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Exploring City Evacuation Scenarios using a Multi-Agent System

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Résumé — L'augmentation de l'exposition humaine aux aléas d'origine naturelle replace la gestion de crise et ses outils au cœur de la recherche scientifique dans le domaine des risques. Cet article aborde les évacuations de population. Processus complexe à mettre en œuvre, la réalisation d'exercices est également difficile de par le nombre d'acteurs impliqués. Le développement de nouveaux outils permet, en revanche, d'adopter une approche numérique. Ainsi, dans cet article, la simulation d'une évacuation préventive d'une agglomération de taille moyenne (Alès) à l'aide d'un système multi-agents, est présentée. Plusieurs scénarios d'événements sont appliqués à la simulation. Les résultats sont ensuite comparés et remis en perspectives avec la réalité du processus.

Mots-clefs — *Evacuation, Risque, Multi-agent, Simulation*

Abstract — The increase in human exposure to natural hazards puts crisis management and its tools at the forefront of scientific research in the field of risk management. This article deals with population evacuations. This is a complex process to carry out, and the conduct of exercises is challenging due to the number of stakeholders involved. The development of new tools enables, on the other hand, to adopt a numerical approach. Thus, in this article, the simulation of a preventive evacuation of a medium-sized town (Alès) using a multi-agent system is presented. Several event scenarios are applied to the simulation. The results are then compared and put in perspective with the actual process.

Keywords — *Evacuation, Risk, Agent-based models, Simulation*

I. INTRODUCTION.

Population evacuations are a process consisting of the move (and sometime the relocation) of a variable amount of population from a threatened area to safe zones. The threatened populations may make the decision to evacuate by themselves. Most of the time, a crisis management team specially gathered to manage a potentially disastrous event make the decision. Crisis management teams trigger an evacuation process when no other solution is suitable to avoid injuries and deaths. Authorities can plan population evacuations to a greater or lesser extent. However, despite these plans, evacuation is a crisis management process [1]. From this pattern, the outcome of population evacuations can vary depending on the context, temporality of the event or the type of hazard. It can also vary according to strategic

decisions taken by the organization in charge of setting up the population evacuation process.

From institutional planning to the application of evacuation instructions by the population, three classes of uncertainty have been identified.

- **Contextual uncertainty:** Contextual refers to all events over which the human actors of the process have no power of action. This can be, for example, the intensity and spatial extension of the hazard or the temporality of the event.
- **Organizational uncertainty:** The term organization refers to the crisis management team. It is considered an organization. It is a group of individuals gathered within the same team in order to reach an objective (to reduce the effects of a hazard on stakes). Organizational uncertainty refers to the variable and unpredictable consequences of all strategic decisions that may be made by the organization during an event.
- **Individual uncertainty:** Individual uncertainty refers to the behavior of evacuees. This can vary widely around certain factors. The list includes choice of shelter, preparation time, choice of a route, or sometimes even the decision not to evacuate when instructed to do so or vice versa.

Developing knowledge about evacuations can be done through practice [2]. However, exercises involving all parties (populations, crisis management actors, and field teams) are difficult to set up. Moreover, the effect of contextual variations observable in a real event is not reproducible. The literature on population evacuation simulation shows a variety of approach. Several publications have appeared in recent years proposing ever more accurate and powerful simulations [3], [4]. However, although they sometimes integrate different scenarios, the major drawback of these research is a lack of uncertainty management.

This contribution proposes a numerical simulation of a preventive evacuation process using a multi-agent system. It is applied to an evacuation of Alès municipality (Gard,

France) a medium sized city under the threat of a dam-failure (Sainte-Cecile d'Andorge, France). The aim is to study and assess the possibility of evacuating a large amount of population in a decreased amount of time.

To do so, section 2 proposes a state of the art of population evacuations simulations, as well as a short reflection on the use of scenarios in these simulation models. Section 3 presents the global approach developed in this paper as well as the design of the simulation model used and the scenarios. Section 4 develops the results obtained. Section 5 proposes to contextualize the results obtained with regard to the reality of population evacuation.

II. STATE OF THE ART.

A. Historical evolution of simulation methods.

Later on, the development of the distributed branch of artificial intelligence, the multi-agent systems, allowed the simulation of models with a higher level of complexity. Multi-agent systems are an improvement of the cellular automata introduced in the 1950s by the mathematicians Ulm and Von Neumann. They have four characteristics (mathematicians generally refer to these as "quadruplets"), namely a position, a neighborhood, a set of possible states and transition rules [5]. Multi-agent systems have brought new possibilities. In addition to cells, it is now possible to introduce complex geographical objects. This is a privileged method in the study of complex systems, using simple local transition rules and neighborhood effects.

1) Simulation using a grid and cellular automata.

In cellular automata (or automaton), the simulated space is divided in cells. Each cell of this grid is homogeneous at any point. Environmental variables are held at cell level. The agents move from cell to cell following predefined navigation rules. The value of environmental variables held by the cells may evolve through time.

The use of cells enables to program agents-environment interactions rules. It also allows giving an agent a perception of its environment (neighboring cells). To model perception in a simpler way. The agent is on a cell x , it can move forward by choosing among neighboring cells based on their characteristics [6]. Cells also allow for a greater intuitiveness in the evolution of the environment. For instance, it is possible to block a portion of the environment cells to agents, representing falling pieces during an earthquake [7]. The addition of obstacles is of particular interest to study the movement of agents in a microscopic environment. For example, by comparing the paths of agents with different shapes of obstacles [8]. The use of cells allows agents to move without pre-computed routes. By only indicating a direction, each agent builds its path within the environment [9].

2) Graph theory and "network clearance" simulations.

