Large Event Halls Evacuation Using an Agent-Based Modeling Approach

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ABSTRACT The paper explores the usage of agent-based modeling in the context of large event halls evacuation during music festivals and cultural events. An agent-based model is created in NetLogo 6.2.2 for better representing the human behavior when involved in such situations. A series of characteristics have been set for the agents in order to preserve their heterogeneity in terms of speed, age, locomotion impairment, familiarity with the environment, evacuating with another person, choosing the closest exit or not, selecting the closest path to the exits. An ''adapted cone exit'' approach has been proposed in the paper in order to facilitate the guidance of the agents in the agent-based model to the closest exit and its advantages have been proved in comparison with the classical ''cone exit'' approach. Different evacuation scenarios have been simulated and analyzed for better observing the capabilities of evacuation modeling in the case of evacuation emergencies. Besides the overall evacuation time, an average evacuation time has been determined for the agents based on the individual evacuation time, which can be easily connected with a risk indicator associated to each situation. Due to the visual interface offered by the agent-based model, coupled with the evacuation indicators, the proposed model can allow the identification of the main factors that may contribute to a prolonged evacuation process (e.g. overcrowding at one of the exits, not choosing the appropriate door, evacuating with a friend/parent) and the potential measures to be considered for insuring a safe evacuation process.

INDEX TERMS Agent-based modeling, large event halls, evacuation process, simulation.

I. INTRODUCTION

Evacuation in a timely manner and in compliance with safety regulations is of great importance when it comes to an unforeseen situation [1]. In general, emergency evacuation can be considered as a traditional problem of identifying the optimal route. Numerous classical algorithms have been proposed to solve this problem, for example the Depth-First-Search algorithm [2], dynamic programming [3], Dijkstra's algorithm [4] and ant colony optimization algorithms [5]. However, evacuating a mass of people is a complicated process. The algorithms mentioned above do not take into account psychological factors, particularities of the population (gender, age, locomotion impairments) and interpersonal relationships. All these factors have a decisive impact on evacuation [6], [7].

Currently, simulations are an effective way to estimate evacuation times under the influence of variable and invariable factors. In the field of emergency evacuations, researchers most often use virtual models to simulate such evacuations. Isobe *et al.* [8] tested a walking situation and determined that human behavior differed depending on the environment. Yang *et al.* [9] through computer simulations found out that a point of interest consists in the stairs of buildings, because in case of emergency evacuation, that is the place where the traffic of people is congested. Helbing and Molnar's social model [10] and Blue and Adler's automatic model [11] have often been applied in evacuation simulations. The real-world simulation of an emergency evacuation allows the recording of the entire evacuation procedure. However, the current studies are limited by the environment

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characteristics and factors that are difficult to implement, such as the multitude of behaviors that people could manifest in such a situation, unforeseen events that obstruct the evacuation process and the diversity of the evacuees. In most of the cases the simulations are limited to the evacuation of some rooms/interior buildings.

Emergency evacuation of a location during an event is of major importance due to the large number of persons participating, in general, to the event. The simulation of the large spaces evacuation in dangerous conditions is a necessary measure to prevent or to reduce the number of victims [3]. If, when exposed to a source of danger, the participants at an event are not evacuated effectively, serious consequences may arise as a result. For example, in the tragedy of October 30, 2015 in Club Colectiv,[1] located in Bucharest, Romania, a place where after a fire broke out, 64 people died and another 186 people have been injured. This incident represents the worst fire in Romania in a nightclub and the worst accident in the country in recent decades. In order to prevent such accidents, emergency evacuation planning is essential in carrying out such an activity.

Considering the other approaches from the public spaces evacuation scientific literature, it can be observed that in some of these approaches the evacuation population is regarded as a single homogenous population.

As a result, the emergency evacuation of a large number of people from a location, in the shortest possible time and at the highest possible level of safety, is extremely important. In this context, the present study uses an agent-based model created in NetLogo 6.2.2 for simulating the evacuation process from a large event tent in order to highlight the evacuation times and to find the potential issues that might appear during the evacuation. The use of an agent-based approach for modeling the evacuation population from large event halls is intended to overcome the gaps in the literature which derive from the assumptions made in other approaches. For example, one of the assumptions in the social force models is that the population is homogenous, not accounting for the individual characteristics or behavior of the people involved in such an event. On the other hand, the use of cellular automata models, which are able to account for these characteristics, conducts to complex models, hard to implement and run due to the existence of only one type of agent that should possess at the same time the characteristics of the evacuation population and of the environment. Even more, in the case of cellular automata models, as the evacuation agents are represented by fixed pieces of ground, the movement can be made only from one piece of ground to the other – in this manner, an agent is not able to initiate a movement of a lengths smaller than the size of a patch. This limitation of the cellular automata models makes the models using this approach to move away from the real-life evacuation scenarios. All these limitations can be overpassed in an agent-based model. As a result, the use of agent-based modeling for such evacuation

situations comes easier as the population can be constructed as heterogenous and, by providing a series of agents, in the agent-based models, the design of the environment, the interactions among evacuation population and the individual rules of movement and characteristics of the evacuees can easily be modeled. In terms of movement, as the evacuation agents are not modeled as part of the ground, but as moving agents on top of the ground, the evacuation agents can stop at any position, not being forced to move from one patch to another.

In the present paper, for modeling the evacuation process of a large event hall, six different scenarios are considered, in which we have varied the doors availability, the size and the structure of the evacuated population, the option to evacuate with a friend or a family member and the choice for evacuating through the closest door. The proposed agent-based model can be easily adapted to other types of large buildings by adjusting the characteristics of the event halls from the interface. In the same manner, using the interface of the model, one can easily define the type of population expected to attend such an event, by selecting different characteristics in terms of age, speed, rules of movement, or in terms of behavior, e.g. evacuating with another person or selecting or not the closest exit door as a result of the familiarity with the environment/panic, etc. In order to facilitate the shortest route to the exits, the paper proposes, based on the scientific literature, an "adapted cone exit" approach which provides to the agents the best route from any location they might be within the considered event hall.

The contribution of the paper is twofold. First, the paper shows that by using the agent-based approach the evacuation process from a large even hall can be easily simulated and observed by any interested party – thanks to the graphical interface offered by such a model, in which the elements involved in such a process are clearly identified (e.g. walls, exit doors, position of each evacuating agent, path chosen by each evacuated agent, obstacles, etc.). Second, the paper proposes an "adapted cone exit" approach through which the agents are able to find the best route from any point to the evacuation exit, making the simulation of the evacuating agents movement closer to a real-life situation. Compared to traditional evacuation methods, the advantages of the proposed approach used in the paper resides from the fact that: (1) the method clearly shows the differences in evacuation times depending on the number of exit routes available during the process; (2) the speed of movement of each individual can be customized according to the age category; (3) the simulated population takes into account the characteristics of a population under evacuation, being able to be diversified in terms of physical peculiarities (e.g. presence of people with locomotion impairment, keeping a specific distance among agents, evacuating with another agent, choosing or not the closest exit). The study has been conducted based on the court of events available in the cold seasons at the Roman Arenas,[2]

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[1] https://www.euronews.com/2020/10/30/colectiv-fire-romania-s-deadly-nightclub-blaze-is-still-an-open-wound-five-years-on

[2] https://communistism.wordpress.com/2013/02/13/the-roman-arenas-bucharest-romania/

Bucharest, Romania, one of the locations highly used for public events in Bucharest in both the warm and cold seasons.

A series of scenarios are used in the paper in order to determine the changes in the evacuation times due to various factors. Based on the simulation results, coupled with a visual analysis of the simulated scenarios, the identification of the main factors affecting the evacuation process can be easily made and the potential measures for improving the safety during the evacuation process can be timely observed.

The paper is structured as follows: section II provides a literature review related to the state of the art in evacuation. Section III briefly presents the selected location and the characteristics of the persons attending the events in the selected location. Section IV discusses the agent-based model assumptions, type of agents and implementation. Section V presents the scenarios considered for the simulations, while Section VI discuss the simulation results. The paper ends with limitations of the research presented in Section VII and discussions, conclusions and further developments in Section VIII.

II. THEORETICAL BACKGROUND AND STATE OF THE ART ON EVACUATION

Empirical data has shown that the main cause of death and injury of the participants in emergency evacuations is not the disaster itself, but the irrational and impulsive behavior of crowds under the influence of panic induced by the situation [12], [13]. In order to minimize the number of casualties, it is important that architects and engineers design the buildings in an optimal way to evacuate in panic conditions as safely as possible [14]. The behavior of certain individuals under stress is very difficult to predict since each person reacts differently depending on the environmental conditions. This is due to differences in age, gender, culture, physical and mental condition and background [15], [16]. Despite this, during an emergency, crowd behavior tends to follow some common characteristics independent of specific cases [17]–[21]. The emergence of a certain behavior has been observed in evacuation situations with crowded populations, where people tend to collide with each other on their way towards the exits, with the aim of faster escaping the location they are evacuating from in order to protect themselves [12], [13]. This makes an emergency evacuation even more dangerous than a coordinated one, significantly increasing evacuation times [11], [13], [14], [22].

