage\_state*, as well as the injury rates of a person in the building during the earthquake.
- The *debris\_zone* class represents the debris around a building, it has attributes related to the *height* of the debris and the injury rates of a person in the debris zone during the earthquake.
- The *open\_space* class, represents the open spaces. The open space's attribute *has\_lock* indicates if the open space has a gate, and the open space's attribute *is\_locked* indicates if the gate is locked or not. Each open space has an attribute that indicates its maximum capacity. The open space class has methods to count the number of arrivals and update the *nb\_occupants* attribute, which indicates the number of people in the open space. Additionally, the method *check\_occupancy()* updates the *percent\_occupied()* attribute of the open space, which designates the ratio of the open space's number of occupants to its maximum capacity. Finally, the boolean *is\_fully\_occupied* indicates if the open space is saturated or not.
- The *group* class represents the groups formed by the people from the same household when realistic behaviors are considered. The group's method *capture\_people()* adds people to the group, and updates the list of group members contained in the attribute *group\_members*. The method *evaluate\_leader()* assigns the *group\_leader*. Finally the method *count\_members\_and\_adapt()* updates the attributes related to the group's evacuation decision, evacuation delay, target location and speed.
- The class *people\_in\_group* designates the people who are in a group. This class inherits from the class *person*: each

*people\_in\_group* object is also a *person*. However, in addition to the attributes and methods of the *person* class, the *people\_in\_group* has two additional methods. The *update\_speed()* method changes the speed of the *people\_in\_group* to the speed of the slowest group member, and the *follow\_leader()* method that updates the target location of the *people\_in\_group* who are not group leaders, to the position of the leader.

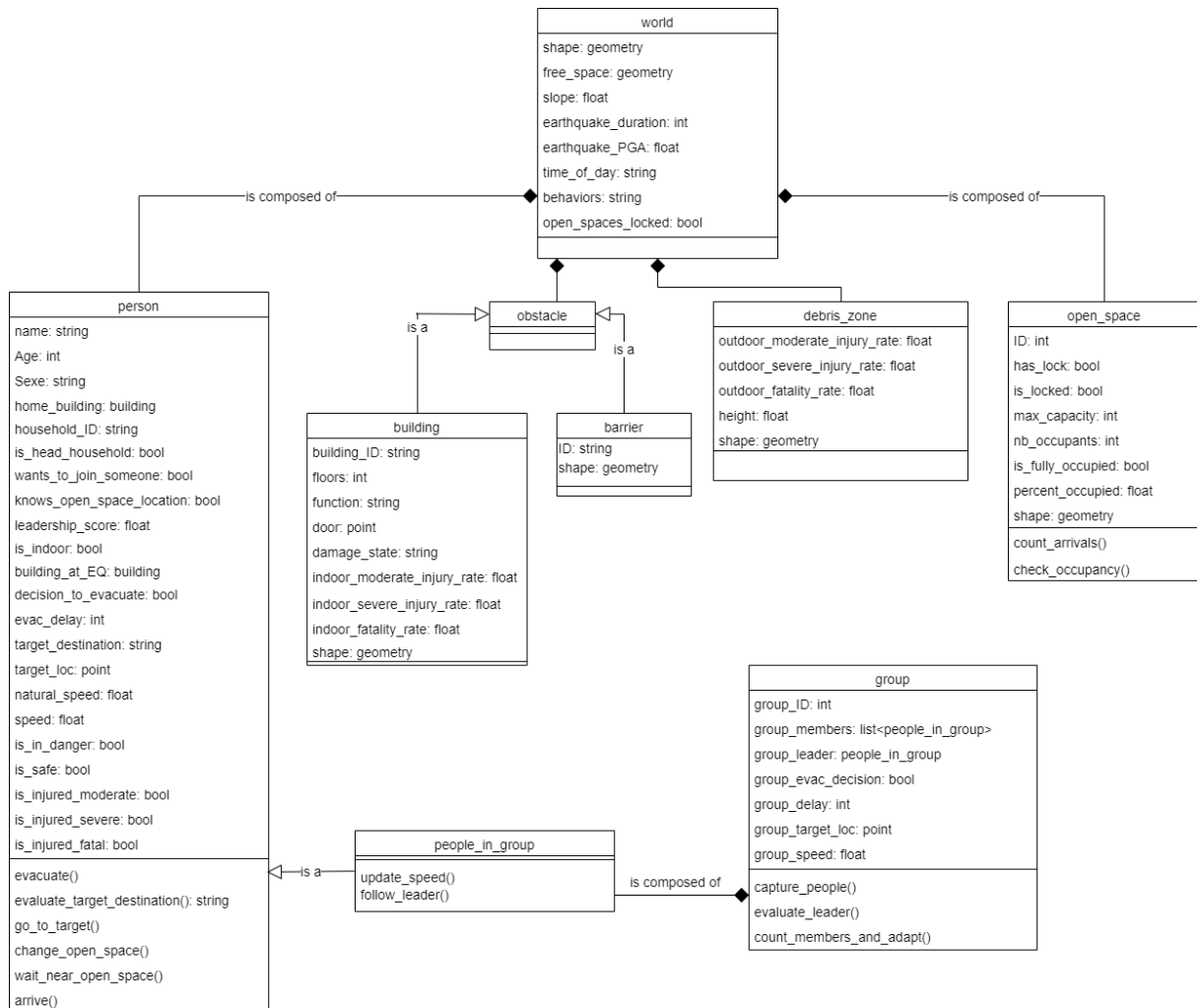


Figure 10: Simplified UML class diagram of PEERS

## 2. Activity diagram

Figure shows the activity diagram of a person agent in PEERS when realistic behaviors are considered.