Numerical simulations of population evacuation have been recurrent since the early 1980s. The first simulations of population evacuation at the scale of a city or a region were proposed in the case of a car evacuation, over large distances. It is in the United States that the first works emerge, in order to prepare for the explosion of a nuclear power plant or a hurricane. The first simulations of this kind were based on a graph, with users moving between nodes at regular time steps [10]. Originally designed for automobile evacuations, they

assumed that user choice would be deterministic (shortest paths). Some models use a weight on road sections according to different parameters, congestion in NETVACI, for example [11].

These simulations serve a very specific purpose, which is to measure the time required to move a given amount of population through a network. This specific part of evacuation is sometimes referred to as network clearance. Graphs are still used today mainly in the simulation of automobile evacuations [12], they allow the calculation of "shortest path" type routes or the definition of a road network topology [13].

3) A mixed approach using scenarios.

A first stage of evacuation simulation using grid-based method allows to simulate evacuations on small portions of territory, mostly pedestrian. Another part, graph-based, allows to simulate evacuations on large portions of territory, involving a high number of people. The first one allows to account for the interactions between pedestrians at the local scale, the second one to organize the path of a high number of people. The interest of this paper lies in the simulation of a large-scale evacuation, pedestrian, which uses a graph and thus route generation. The advantage of using complete routes calculation is thus coupled with the navigation of evacuees no longer cell by cell, but in a continuous environment.

Population evacuations are a complex process. Complex because of the variety of decisions that individuals can make during the process. Complex also by the number of individuals who might be involved in an evacuation, often reaching thousands. Uncertain due to the explanatory factors of the emergence of these behaviors, although widely studied in various research works [14], do not manage to systematically and totally explain the emergence of these behaviors. Added to this the consideration of other uncertain elements such as the context and timing in which the evacuation is triggered (schedule, hazard, weather conditions). The study area often experiences intense rainfall events, putting high pressure on crisis management teams. Taking into account the performance of the crisis management team, the level of uncertainty increases again.

The simulation works are therefore numerous, and in a sense, properly investigate evacuations and the way they work. Lots of phenomenon are investigated and simulated, which helps to provide valuable information to crisis managers. However, evacuation, and more specifically, preventive evacuations, are almost never looked at from a holistic and integrative perspective.

III. GLOBAL APPROACH.

A. The simulation support architecture.

1) Multi-agent system.

The simulation is carried out using GAMA [16], the multi-agent platform. GAMA allows the creation of agent-based simulations in a simple and intuitive way thanks to its high-level programming language, which makes it easily accessible to researchers from any discipline. GAMA also allows the intuitive import and reading of geographic objects contained in shapefile layers, as well as the variables contained in these objects. It also enables the integration of

socio-demographic characteristics of the simulated populations using census data.

In this paper, the environment was imported into GAMA using data from the IGN topographic database and Open Street Map for the environment (Fig. 1.) The INSEE data were processed at the building level for demographic characteristics of the population.

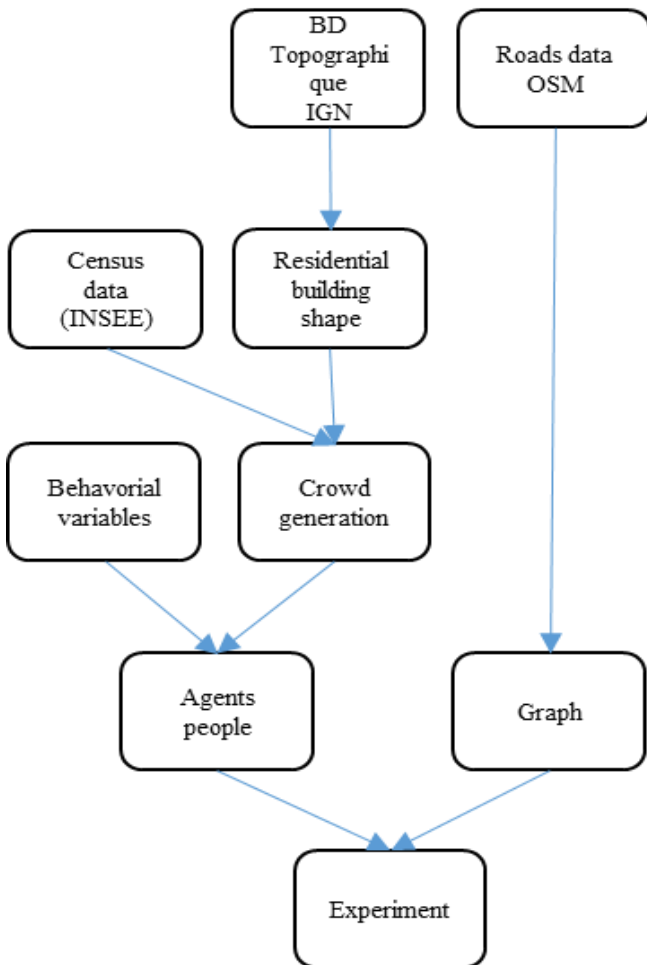


Fig. 1. – Flowcharts diagram of the agents generation.

2) The simulation architecture

The functioning of the simulation is essentially based on three classes of agents. Each agent class is set with its own characteristics and rules of interaction between them and with the other classes of agents. They can also be called agents "species".