Traditionally, crowd management and building evacuation are analyzed by observing the pedestrians moving in controlled spaces. The movement of these pedestrians is recorded and subsequently analyzed to produce mathematical analytical models that explain the behavior of crowds [19], [23]. These analytical models provide a better understanding for engineers and architects, helping them make decisions about the design and construction of buildings and evacuation procedures. However, the models in question are limited by the complexity of the buildings. The increased processing power of modern computers makes it possible to study the behavior of large populations during the evacuation of buildings through numerical simulations.

Two types of evacuation simulation models can be encountered in the scientific research: macroscopic and microscopic [24]. In the macroscopic models the crowds are considered as a single homogenous population, whereas the microscopic models rely on considering individual behavior and interactions.

From the macroscopic models, the social-force model, based on a molecular dynamics-based approach, is one of the most-known [25]–[27]. The model considers each pedestrian to be an unstructured particle whose motion is governed by Newton's equations [28]. A series of studies have been conducted to inspect individual-level interactions between people in a complex system with the purpose of exploring the mechanisms involved in the behavior of large human populations caught in an evacuation process [29]–[31]. The emergency evacuation simulations based on the social-force model have been widely used in scientific research [32]–[34]. One of the disadvantages of using such an approach is related to the fact that it does not properly incorporate the different individuals' behavior. Another one is related to the difficulty in implementation due to the relatively high number of non-linear differential equations and the hypothesis needed for properly establishing those equations [24].

On the other hand, the microscopic models succeed in passing these shortcomings, but have been proven to become expensive due to the complexity they exhibit for very large populations or environments [24]. In order to reduce the complexity of the microscopic models, one can either choose to reduce the complexity of the characteristics and interactions of the considered population, or choose to reduce the complexity of the environment. Regarding the advantages of the microscopic models, one can name the emerging and sometimes unexpected behavior of the mass, which could have not been observed by simply reading the behavior rules of the individuals [35], [36]. Two types of microscopic models can be encountered: discrete – based on cellular automata [37]–[39] and continuous – based on agent-based modeling [40]–[42].

As for the studies featuring large-scale crowd evacuation using microscopic models, it can be observed that both cellular automata [43], [44] and agent-based modeling [45], [46] have been used in the scientific literature. A selection of the studies in each of the two modeling categories is discussed in the following.

Dang *et al.* [43] use cellular automata and virtual reality for simulating an evacuation scenario from a shopping mall. Based on the results, the authors state that the proposed approach is more appropriate to the type of selected environment than a simulation conducted using the Pathfinder software as it can easily incorporate a variable related to evacuees' environmental familiarity. One of the criticisms that can be brought to the approach is related to the movement of the evacuees, which can only be made into steps equal to one size unit. The start point, the endpoint and all the intermediate

points of the path are set to the center coordinates of the cells, the evacuees not being able to stop in any other point of the cell, as expected in a real-life situation. This limitation is common, in fact, to all the cellular automata models. As a result, the authors introduce in their paper the calculus of some interpolation points, which have the property of smoothing the path of the evacuees, but, as the authors state, the calculation accuracy of the chain navigation grid needs to be further optimized. Abdelghany *et al.* [44] incorporate genetic algorithms into a cellular automata model in order to find the optimal evacuation plan for a given situation. The proposed framework is applied to a hypothetical pedestrian facility with ten exits. The authors state that the approach can be used in practice, as it provides a superior evacuation plan when compared to a traditional approach [44]. Considering the location to be evacuated, one can state that the design of the location is rather simple, with no elements related to dynamics of the environment conditions, while the presence of obstacles reflects only partially a real-life situation. Wu *et al.* [47] extend a classical cellular automata model by incorporating a route choice model in the case of a large indoor space. The authors state that the proposed model has the ability to successfully incorporate various aspects related to evacuation. The limitations of the work are related to the interactions among the evacuating agents, which are not included. Considering a stadium scene, Zhou *et al.* [48] included in their model different types of emotions that can be experienced by the persons involved in an evacuation process, showing that during the evacuation, the individual emotions are changing, reaching calm for all the participants at the end of the simulation. Even though the introduction of emotions into an evacuation model makes it closer to a real-life situation, it is not clear to which extent one can succeed in knowing the personality of the individuals involved in such a process.

In the area of agent-based modeling, Ronchi *et al.* [45] use the Pathfinder software for modeling a large-scale evacuation from a music festival. The authors state that the modeling approach has been appropriate for the situation under investigation, mentioning that, in general, the evacuation models have limited capabilities in representing the complex behavior of the evacuees, as most of them do not account for propagation of information or social influence. Considering the model, more experimental data is needed to be introduced in the model for improving the reliability of the model results, as, in the current form, the model is only based on scarce literature. Ren *et al.* [49] propose an agent-based model created in Repast software. Based on the simulations, the authors observed a "faster is slower" phenomenon during the evacuation process. As the authors mentioned, the computational costs of such a model should be evaluated if one needs to simulate a more accurate model with an increased number of agents. The evacuation from elevated lecture halls has been simulated using an agent-based model in NetLogo by Delcea *et al.* [50] with the purpose of determining an adequate seat arrangement for a faster evacuation process.

The authors show that the proper combination between the seat arrangement and the position of the evacuation doors can diminish the evacuation time.

Siyam *et al.* [51] provide a comprehensive overview on agent-based simulation in the case of pedestrian evacuation, while Sharbini *et al.* [52] and Bayram *et al.* [53] provide an extended review on evacuation planning and management. Chen *et al.* [54] discuss the approaches, models and tools used for pedestrian evacuation in indoor emergency situations.

III. PREREQUISITES
Details related to the selected location and types of participants to the events held in the analyzed hall are discussed in the following.

A. LOCATION
The selected event hall is in a central area of Bucharest, Romania and it is usually used for unreeling international music festivals and international concerts – Fig. 1.

The central part of the location provides during a large period of the year (October-May) a heated tent with a length of approximately 45 m and a width of approximately 25 m, being able to accommodate up to 2500 persons per event. This part of the location is the one analyzed in the current paper and we will refer to it as the "hall" or the "tent" in the remainder of the paper.
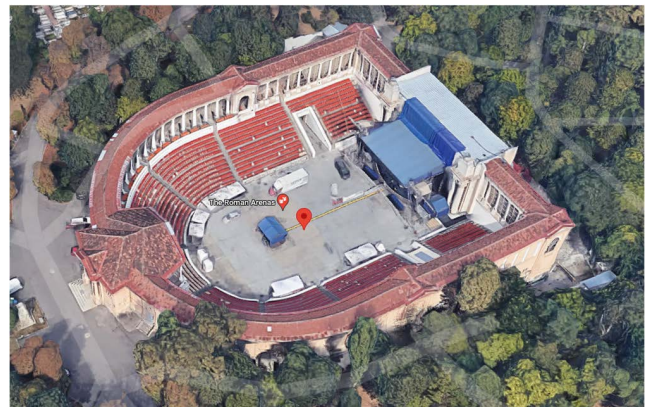

FIGURE 1. The Roman Arenas Location.

The tent disposes of four ways of access, two of them being used for entering the location in normal use situations and the other two are dedicated to the emergency situations that might occur.

Fig. 2 presents the architectural scheme of the tent in which we have marked the two exit doors with A and B, the emergency doors with C and D, the stage is represented in blue, the two storage spaces located in the upper-left and bottom-left sides of the view are marked with cyan, the four pillars near the stage are colored in light-blue, the two food stands marked in orange, the sound-operators stand is marked in magenta, the two token-stands are colored in orange-red, while the three merchant stands located in the right side of the view are marked in light-pink.

The dimensions of the tent, the entrances and the obstacles present inside it are proportional with the real ones. It should be noted that the front of the tent is delimited by a fence guarded by security guards and access to the stage is allowed only to the persons with special permission (artists, managers, and photographers).

B. POPULATION

The persons attending the events held in the tent can be divided into two categories: ''standard occupant'' and ''people with locomotion impairments'' [45]. In the first category, one can include children, adults and seniors, while in the second category all the persons with locomotion impairment (wheelchair persons, persons with crutches/canes) are considered.

Based on the data reported by the firms organizing events in this location, it has been observed that most of the time, the average number of tickets sold for attending such an event is 2000 tickets. The distribution of the population differs according to the type of event held in the tent. An average distribution determined based on the events held in the pre-pandemic period has revealed that most of the participants belong to the adults category (approximatively 81.8%), followed by seniors (15.0%), children (3.0%) and people with locomotion impairments (0.2%). Besides the participants, an approximate number of 39 persons – part of the staff – are present, on average at the location.