In order to facilitate the readability of the activity diagram, the following are not represented:

- the decision changes caused by group behavior;
- the interruption of a person agent’s activity if the agent has a fatal or severe injury (severity 3 and 4).

At the start of the simulation, if the agent is indoor it evaluates its evacuation decision. If the agent decides not to evacuate, it stays indoor and does not execute any further actions. In the case where the agent decides to evacuate, an evacuation delay time is assigned to the agent as a random number between 0 and 180; the agent waits until its evacuation time arrives and then exits the building.

The target destination is evaluated for the person agents who are outdoor at the start of the simulation, as well as the agents who evacuated from buildings. After the target destination is evaluated, the agent moves toward its target and keeps moving until reaching this target. The agent’s activity is terminated when it arrives to its target. However, if the agent’s target is an open space, two conditions have to be satisfied before ensuring the person’s arrival and termination of activity. (1) The open space has to be unlocked; otherwise the agent changes its target open space to the nearest open

space that is unlocked; and (2) the open space needs to be non-saturated, otherwise the person waits outside the open space.

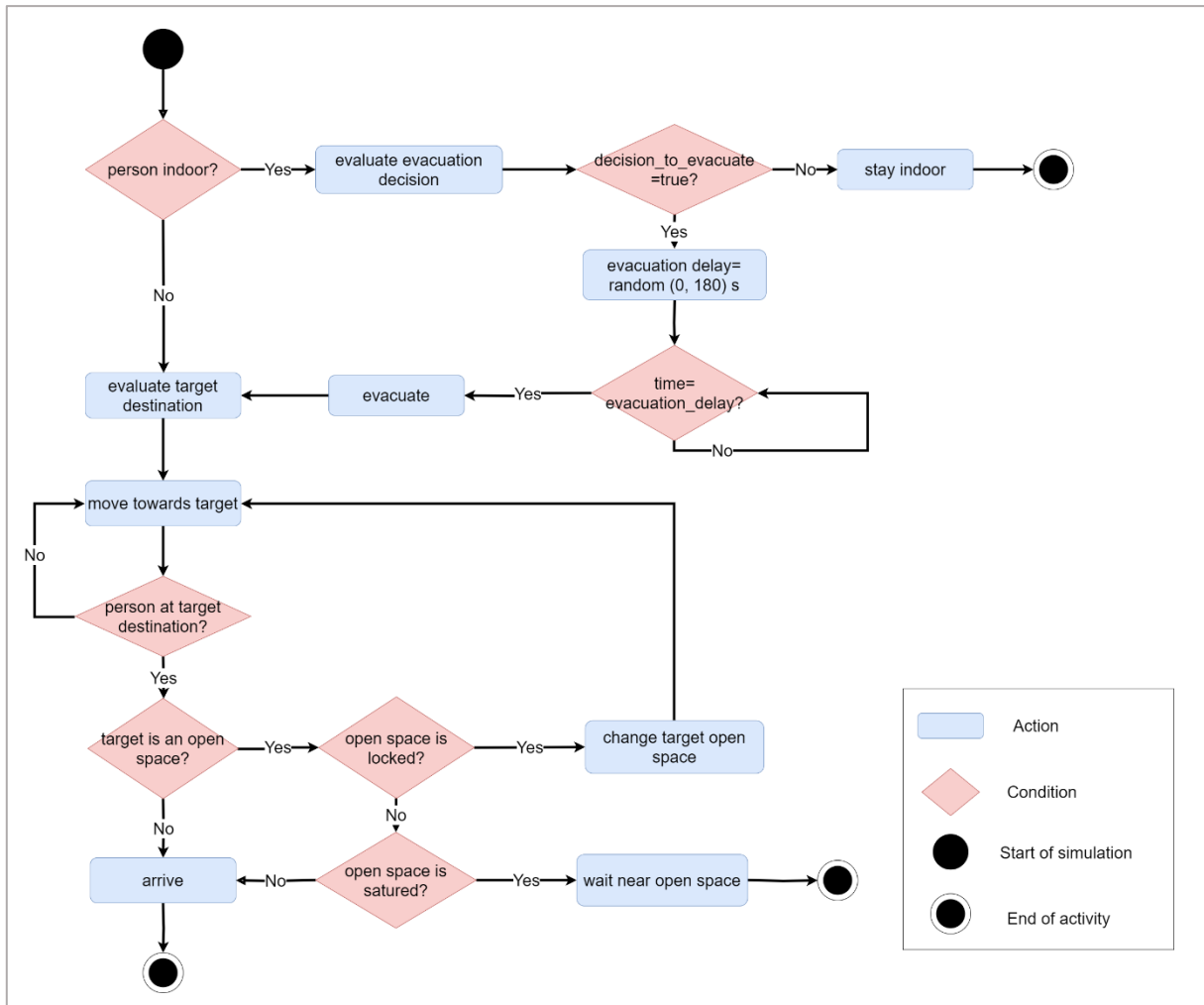


Figure 11: Simplified activity diagram of a person agent in PEERS when realistic behaviors are considered