People agents: they are the main part of the simulation. The people agents represent the residents of the area represented in the case study (the municipality of Alès). Data on the residents of the municipality are meant to be as close as possible to reality. The basic people agent assignment is to evacuate as quickly as possible from the place where they are, to a safe area. He has a set of characteristics that enable him to accomplish this assignment:

- **Evacuation compliance:** It is a Boolean variable. If the value is 1, the agent people evacuates, if it is 0, the agent does not evacuate. The value of this variable is set at the start of the simulation for each agent according to a value chosen beforehand.
- **Preparation time:** Each time step of the simulation, if the people agent choose to evacuate, this Boolean

variable takes the value of 1 or 0 if he does not chooses to evacuate. If the value is 1, the agent starts to evacuate, if the value is 0, the agent does not start to evacuate and the Boolean variable is recalculated at the next time step. The probability value used for the computation of this variable is set at the beginning of the simulation. This probability corresponds to the chance that the agent evacuates at each time step. The probability values are chosen in order to obtain cumulative departure curves observed in previous works [10], [17].

- **Nominal speed:** Each people agent has a (pedestrian) travel speed. The average value for all agents is 1.33 m/s.
- **Real speed:** It is the real speed of the agent, which can move away or return to the nominal speed according to the circumstances.
- **Distance perception:** The agent perceives and avoids other agents on his route.

All people agents share these characteristics. However, the people agents are subdivided into four classes (Fig. 2.) of agents called "children". A "child" class recovers all the characteristics of a parent class, by adding/modifying some variables.

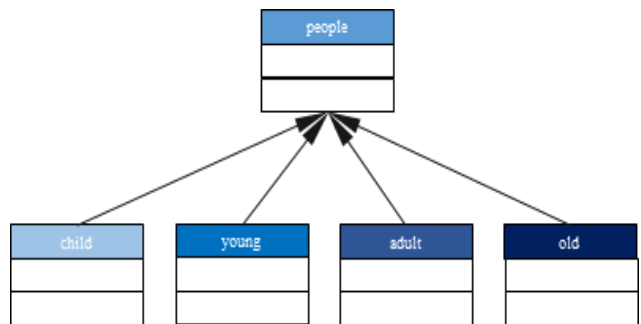


Fig. 2. – Sub-classes of the people agents class.

The instantiation of generational agent classes allows a better distribution of these same agents at the start of simulations. Children can then be at school, adults can be at work. Some individual characteristics can also be varied. Like the walking speed, slower for the elderly (average around 0.8 m/s and for children (average around 1.2 m/s for teenagers and 0.5 m/s for children). The child type agents are also related to an adult type agent. They will adopt the characteristics of this agent during the simulation.

The building agents: they have two purposes in the simulation:

- They generate the people agents at the beginning of the simulation. To do this, the INSEE squared census data are disaggregated into each building according to its volume ratio and its properties. This action provides an information layer of type shapefile (.shp), containing the buildings as geographical objects. The data are composed of the following information: Total number of people, number of people on the second floor (if the second floor is habitable), number of people per floor. This demographic information is also available for each generational instantiation of the agent people class (adults, children, elders, teenagers). This data is then read at the start of the simulation. The building agent generates the number of people agents corresponding to the value it hold based on the data (Fig. 3.)

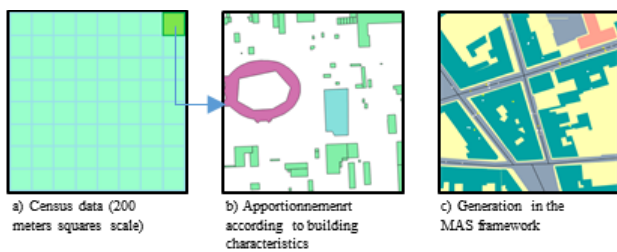


Fig. 3. – Census data integration through the simulation.

Several types of buildings are taken into account in the simulation (Fig. 4.)

- **Residential:** contain the information previously mentioned, i.e. demographics.
- **Shops:** All the stores located within the study area, as well as, by extension, the establishments that receive public (source: Open Street Map).
- **Office:** The buildings filled with offices (source Open Street Map).
- **Health:** Hospitals (source Open Street Map).
- **Schools:** Elementary, middle and high schools within the study area (source Open Street Map / French government public data).
- **Farms:** Buildings of an agricultural nature, this includes farms, greenhouses, and all other types of agricultural operations (source IGN database).
- **Industries:** Buildings of an industrial nature (source IGN database).
- **Food and leisure establishments:** Include restaurants, fast foods and drinking establishments (source Open Street Map).

The road sections are also agents. Together they form a graph. They carry information about their length, information that the pedestrian agent can retrieve when building its route. They are imported into the simulation as segments. However, they also have information about their width. This information determines the maximum distance of the agent from the center of the road and thus allows reproducing a realistic navigation behavior. They may also generate a random number of agents, depending of the scenario chosen.

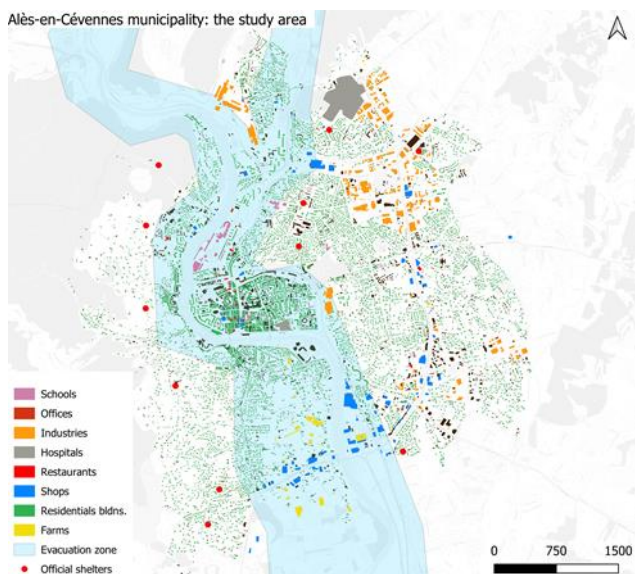


Fig. 4. – Mapping of building typology through within the study area.