IV. THE AGENT-BASED MODEL

An agent-based model is part of a class of computational models created to simulate the actions and interactions of autonomous agents (both individuals and collective entities) that aim to ascertain the effects on systems or other entities [55]–[57]. These models combine elements of game theory, complex systems, emergencies, computational sociology, operations research, and evolutionary programming [58]–[60]. Different methods are used to introduce randomness when stating the agents' behavior. In the recent literature it has been observed that agent-based models are used in non-computational scientific fields, including biology, ecology and social sciences [61]–[63]. Agent-based models are related to the concept of multi-agent systems or multi-agent simulations, as their purpose is to provide an explanation for the collective behavior of agents that follow simple rules.

Individual agents are characterized as being rational, namely their behavior is oriented for the good of their own interest, using simple decision-making or heuristic rules [64], [65].

Agent-based modeling, in some respects, is the most complex method through which a real environment is reproduced in a controlled environment. This type of modeling integrates environmental data with the behavioral and demographic aspects of the population to provide important data for theoretical studies and estimates.

As a result, the agent-based models are virtual models that aim to reproduce the behavior of individuals in a given environment. They are more intuitive than mathematical or statistical models as they can represent objects in a similar manner in which they are seen in reality. Due to the emphasis in the last 30 years on object-oriented programming, agent-based models have become easier to implement, while their structure is easy to model based on mathematical and behavioral statistical models.

In the case of large event halls evacuation, an agent-based model has been created using NetLogo 6.2.2 The model's graphical user interface (GUI) is presented in Fig. 3, while a close-up on the elements in GUI are depicted in Appendix B. A series of elements can be configured from the interface and/or by uploading a text file containing the structure of the hall to be represented. Appendix A provides a table of nomenclature for the variables included as inputs and outputs in the agent-based model. The variables that refer to the characterisics of the evacuation population have been extracted from the scientific literature (e.g. speed), the variables needed for building the agent-based model's environment have been taken from the measurements of the concert hall, the variables related to population structure have been extracted from the statistics associated with the usual attendance for the events organized in the selected concert hall, while the variables related to the population's rules of movement have been taken from the evacuation simulations.

The configuration of the hall allows the user to establish the structural elements of the hall, such as the dimensions of the hall (length and width), the different stands, the position of the stage, the position of the doors and the availability of the doors.

In terms of population, one can configure the number of persons attending an event, the structure of the population attending the event (children, adults, seniors and persons with locomotion impairment), the presence/absence of staff persons, the location of the persons acting as staff at the event, the possibility to set-up families who might/might not evacuate together.

A series of assumptions have been stated in order to build the agent-based model, as presented in sub-section A. In terms of types of agents, two types have been used: *turtles* – agents possessing human characteristics in terms of evaluating the surrounding world and making needed evacuation decisions and *patches* – small pieces of ground through which the event hall has been divided into squares, having a series of characteristics which help the turtle agents to better understand the environment and to guide them to the available exits. The characteristics of each type of agent are described in sub-section B, along with the agents' movement rules.

A. ASSUMPTIONS

For building the agent-based model, the considered environment has been divided into small pieces of ground, having a square surface of 0.5m $\times$ 0.5m [66], [67]. As a result of this division of the surface into small areas, the rest of
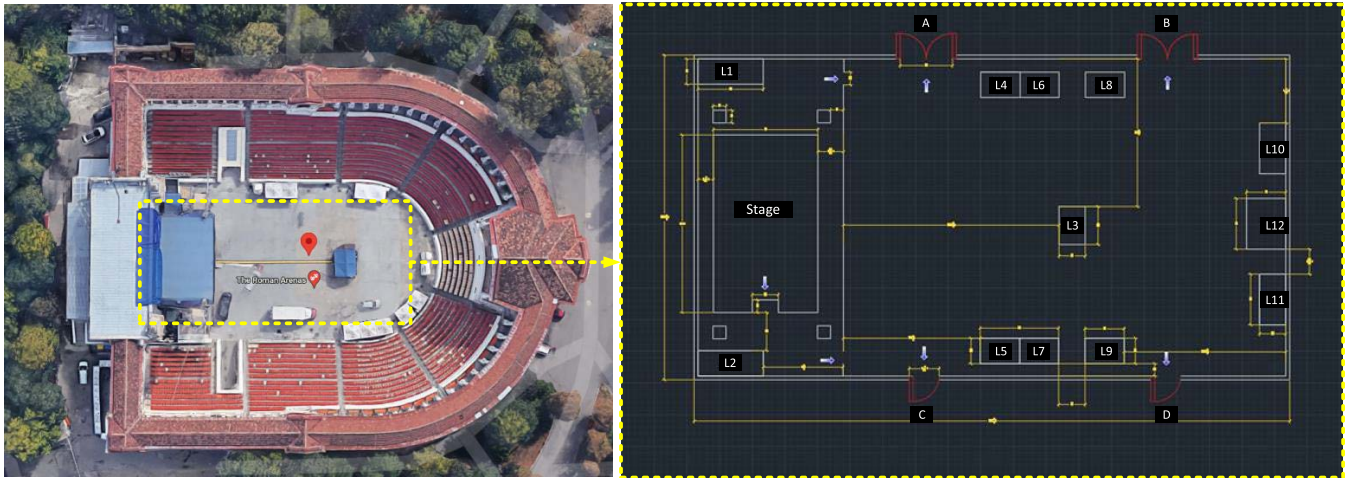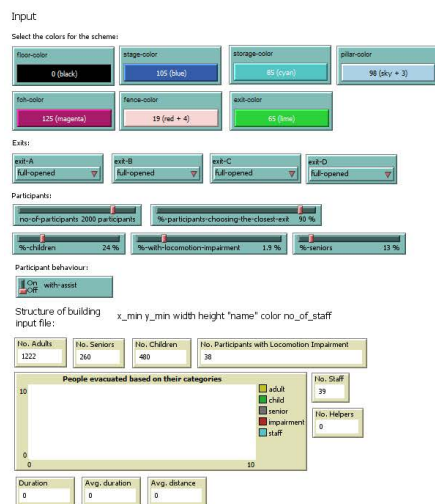
FIGURE 2. The Roman Arenas Tent Hall.

FIGURE 3. The Graphical User Interface of the Agent-Based Model.

the elements represented in the agent-based model (objects, doors, stands, stage, persons, etc.) are scaled to match multipliers of these values.

In particular, a person is represented in space by assuming an agent shoulder equal to 0.4558m, an assumption that is in line with previous studies involving human movement and behavior [45], [68]. As two persons cannot occupy the same space, even in the agent-based model, once an agent is located in an area given by the size of its shoulders, the space occupied by the agent cannot be, at the same time, occupied by another agent.

The walking area for the evacuees is represented by the flat floor of the tent, all the other objects installed by the organizers such as stands and stage cannot be overpassed by the agents in the evacuation process, representing obstacles that should be bypassed.

TABLE 1. Average evacuation time based on the category of participants.

Category	Average movement speed (m/s)	Speed range (m/s)
Child	0.90	0.90 ± 0.30
Adult	1.25	1.25 ± 0.30
Senior	0.80	0.80 ± 0.30
Persons with locomotion impairment	0.79	0.79 ± 0.32

The movement speed of the agents representing the "standard occupants" involved in an evacuation process has been taken from the data provided by Korhonen and Hostikka [68] as presented in Table 1.

As not all the persons involved in an evacuation process have the same evacuation speed, we have considered the uniform probability distribution for the speed as proposed by Korhonen and Hostikka [68] – Table 1. This assumption is in line with the observation stated by Ronchi *et al.* [45] who mentioned that in order to account for the variability of the people abilities, the unimpeded walking speeds can be determined through the use of distributions. As for the persons with locomotion impairment, the average movement and the speed range have been taken from the research conducted by Hashemi [69]. Regarding the staff member, they have been associated with young adult persons, therefore, they are included in the adult population, having similar movement speed rules.

The agents moving towards the exits in the evacuation process are considered rational. As a result of this assumption, when the evacuation process starts, each agent starts moving towards the closest possible exit, using the shortest path to the chosen exit. In reality, the proper choice for the closest door can be made by the agents as a result of the experience/familiarity they have with the location as they might have attended other events in the same location or due to the implementation of some guidance systems by the organizers of the event – e.g., guiding light on the floor or a smartphone application.

In the case in which one or more of the exits are not available for evacuation, the agents will be aware of this situation and will proceed to the closest exit that can be used in the evacuation process. Also, the doors can be partially available for the evacuation, representing the case in which one half of the door is open, while the other half is closed due to various reasons, such as the impossibility to be opened as a result of a technical issue. For simulating such a situation, the user can choose from the interface, for each of the four exits, the "fully-opened," "half-opened" or "closed" option by using the chooser for each of the doors (*exit-A, exit-B, exit-C* and *exit-D*).

As the individual evaluation related to the closest exit position can be sometimes subjective when no support is offered in this process and the persons involved in an evacuation process cannot evaluate correctly all the time the closest exit – this might happen due to panic or stress generated by being in such a situation or due to other conditions generated by the emergency situation itself, such as the view of the exits is restricted by smoke and the evacuees are not familiar with the environment as they have not been previously attended another event in the tent – there might be cases in which the evacuees, even though they are assumed to be rational, might wrongly evaluate the closest evacuation door and choose another door which is not the closest door to their actual position. For such situations, the model can be adjusted from the interface and, for a given number of participants, the choice of the closest exit will be suboptimal, namely the randomly selected participant will not choose the closest exit, but rather one of the remaining exits.

The two situations, in which all the agents choose for sure the closest door and in which they choose the evacuation door following a probability distribution, are implemented in the agent-based model – through the *%-participants-choosing-the-closest-exit* slider – and will be used in simulations for better observing the differences in evacuation times.

When children or persons with locomotion impairment are present at the events held in the tent, it is assumed that they attend the event with an adult agent. As a result, when the population is randomly positioned in the environment, the children and persons with locomotion impairment are always located near an adult agent. In the case of an emergency two situations are possible: the adult might choose to help the child or the person with locomotion impairment to evacuate – case in which the two persons evacuate together, with the adult agent walking all the time behind the children or the person with locomotion impairment at a speed equal to the average speed between the two agents – or the adult choose not to help the other agents and each of the agents are moving towards the exits at their own speed. The choice for one of the two situations mentioned above can be established from the interface, by selecting "on"/"off" in the *with-assist* switcher.

For the situation in which the agents do not necessarily choose the closest exit, as the evacuation exit is determined using the probability distribution, and the adult agent decides to help the child agent or the person with locomotion impairment agent, the evacuation door will be the one selected by the adult agent for both agents.

As for the staff members, it is assumed that all the time they will choose the closest exit as they are familiar with the environment.

The evacuation process is considered complete when all the persons have evacuated using one of the available exit doors.

B. IMPLEMENTATION

The agent-based implementation in NetLogo 6.2.2 has been made through the use of the *patch* and *turtle* agents. The *patch* agents have been used for building-up the environment and for providing the information related to the exit doors to the *turtle* agents. In order to fulfill this purpose, the *patch* agents possess the characteristics in Table 2.

The shortest distance to the available exits is retained using the *exit-energy* variable of each patch through the use of a vector. The vector contains a number of values equal to the number of available exits. In order to better explain how the values are determined, we will consider in the following a hypothetical situation in which only one exit door is available for a certain room. As a result, the vector exit-energy contains only one value. In order to determine the shortest path (exit-energy) to an exit, an "adapted cone approach" based on Biner and Brun's "cone approach" [31] – Fig. 4 (A) – has been implemented, with a few differences.

TABLE 2. Patches characteristics in the agent-based model.

Name of variable	Range / Value	Short description
pcolor	black / dark blue / cyan / sky / magenta / lime / white / pink / orange / red	Patches in black are used to describe the floor of the event tent, while the ones in white for delimiting the tent, representing the walls. Two colors are possible for the exits: lime when the exit can be used for evacuation and red when the exit is closed. Different other colors can be used for the other types of objects, their color can be changed from the interface by using the input boxes.
object	floor / stage / storage / pillar / merchant stand / token stand / sound-operators stand / exit / wall	Indicates whether a patch is a part of the floor, exit or obstacles such as stage, storage, pillar, merchant stand, token stand, sound-operators stand or wall.
exit-index	0, 1, 2 or 3	Indicates the index of the exit. The variable is set only for the patches that represent the four exits in the model.
exit-energy	array of values between 0 and 1000	Contains the shortest distance from the current patch to all the available exits. When the patch is initialized, the vector contains the value 1000 for the distance to each available exit. During setup, the shortest distances are calculated using the "adapted cone exit" approach – as discussed in this section – and the vector is updated to the shortest distances to all the available exits.
plabel	value between 0 and 1000	Displays on each patch the value of the distance to the closest available exit. The value is 0 for the exits and 1000 for all the other patches representing the floor before the program starts computing the distances. The display of the *plabel* on each patch can be activated/deactivated from the *display-energy* switch located in the interface.

The first difference is related to changing the modality through which the numbers associated to the distances are being determined. In the approach we have used in the agent-based model, the available exits have received "0" for the patches representing them, while the numbers associated with the patches located near-by are increasing following a cone rule instead of decreasing as in [31] – Fig. 4 (B).

The second change has been due to watching the evacuation simulations made using the approaches (A) and (B) presented in Fig. 4. Based on simulations it has been observed that when multiple paths are available from an agent's current position to the closest available exit door, not all of them are equal in length. For example, in Fig. 5, an agent located in the upper-left corner of the image, near the obstacle marked in red, on the cell having the exit-energy of 17, can take two paths for reaching the exit patches marked with 0. Following the classical "cone exit" approach, any of the two paths (marked with yellow arrows) are possible to be followed as at every moment of time, the agent chooses among the adjacent patches, the patch with the smallest energy. But looking closer at the length of the paths, one can see that, in fact, they are not equal, as the upper path measures approximately 14 units (6 units horizontally, $5*1.4$ units in diagonal and 1 unit vertically), while the lower path measures 17 units (6 units vertically and 11 units horizontally).

As a result, in the agent-based model we have implemented an "adapted cone exit" approach (Fig. 4 (C)) in which the exit-energy values are determined starting from the exit doors and using the smallest value between the *exit-energy* of adjacent patches updated with the distance between the current patch and each of the adjacent patches. A numerical exemplification is provided in Fig. 6. From the figure it can be observed that the exit-energy of the patch located in the left-bottom, marked with a darker shade of blue than the other patches, is determined based on the *exit-energy* of its adjacent patches for which the *exit-energy* has been determined in a previous step. As a result, the *exit-energy* for the above-mentioned patch is the minimum between the *exit-energy* of the adjacent patches (1.4, 1 and 2) to which we have added the distance between the middle of selected patches (namely 1, 1.4 and 1). As a result, the *exit-energy* of the left-bottom patch is equal to 2.4.

Considering the same situation as in Fig. 5 (representing a part of the selected event hall from the agent-based model) and using the "adapted cone exit" approach, a partial view on the model developed in NetLogo 6.2.2 representing the lower-right exit (noted with exit D in Fig. 3) is presented in Fig. 7.

As it can be observed, an agent located in the upper-left cell of the picture will decide to follow the path marked by yellow arrows in order to arrive at the exit marked with 0. This choice is made by comparing the *exit-energy* of the adjacent cells, namely 13.1 and 14.5, and by choosing the smallest value (13.1 units) which belong to the path highlighted in Fig. 7.

The code for the proposed "adapted cone exit" is presented in Table 3.

In the case in which the agents are blocked and cannot advance anymore on the shortest path, in general due to the fact that they met on this path – for a short period of time – another agent that comes from ahead, the agents are able to choose the next shortest path available until they "escape" the blockage and then return to the shortest path to
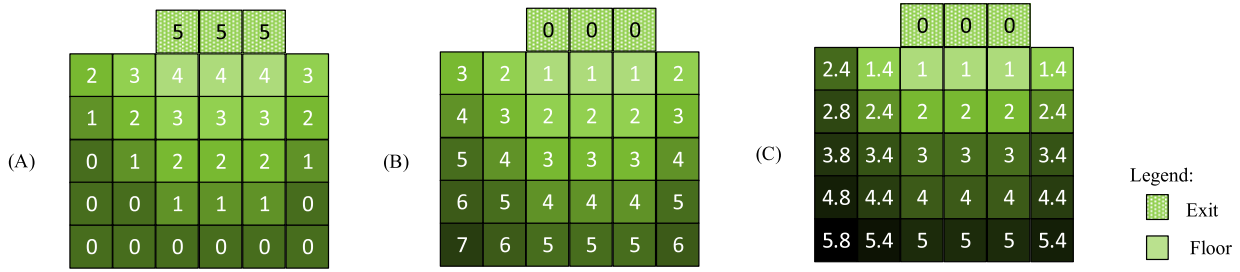
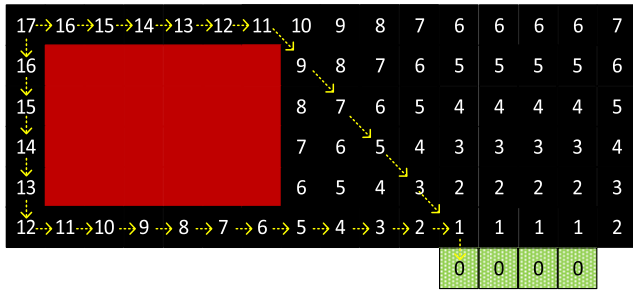**FIGURE 4.** Cone exit approach: (A) classical cone exit; (B) modified cone exit; (C) adapted cone exit.
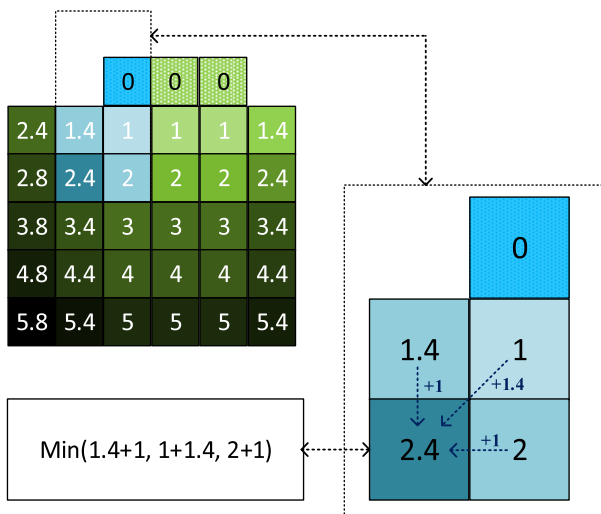

FIGURE 5. Cone exit approach.