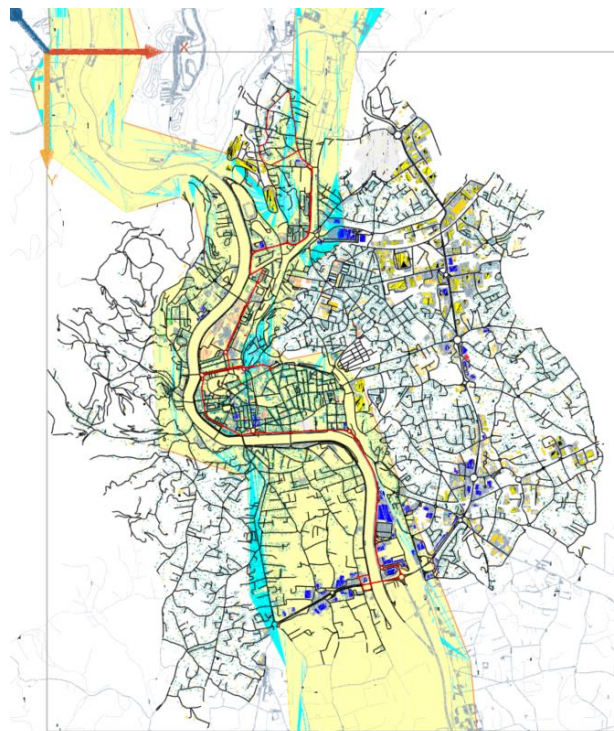


Fig. 5. – Importation of building topology through GAMA.

B. Variables

Scenarios are composed of four parameters. Three thresholds are defined for each parameter. These values chosen as thresholds are based on feedback from past events or research on evacuees' experiences, whenever possible. Each variable contributes to the construction of scenarios. A scenario, therefore, gives a value to each parameter among the three thresholds.

1) Evacuation compliance

The first parameter constituent of scenarios is the compliance of the evacuees. Evacuation compliance refers to the effective application of the evacuation order by the populations. Several factors that can be observed during an evacuation may cause peoples not to evacuate. The populations concerned may not receive the evacuation order. Recent work on the alterability of populations in France still shows weaknesses at this level. Once populations have received the order to evacuate, the question of the application of this order remains. Indeed, on some occasions, a portion of the population may choose not to leave their homes for several reasons : will to protect property [18], lack of confidence to the authorities or lack of risk awareness are the main explanatory factors.

This rate can vary widely from one event to another. They range from 13% to 75% during major North American hurricanes [19]–[21]. In the context of floods in western Europe, they reach 5% in Nijmegen (1995) and 30% in Arles (2003). The effective evacuation thresholds chosen (Fig. 6.) will therefore be 95%, in accordance with the Nijmegen evacuation, 70% in accordance with the Arles evacuation, and 86%, which is an average value, recorded in France [1].

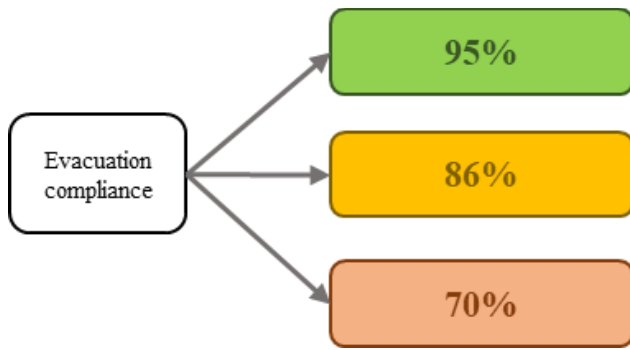


Fig. 6. – Evacuation compliance rate thresholds.

In the simulation, the variable evacuation compliance is an input value, at the start of the simulation. This value is then transmitted to the people agents. The value is given in the shape of a probabilistic index between 0 and 1. At the beginning of the simulation, each agent triggers a function allowing filling the value of a Boolean variable according to a probability between 0 and 1. If the variable returns “true”, the agent evacuates, if the value returns “false”, the agent does not evacuate.

2) Preparation time

The next parameter is the preparation time of the evacuees. There is an elasticity between the receiving of the evacuation order by the populations and their effective presence on the road network. Observations of preparation times at the scale of an overall evacuation process generally lead to cumulative curves. It is possible to find several cumulative curves, which tend to vary according to the perception of the urgency to evacuate experienced by the population. They also vary according to the temporal context in which the evacuation is launched. Populations may be quicker to react during the day. In this article, three cumulative curves have been retained. They are quite different, but they must remain within the scope of what can be possibly observed in the case of application of this paper.

The three curves used in the simulation shown in this paper are from two research works (Fig. 7.). The first curve, the one considered a fast curve, was used in [17]. It is a “fast” cumulative curve, meaning that the populations involved in the evacuation move out quickly. This curve was derived from a curve observed in the case of a Tsunami. Tsunamis often cause a feeling of panic, or at least a desire to get to safety quickly. This curve shows an evacuation of 47% of the population involved in nearly five minutes.

The second curve is defined as “average”, it is a cumulative curve we propose with a regular number of starts between 0 and 60 minutes after the start of the evacuation. The curve reaches 100% one hour after the start of the evacuation.

The last curve proposed is from the work of [10]. It is a departure curve observed during a preventive evacuation in case of a nuclear incident. It is longer than the two previous ones. But it is still within the scope defined above, i.e. the departure of all evacuees in less than two hours. There are other “longer” curves, some of them covering several days (especially in the case of a North American hurricane), but they were not considered relevant for this study.