FIGURE 6. Determining the exit-energy using an adapted cone exit approach.
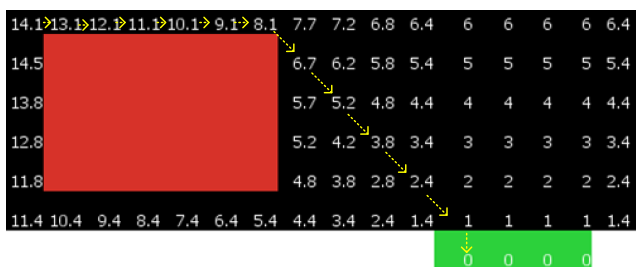

FIGURE 7. Adapted cone exit approach (patches view from the agent-based model built in NetLogo 6.2.2).

the selected exit door. This situation might appear in narrow areas such as the areas between the stands and the walls of the event hall.

TABLE 3. Adapted cone exit implementation.

Adapted cone exit implementation in NetLogo

to setup-energy
  ask patches with [object = "door"][
    compute-energy 0 self
  ]
end

to compute-energy [energy-level floor-patch]
  (ifelse
    object = "door" [set energy energy-level]
    object = "floor" [set energy energy-level + distance myself]
    [ ])
 	
  ask neighbors with [object = "floor" and energy > [energy] of myself + distance myself][
    compute-energy [energy] of myself self
  ]
end
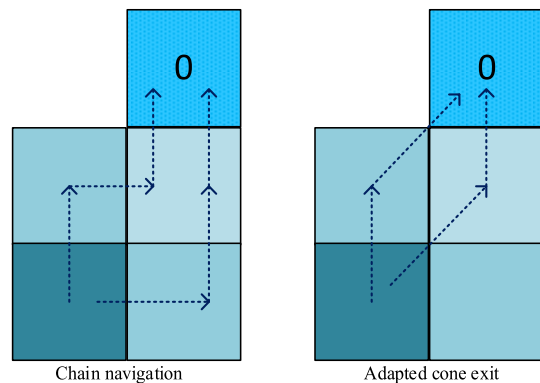
FIGURE 8. Adapted cone exit approach compared to chain navigation.

Compared to a chain navigation grid [43], the "adapted cone exit" offers a more realistic view of the participants evacuation process, with impact on the calculus of the overall evacuation time – Fig. 8.

The advancement of the agents to the exits is not conditioned by the position they have with respect to a certain patch (e.g., the agent does not have to be positioned in the middle of the patch at the beginning of the walk and does not have to arrive in the middle of a patch at the end of a time unit). As it will be discussed in the following, when the *turtle* agents are described, the agent's advancement within each moment of
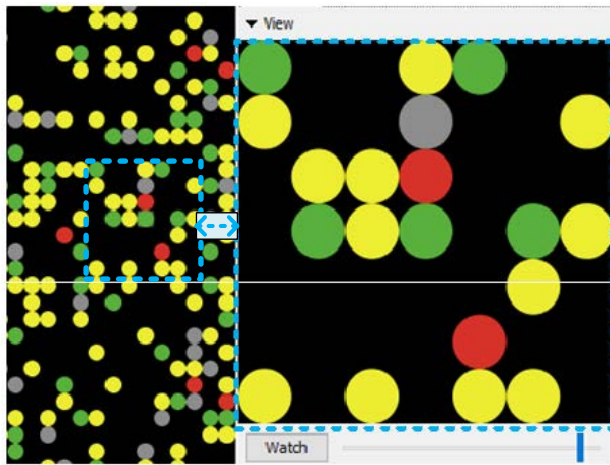
FIGURE 9. Up-close look of the *turtle* agents.

time depend on its speed and is made by selecting each time the adjacent empty patch with the smallest *exit-energy*.

The *turtle* agents are used for representing the participants involved in an evacuation process. Each *turtle* agent is depicted using a circle of a different color in accordance with the type of participant to the event (child: green, adult: yellow, senior: grey, person with locomotion impairment: red, staff member: blue) – Fig. 9.

The *turtle* agents are randomly created within the event hall at the beginning of the simulation and the proportion of agents from each category is set from the *%-children*, *%-with-locomotion-impairment* and *%-senior*s sliders in the agent-based model interface. The staff members are created at random positions in the adjacent areas of their working locations.

For better shaping the *turtle* agents, a series of characteristics have been implemented in the agent-based model, as presented in Table 4.

After setting the environment and creating the agents to be evacuated, in a simulation run, the *turtle* agents proceed to the exit doors based on their *chosen-exit-index* and at their *speed*, being guided in the decision related to the chosen path by the values of the vector *exit-energy* stored at the level of every patch.

In order to test the choice for the shortest path to an exit, we have simulated the situation presented in Fig. 7 by manually placing an agent in the patch located in the upper-left corner of the figure. The moves of the agent towards the evacuation exit are provided in a few screenshots in Fig. 10 (it should be mentioned that we have not depicted the moves at every tick as the figure would have occupied more space).

From Fig. 10 it can be observed that the agent is following the same path as depicted in Fig. 7.

Depending on the speed of the agent, the time needed to cover the distance in Fig. 10 may vary.

As the turtle agents advance towards the selected exit at their own speed, the agents can arrive at the end of each moment of time (at each tick) anywhere inside a patch, not being conditioned to arrive in the middle of the patch.

TABLE 4. Turtles characteristics in the agent-based model.

Name of variable	Range / Value	Short description
speed	[0, 1.24]	The speed range for the considered categories has been determined by translating the m/s measurement unit into patches/tick, considering the length of a patch of 0.5m and the duration of a tick of 2.5s [6]. As a result, the speed of a child is 0.72 $\pm$ 0.24 patches/tick, while for the adult is 1 $\pm$0.24 patches/tick, for a senior is 0.64 $\pm$ 0.24 patches/tick, for a person with locomotion impairment 0.632 $\pm$ 0.256 patches/tick. When evacuating together, the speed of two agents is the average between their default speed. The maximum speed can be up to 1.24 patches / tick, representing 1.55 m /s when the turtle agent is an adult and has no other agent or obstacle in front of it. The minimum speed is 0 patches/tick and might occur when the agent is blocked and can no longer advance due to congestion or when it has evacuated. In the agent-based model, the uniform distribution of the speed has been introduced using the "random-float" function in NetLogo having as parameters the values of the speeds mentioned above. For example, in the case of a child agent, the NetLogo code for computing the speed is written as follows: set speed 0.72 + random-float 0.48 − 0.24 Random-float function generates a floating-point value between 0 and 0.48 and by subtracting 0.24, one obtains a floating-point value between -0.24 and 0.24. This value is afterwards added to the 0.72, resulting the final speed of the agent.
current-speed	[0, 1.24]	Indicates the speed of each agent at every tick.
category	adult, child, senior, locomotion-impairment, staff	Indicates the category of the agent.
travelled-distance	$\mathbb{R}_+$	Retains the distance travelled by the agent from its initial position to the current position. At the start of the simulation the travelled distance is zero for all the agents. At the end of the simulation, the travelled distance provides the distance travelled by the agent

The speed of an agent involved in an evacuation process is equal to its speed determined at the beginning of the simulation process but can be reduced at any time if in front

TABLE 4. *(Continued.)* Turtles characteristics in the agent-based model.

		from its initial position to the evacuation door.
chosen-exit-index	0, 1, 2 or 3	Retains the *exit-index* of the door to which the agent proceeds when involved in an evacuation process. The *exit-index* is a variable that can take 0, 1, 2 or 3 as values in the agent-based model, corresponding to the characteristics of the patches representing one of the four exits in the model.
my-teammate-ID	0, …, number of agents in the model -1	In the case in which an agent is evacuating with another agent (e.g., the case in which the *with-assist* slider in the interface is "on" – the agents representing children or persons with locomotion impairment are evacuating with another agent) the variable retains the *who* number of the other agent. The *who* number is the unique identifier used by NetLogo for distinguishing among the turtle agents and starts from 0 to the number of agents created in the interface - 1.

of the agent there are agents which move at a lower speed on the same path and congestion appears.

The evacuation simulation stops when the last *turtle* agent has evacuated, no matter the door used for evacuation.