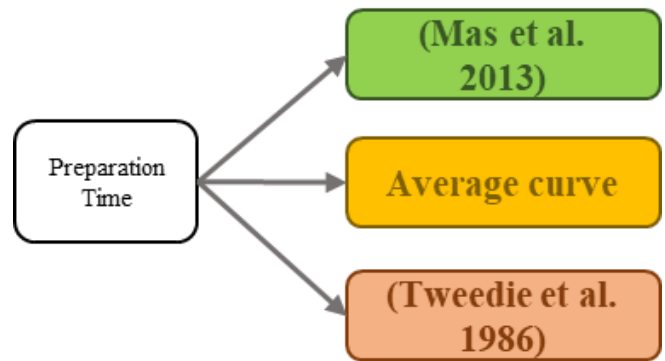


Fig. 7. – Preparation time curve options.

3) Crowd generation

When the preventive evacuation starts, the population is not necessarily in their homes. Spatial configuration of the population can vary widely depending on the temporal context of the evacuation start. On weekdays, weekends, during the day or at the beginning of the night. This means that there is an infinite range of possible starting positions for each evacuee. The prediction of this position remains a complex challenge. Two methods have given satisfactory results. On the one hand, it is the simulation of the territorial functioning in “normal” situation. First, the territory is simulated in its normal functioning. Individuals move around, they go to their workplace and return home according to a time schedule. The second uses scenarios, for example the CAMC (Maximum Credible Carrying Capacity), in [22], the maximum credible carrying capacity is calculated for each non-residential building. Counts were then used to validate the figures obtained.

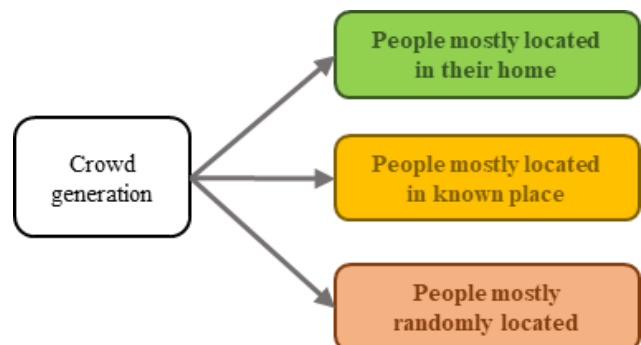


Fig. 8. – Crowd generation options.

In the simulation, the crowd generation variable can take three values (Fig. 8.):

- People are mostly located in their place of residence at the time of evacuation: all people agents (child, youngs, adults and elders) are located in a residential type building. A small part of the adults is located in a shop building. Another part is located on the road network.
- The majority of people are located at their place of work: This corresponds to a configuration that can be observed during a day in the middle of the week. Adults are mostly located at their place of work (office, industry, shops, food, health), the distribution is made from INSEE data. Teenagers are located in schools (Fig. 9.). Children are located in residential buildings with the remaining adults and elders.

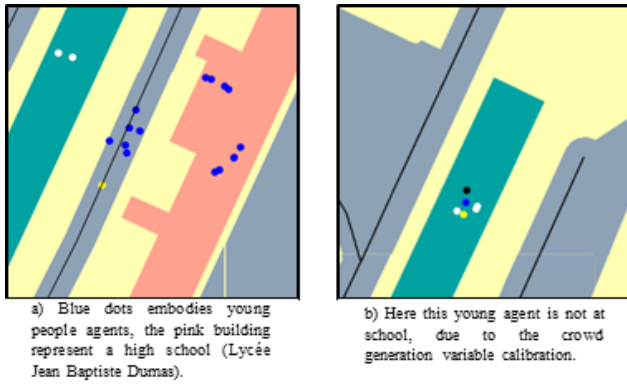


Fig. 9. – Crowd generation variation example.

The people are mostly located in random places: all the people agents are located in places that can receive the public (restaurant, shops...), some of them are at home. A part of the agents is randomly distributed on the road network.

4) Destination choice

An evacuee's destination defines the point in space to which he or she will move. Studies carried out in the context of a one-time incident (e.g., a factory or power plant explosion), may consider that some evacuees will simply flee the disaster [13], or seek to reach a point high in the ground. In this article, evacuation is not considered a one-time event, but may last for several days. The destinations considered will be those found in data collections on post-disaster behavior. In particular in the context of hurricanes in the United States, events that have been widely documented. In this type of work, the typical destinations are the following:

- At a friend's accommodation.
- In an establishment open to the public.
- A pre-defined (official) shelter.
- Other (can sometimes include the evacuee's place of work or other more unusual locations such as churches).

These places are likely to offer shelter, but also to allow the evacuee to subsist there until the situation calms down. This is in contrast to a high altitude escape or a simple evacuation to an undetermined point.

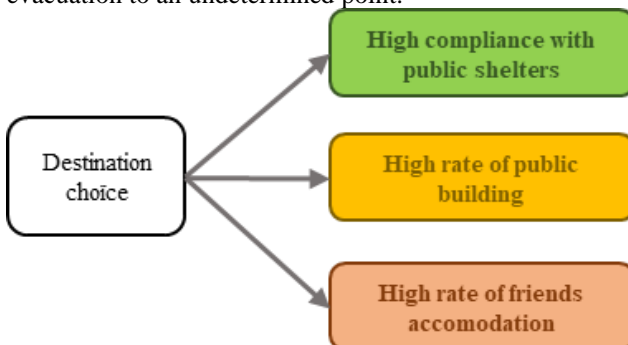


Fig. 10. – Destination choices options.

The destination variable chosen belongs to the agent. At the beginning of each simulation, this variable can take three values with different probabilities (Fig. 11.).