Regarding the evacuation process, two indicators can be determined through the agent-based model. The first one refers to the *overall evacuation time* and measures the time needed for the entire participants population to evacuate from the event tent, while the second one retains the *average evacuation time* and is determined by summing up all the individual evacuation times and dividing the result by the number of the agents. Both indicators are expressed in ticks in the agent-based model and can be transformed in seconds by dividing the result by 0.4.

For validating the model, a population composed by 53 adults (Fig. 11) have been evacuated from a small room, 4m × 13m, featuring a single exit door and a fixed obstacle placed in the central-left side of the room. An informed consent has been obtained from the participants.

The agent-based model has been adapted to fit the new environment and the agents, all adults, have been set on the random positions. A view of the evacuation process corresponding to one simulation run is presented in Fig. 12.

The overall evacuation time has been recorded by conducting three rounds of evacuation, with the evacuees placed at random locations within the considered space. The time has been compared with the one obtained through the use of the agent-based model adapted for the new situation, run for
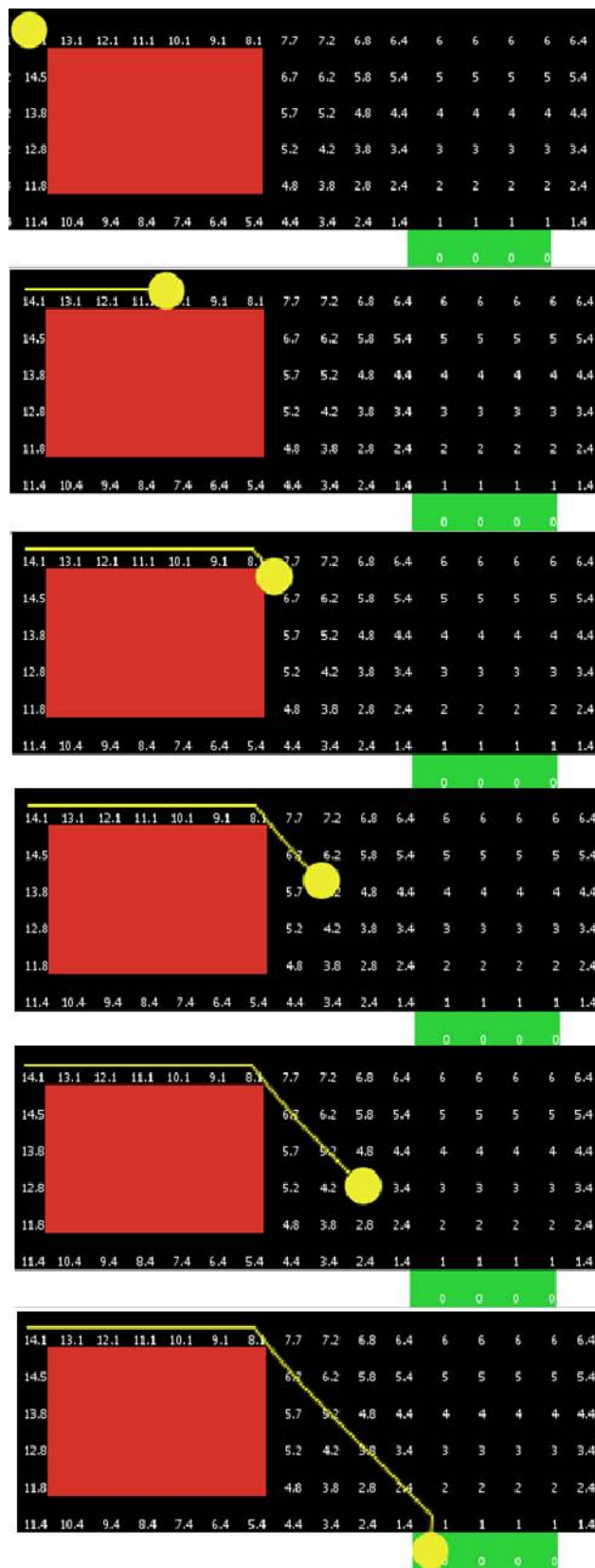

FIGURE 10. Evacuation of a turtle agent using the adapted cone exit approach.

FIGURE 11. Evacuation of a small population made by adults from a small room.

10,000 times by using the BehaviourSpace option in NetLogo [56], [64]. In terms of time differences, it has been determined an average difference in evacuation time of 4.58%, which has been considered acceptable given the randomness in the speed of the agents and the position of the agents among the considered environment.
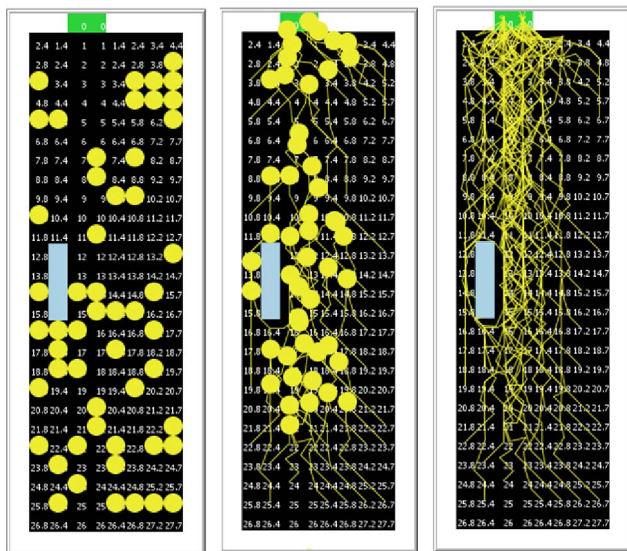

FIGURE 12. Agent-based simulation evacuation of a small population from a small room.

V. SCENARIOS
All the simulations have been conducted using the BehaviourSpace tool offered by NetLogo. Each scenario has been run 10,000 times and the average values have been reported in the paper, rounded to the nearest integer. The tool has been designed for conducting a large number of simulation experiments with the agent-based model [64].

An evacuation simulation can be considered complete when all participants in the event have been evacuated to a safe place. In general, a safe area is a location that is not affected by a disaster or emergency. In this article, the

safe space is considered to be the outside of the event tent, which means that the simulation is completed once the entire population is evacuated from inside the tent.

Fig. 13 presents an evacuation simulation using the agent-based model for the considered event hall with 1500 participants and 39 staff members, all of them choosing the closest exit, in which the *display-energy* option has been set to "off" for providing a better view of the agents' paths. Additionally, the *display-path* option has been set to "on" for better observing the paths considered by the agents involved in the evacuation process. The images in Fig. 13 depict the evacuation environment and the position of the agents before the evacuation started (A), at a random moment of time (B), when the participants are only evacuating using Exit D (C) and at the end of the simulation process (D).

The scenarios considered in the study have been set up by varying different aspects related to the considered population, such as the doors availability (Scenario I), the size of the evacuated population (Scenario II), the structure of the population (Scenario III) and the choices made regarding evacuating with a friend/family member (Scenario IV) or not choosing the closest door (Scenario V). Each scenario has been divided into sub-scenarios for better highlighting how the variation in the selected indicators will impact the overall result. Each sub-scenario has been simulated 10,000 times and the average results have been reported in the paper by rounding them to the nearest integer. Additionally, a combined scenario has been set up (Scenario VI) in which some of the elements analyzed individually in Scenario I – Scenario V have been included in the same experiment. In all the scenarios, besides the *overall evacuation time* and the *average evacuation time*, the *average distance travelled* has been reported for giving more insight on the paths considered by the agents in their evacuation process. The results for the *overall evacuation time* and the *average evacuation time* have been transformed from ticks to seconds, while the values for the *average distance travelled* have been reported in meters instead of patches for ensuring a proper connection to the units used in our every-day life.

VI. SIMULATIONS RESULTS
In the following, the results obtained in the case of each scenario set-up in the previous section are presented and discussed.

A. SIMULATIONS RESULTS FOR SCENARIO I
For setting up the conditions for Scenario I, the population has been held equal to 2000 participants (81.8% adults, 15.0% seniors, 3% children and 0.2% persons with locomotion impairment – as it is in most of the events organized in the selected location) and 39 staff members. Additionally, it has been assumed that the children and the persons with locomotion impairment evacuate individually, all the agents choosing for sure the closest evacuation door.