S : The agent goes to the nearest public shelter.

B: The agent goes to a building that can accommodate him outside the flood zone nearby (shopping center, hotel or church).

F: The agent goes to a "friend's" apartment, which means that he/she is actually going to a random building outside the flood zone.

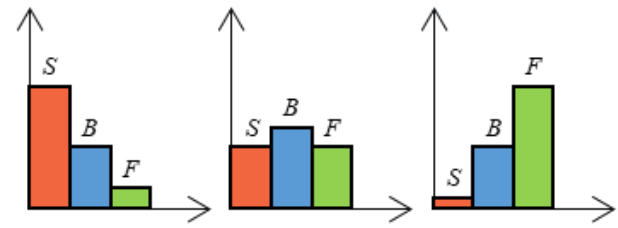


Fig. 11. – Destinations distribution through options.

C. Scenario

Scenarios are often used in the construction of crisis management exercises. A scenario can be defined as the pre-established course of action or sequence of actions. The scenario is also an assumption. This means that when a scenario is studied, it has been determined in advance. In crisis management, the construction of scenarios can serve several purposes:

- To develop the skills of the crisis management actors around events that have already taken place, or that have a high probability of occurrence.
- Develop the skills of crisis management actors around events that can potentially generate a strong disruption on a territory.

In a crisis management exercise, the use of scenarios targets the "players", who are also called "learners" [23].

The use of scenarios also enables the calibration of simulations with high uncertainty. A reliable estimation of variables can then compensate for the lack of reliable observation data or the high unpredictability of a parameter. This is the point of view that is defended in this paper. The use of scenarios allows to calibrate the parameters of the simulation to generate "realistic" or "possibly observable" situations, but the content of these scenarios can be questioned. They correspond indeed to a possible reality, but are not the only one.

The “night evacuation” scenario:

This scenario simulates a night evacuation. The majority of people are at home (Fig. 12). The preparation time is average. The compliance is higher. The majority of evacuees will go to official shelters.

Crowd generation
Preparation time
Evacuation compliance
Destination.

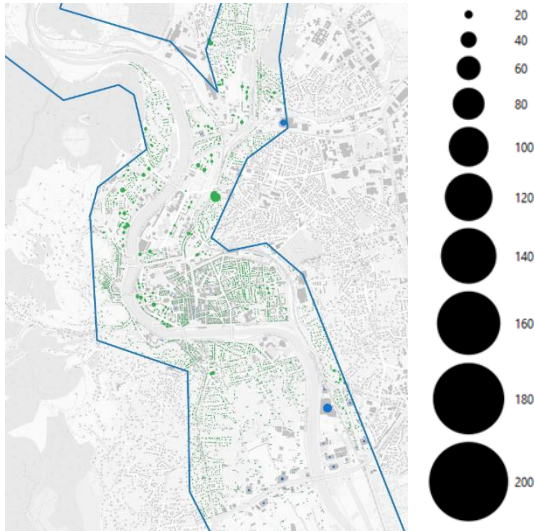


Fig. 12. – Map of the crowd generation for the scenario “night evacuation” (color have the same meaning as Fig. 4.)

This scenario assumes an evacuation on a weekend day. This means that a low number of people are in their homes (a value that is nonetheless higher than the previous scenario). The establishments receiving the public are full but the industries, offices and other workplaces are less full than in the previous scenario. In addition, schools are empty.

Crowd generation
Preparation time
Evacuation compliance
Destination.



Fig. 14. – Map of the crowd generation for the scenario “night evacuation” (color have the same meaning as Fig. 4.)

The “mid-day” evacuation scenario:

This scenario simulates a mid-day evacuation. People would be more reactive to the evacuation order. Compliance is lower. The crowd generation gives a larger quantity of people in public buildings (Fig. 13.), as well as in different workplaces.

Crowd generation
Preparation time
Evacuation compliance
Destination.



Fig. 13. – Map of the crowd generation for the scenario “mid-day scenario” (color have the same meaning as Fig. 4.)

IV. RESULTS

The graph in Fig. 14. illustrates the cumulative curves of the total percentage of evacuees who reached their destination as a function of time (in minutes). The curves are compared for each of the three scenarios. The curves are plotted between t-0 and t +120 minutes, but the evacuation process actually takes longer.

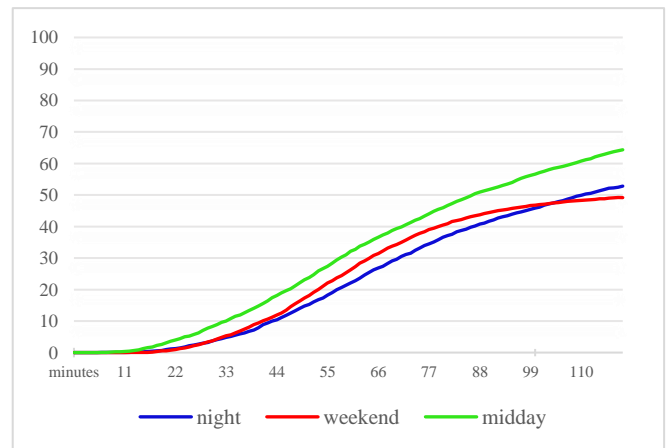


Fig. 15. – Map of the crowd generation for the scenario “night evacuation”

The graph in Fig. 16. shows the same information as the previous graph. However, the values are absolute. In fact, the crowd generation gives values of total population to evacuate different for each scenario. 3'621 for the night evacuation scenario, 6220 for the mid-day evacuation scenario, 3726 for the scenario taking place during the weekend.

The “weekend” evacuation scenario:

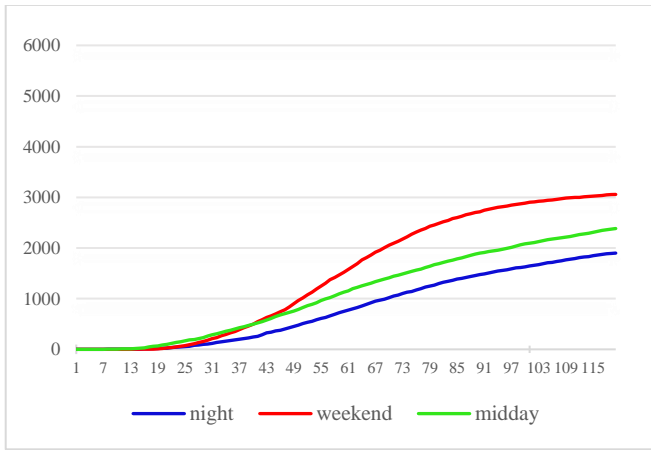


Fig. 16. – Map of the crowd generation for the scenario “night evacuation”

Fig. 17. and Fig. 18. represent the number of people per 50 meters of network. Fig. 17. represents the situation 30 minutes after the evacuation, Fig. 18. 1h30. These two maps are associated with the night evacuation scenario. The legend in Fig. 17. is applicable to all other maps of the same type.

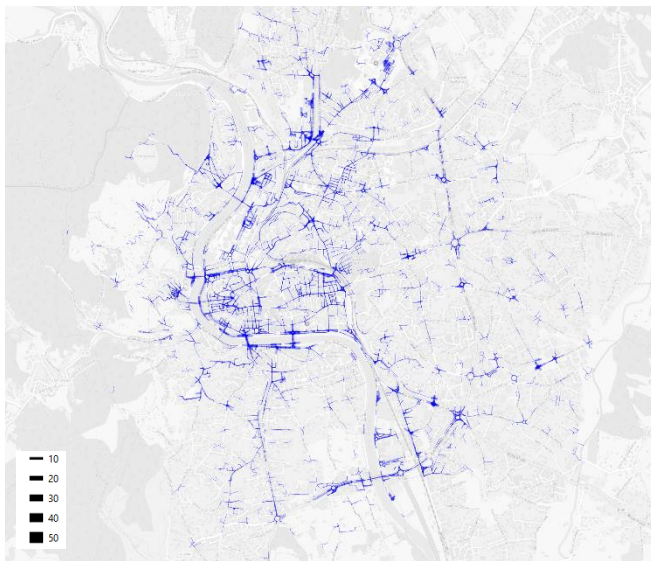


Fig. 17. – Mapping of the evacuees 30 minutes after the start (night scenario).

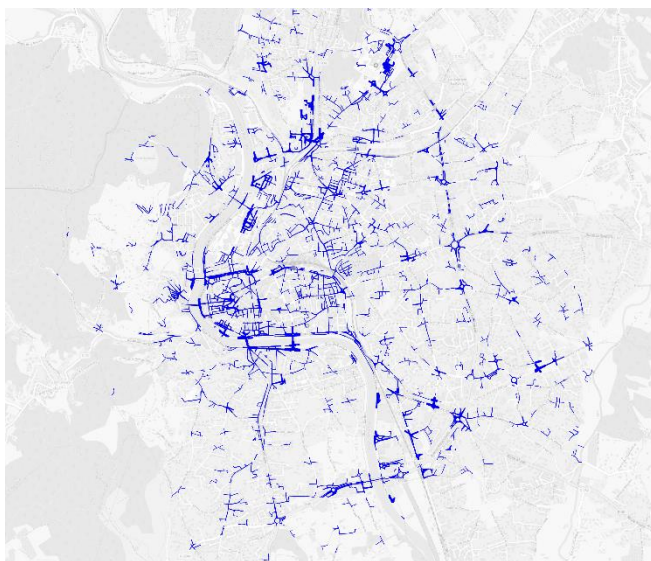


Fig. 18. – Mapping of the evacuees 90 minutes after the start (night scenario).

Fig. 19. and Fig. 20. represent the number of people per 50 meters of network. Fig. 19. represents the situation 30 minutes after the evacuation, Fig. 20. 1h30. These two maps are associated with the weekend evacuation scenario. The legend in Fig. 19. is applicable to all other maps of the same type.

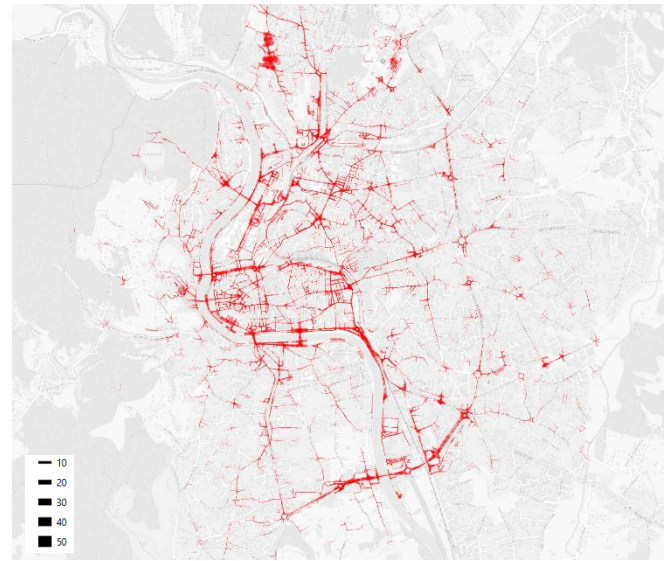


Fig. 19. – Mapping of the evacuees 30 minutes after the start (weekend scenario).