The availability of the four doors has been varied within the sub-scenarios as presented in Table 5.
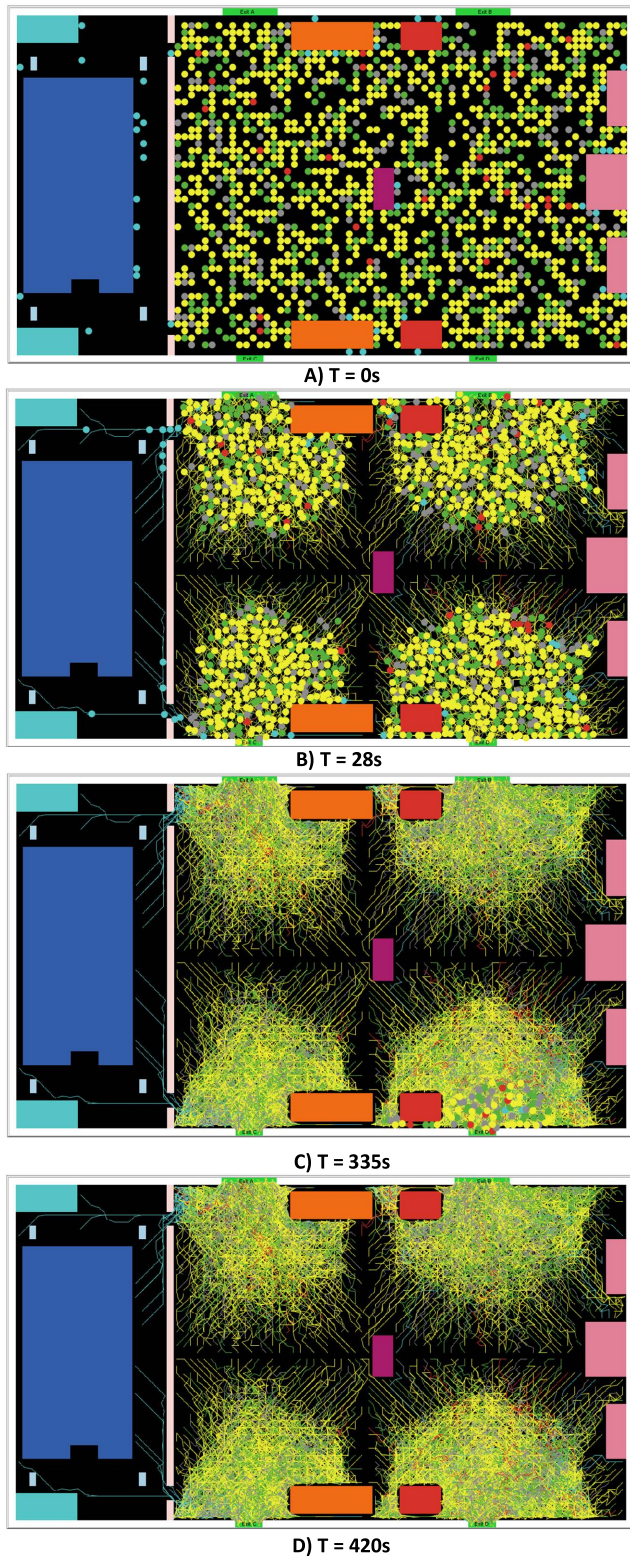
A) T = 0s

B) T = 28s

C) T = 335s

D) T = 420s

FIGURE 13. Evacuation simulation using the agent-based model for the event hall at different moments of time: A) 0s, B) 28s, C) 335s and D) 420s.

The baseline scenario, S-I.1., has considered the case in which all the exits are available for evacuation, and they can be completely used in the evacuation process.

TABLE 5. Exit doors availability.

Scenario	Exit[*]			
	A	B	C	D
S-I.1. (Baseline)	✓	✓	✓	✓
S-I.2.	✗	✓	✓	✓
S-I.3.	✓	✗	✓	✓
S-I.4.	✓	✓	✗	✓
S-I.5.	✓	✓	✓	✗
S-I.6.	✗	✗	✓	✓
S-I.7.	✗	✓	✗	✓
S-I.8.	✗	✓	✓	✗
S-I.9.	✓	✗	✗	✓
S-I.10.	✓	✗	✓	✗
S-I.11.	✓	✓	✗	✗

[*] ✓ = available (open), ✗ = unavailable (closed)

Scenarios S-I.2. – S-1.5. assume that only three of the evacuation exits can be used at their full capacity, while in the S-1.6. – S-1.11. scenarios only half of the exits are available for the evacuation process. As the case in which only one door is available is hard to be encountered in practice, we have excluded this assumption when building the scenarios.

TABLE 6. Simulation results for scenario I.

Scenario	Indicator		
	Overall evacuation time (seconds)	Average evacuation time (seconds)	Average distance travelled (meters)
S-I.1. (Baseline)	547	192	26
S-I.2.	597	263	33
S-I.3.	882	294	35
S-I.4.	779	253	32
S-I.5.	694	245	32
S-I.6.	1096	487	50
S-I.7.	958	382	42
S-I.8.	857	356	41
S-I.9.	1038	397	43
S-I.10.	984	403	43
S-I.11.	641	275	38

As presented in Table 6, the best values for the reported indicators have been obtained for the S-I.1. situation in which all the four exit doors are available for the evacuation process. This result was expected, and it confirms the observations made in the research literature related to the fact that a higher number of exits will produce a faster evacuation process. The *overall evacuation time* is approximately 9 minutes and 7 seconds for S-I.1. On average, an agent needs 3 minutes and 12 seconds to evacuate, walking approximately 26m.

For the scenarios featuring the unavailability of one of the exits during the evacuation process, S-I.2. – S-I.5., it can be observed that the most unfavorable situation is the one in which Exit B is closed, which increases the *overall evacuation time* with 5 minutes and 35 seconds, representing an

increasement of 61.24%. As expected, the values recorded for the *average evacuation time and average distance travelled* are higher in S-I.3. compared to S-I.1. with 1 minute and 42 seconds, respectively with 9m. The lowest impact on the *overall evacuation time* for S-I.2. – S-I.5 is recorded in the case of S-I.2., when Exit A is closed – lower with 4 minutes and 45 seconds than in the case of S-I.3 and higher with 50 seconds than in the case of S-I.1. Even though Exit A is larger than Exit C and Exit D, the impact of not being able to use Exit A for evacuation is smaller on the *overall evacuation time* than in the case of the other two exits (C and D), with up to 3 minutes and 2 seconds.

As the agent-based model offers a GUI that facilitates the observation of the agents' behavior during the entire evacuation process, a visual comparison between the S-I.2. – S-I.5. scenarios have been conducted on the purpose of identifying the differences in the recorded values of the three indicators reported in Table 6. Based on the observations, it has been determined that the prolonged evacuation time for some of the S-I.3. – S-I.5. scenarios compared with S-I.2. is due to the congestion around one of the available exit doors.

Specifically, it has been observed that in the case of S-I.2. the last agent evacuates through Exit D around T = 525s (with T = the moment of time), through Exit B at approximatively T = 580s and through Exit C at T = 597s. As for the S-I.3., it has been observed that no agent evacuates through Exit C after T = 432s, through Exit A after T = 553s, all the remaining agents evacuate through Exit D until T = 882s.

A similar situation is observed for S-I.4., where the agents are evacuating through Exits A and B until T = 348s, respectively T = 335s, while on Exit D until T = 779s. Lastly, for S-I.5., the agents evacuate through Exit A until T = 248s, Exit B until T = 513s and Exit C until T = 694s. Fig. 14 depicts the evacuation state exits in the considered scenarios S-I.2. – S-I.5 for the moment of time in which the agents are only left near one of the three evacuation exits.

Nevertheless, the evacuation doors position, and their width have a decisive role in the recorded *overall evacuation time*. For example, in the S-I.2. and S-I.5. scenarios, when the unavailable doors are Exit A and Exit D, the overall impact of these doors unavailability on the *overall evacuation time* is reduced compared to the S-I.3. and S-I.4. scenarios, when Exit B and Exit C are unavailable. These situations occur as, in S-I.2. Exit A, even though a large door, is located in the very front of the hall and does not "gather" as much agents as Exit B, a large door, which is opened in this scenario and is able to balance the absence of Exit A. A similar situation occurs in the case of S-I.5., where Exit D, even though a small exit placed in the middle-back of the hall with the potential of being the closest exit to more agents than Exit C, is closed and a series of agents decide to use Exit B, a large door which can balance the situation, providing enough space for agents evacuation. On the other hand, considering S-I.3. and S-I.4.
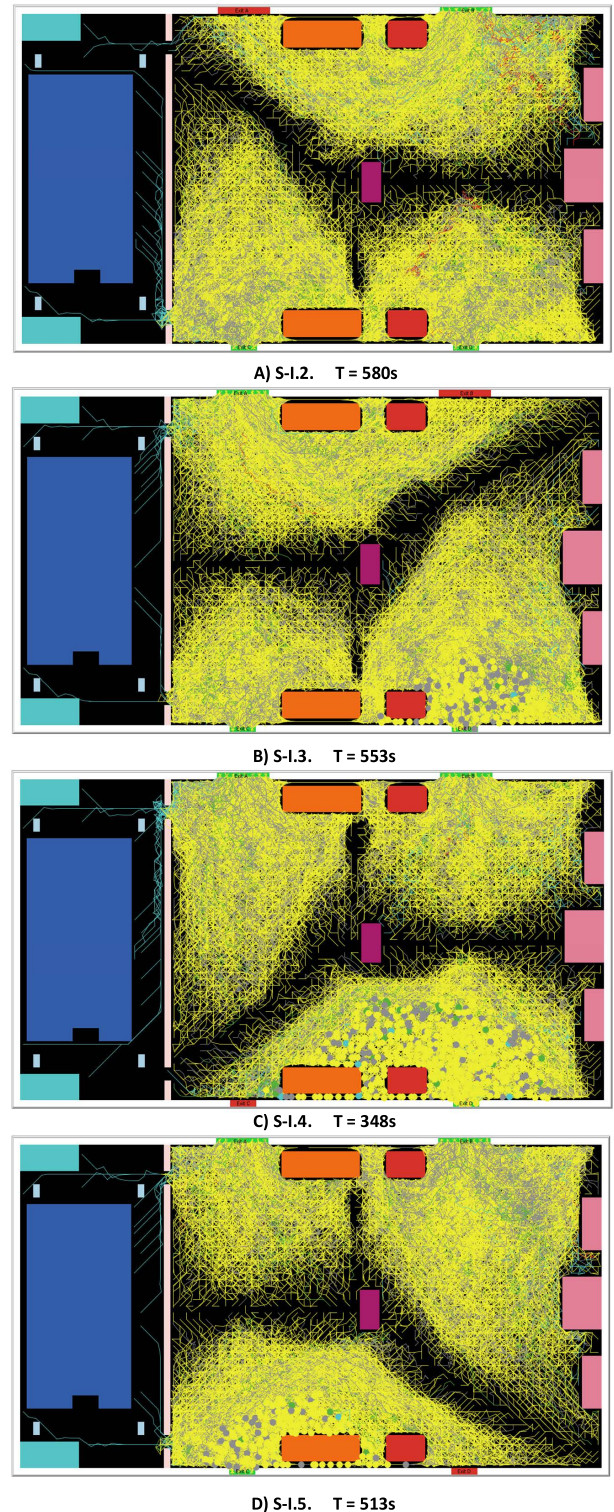