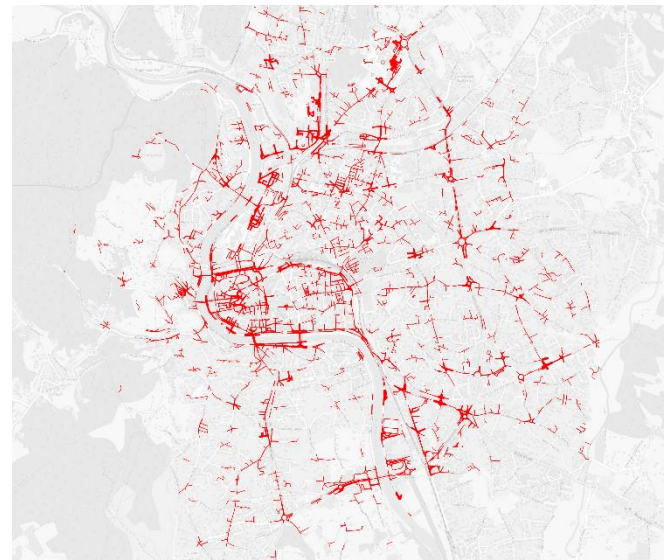


Fig. 20. – Mapping of the evacuees 90 minutes after the start (weekend scenario).

Fig. 21. and Fig. 22. represent the number of people per 50 meters of network. Fig. 21. represents the situation 30 minutes after the evacuation, Fig. 22. 1h30. These two maps are associated with the weekend evacuation scenario. The legend in Fig. 21. is applicable to all other maps of the same type.

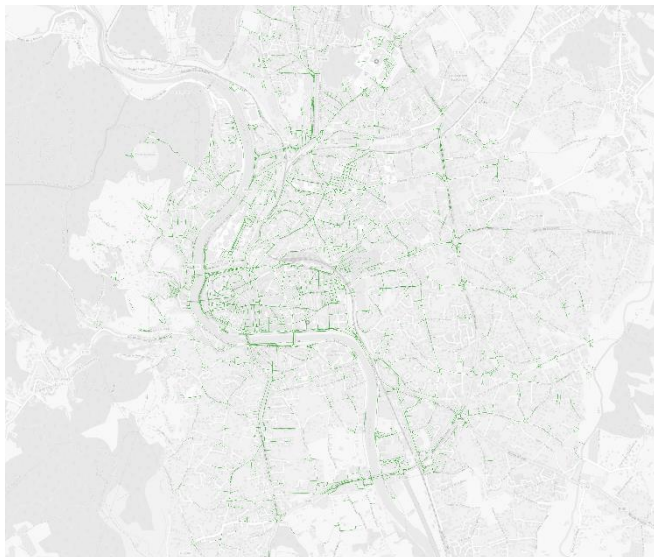


Fig. 21. – Mapping of the evacuees 30 minutes after the start (mid-day scenario).

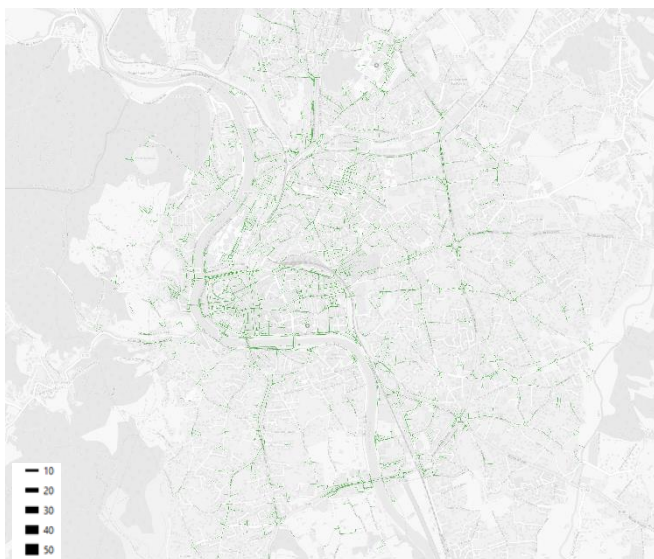


Fig. 22. – Mapping of the evacuees 90 minutes after the start (mid-day scenario).

V. DISCUSSION

All the scenarios lead to an incomplete evacuation within two hours. The "mid-day" evacuation scenario would be the most favorable (Fig. 15.), the mapping done in (Fig. 21 and 22) show that despite the amount of population to evacuate (close to 4'000), the mid-day scenario is also the one where the streets are the least densely used. The maximum measurement of the number of people per 50 meters section is only 11, compared to 26 for the weekend scenario. The weekend scenario and the high population presence in the southwest of the conurbation is explained by the existence of a commercial area. It is also visible in Fig. 19 and 20 that the southwestern ring road is overloaded in 30 minutes.

Although informative, the results presented are speculative, and rely on several assumptions made to overcome the lack of information. However, these results also show that the variability of the parameters included in this paper has a significant impact on the final evacuation process. Of course, to confirm these leads, it is necessary to test the parameters independently of each other to be able to evaluate their real impact.

VI. CONCLUSION

Population evacuations are crisis management measures that require the relocation of people from a threatened location to a safe place. The number and variety of elements involved in an evacuation make it a difficult process to implement. Three broad categories of uncertainties inherent in such a process have been identified. Contextual, organizational, and individual. While there is currently no method capable of addressing these uncertainties, the approach proposed in this paper aims to explore some of them, using a multi-agent simulation model and event scenarios. The results showed significant differences between the different scenarios. The evaluation of the impact of each of the parameters on the process as a whole will allow to specify the content of these differences.

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