FIGURE 14. Evacuation simulations state and time for S-I.2. – S-I.5 when the agents are near one of the three evacuation exits: A) S-I.2., B) S-I.3., C) S-I.4. and D) S-I.5.

and the state of the simulations in Fig. 14, it can be observed that after T = 553s, respectively T = 348s, the only door with congestion is Exit D, which, due to its small dimensions,

does not succeed to produce a faster evacuation process. As a result, for this particular case of the considered event hall, one can consider enlarging Exit D as this will conduct to a smaller *overall evacuation time* in the case in which S-I.3. and S-I.4. scenarios occur – the scenarios with the higher *overall evacuation time*.

In terms of *average evacuation time*, it can be observed that the difference between the four situations (S-I.2. – S-I.5.) is up to 49 seconds, while the *average distance travelled* is up to 3m.

As for the scenarios in which two of the exit doors are unavailable, S-I.6. – S-I.11., it has been observed that the most unfavorable situations are the ones in which Exit B is closed, either in combination with Exit A (S-I.6.), Exit C (S-I.9.) or Exit D (S-I.10.). The *overall evacuation time* for the three situations in which Exit B is closed along with any of the remaining exit doors, range between 16 minutes and 24 seconds and 18 minutes and 16 seconds, being up to 24.26% higher than the case in which only Exit B is closed (S-I.3.) – Table 6. Considering the position of Exit B within the event hall and the size of this exit, the results were expected. Even in terms of *average evacuation time and average distance travelled*, the three situations (S-I.6, S-I.9. and S-I.10.) score the higher values among the scenarios featuring two closed exits, the *average evacuation time* being with up to 85.17% higher than the one recorded for S-I.3. where only Exit B was closed, while the *average distance travelled* is with up to 51.52% higher than in S-I.3.

The scenarios featuring two unavailable exit doors that produce the lowest *overall evacuation time* are S-I.11. and S-I.8., both having Exit D closed in combination with either Exit C or Exit A. While for the results obtained for S-I.8. (*overall evacuation time* of 857s, *average evacuation time* of 356s and average travelled distance of 41m) were expected given the fact that S-I.2. (having only Exit A closed) and S-I.5. (having only Exit D closed) produce the lowest *overall evacuation time* (597s, respectively 694s) among the scenarios with one unavailable door, being also lower than the *overall evacuation time* obtained for S-I.8. (where both Exits A and D are closed), the results obtained for S-I.11. in terms of *overall evacuation time* are surprising. By "surprising" we do not refer to the fact that the *overall evacuation time* for S-I.11. is lower than all the other scenarios in which two doors are unavailable (S-I.6.-S-I.10) as this result was expected given the fact that both exit doors C and D are smaller than the remaining opened exit doors A and B, which could ensure a faster evacuation process than the case in which exit doors C and D are opened, but surprising in comparison with S-I.5. scenario in which only Exit D is opened. For a more in-depth analysis, we have run several times the two scenarios, namely S.I.11. with an *overall evacuation time* of 641s, Exits D and C closed, and S-I.5. with an *overall evacuation time* of 694s, only Exit D closed. An evacuation state at the

end of two simulations for the two scenarios is provided in Fig. 15.

As it can be observed in Fig. 15., the difference in the *overall evacuation time* in favor for the case in which only one door is closed instead of two derives from the imposed rule that the agents evacuate using the shortest path to the available exit. In the case of S-I.5. a series of agents decide to evacuate using Exit C as it is located near them, but it is a smaller exit, which leads to congestion, ignoring the fact that Exits A and B, situated at a longer distance than Exit C, are larger and might represent a better option. This choice conducts to an increased *overall evacuation time*. Fig. 16 depicts the evacuation time versus the number of evacuated participants for the two scenarios, considering time intervals of 25s. In the case of S-I.5. approximately 1193 participants evacuate in the first 250s, compared to 947 participants in the case of S-I.11., while between 250s and 600s the number of evacuees changes in favor of the S-I.11. (1076 participants vs. 773 participants in S-I.5.). On the other hand, at personal level, the *average evacuation time* and the *average distance travelled* are lower in the S-I.5. scenario (245 seconds, 32m) compared to S-I.11. (275 seconds, 38m). Considering these results, it can be stated that for a large number of participants, the evacuation process has been shorter when only one door is unavailable (S-I.5.), but, on the same time there have been some participants, a relatively small number, for which the evacuation process has been longer, increasing their personal risk. Based on these observations, if needed, the agent-based model can be adjusted in order to incorporate congestion as a second criterion when choosing the evacuation door. This improvement applies to some evacuation cases in which the participants have the ability to observe the congestion from the other doors and change their mind related to the selected evacuation door. In reality, in large crowd evacuation cases, due to the large number of participants, it is hard to be in a congestion situation and to have the visibility to other evacuation doors. Even more, for the cases in which the emergency involves a lot of smoke or the lack of light or the occurrence of other hazardous conditions, such as fallen large objects or ceiling, the adjustment of the selected door based on observing the congestion around the other evacuation doors does not seem a realistic scenario.

As a general result based on the data provided in Table 6, it can be stated that the position, the number and the width of the evacuation exits impact the evacuation time, but as observed in the results of the simulations made for Scenario I, the results are highly dependent on the overall structure of the event hall, which implies the need for building a model that reproduces as precise as possible the characteristics of the simulated environment.

B. SIMULATIONS RESULTS FOR SCENARIO II

Scenario II discusses the differences in evacuation time when the number of participants varies. Table 7 presents the cases
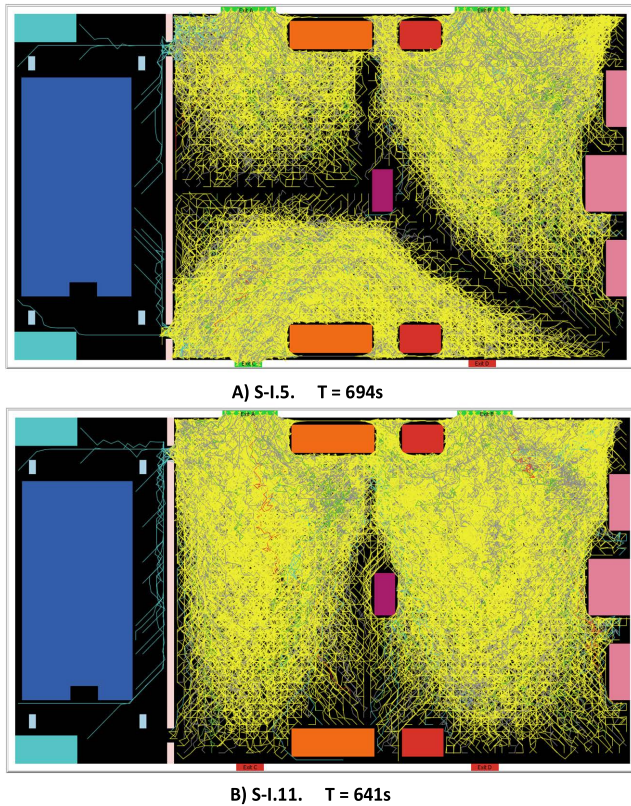
FIGURE 15. Evacuation simulations state and overall evacuation time for S-I.5. and S-I.11: A) S-I.5., B) S-I.11.
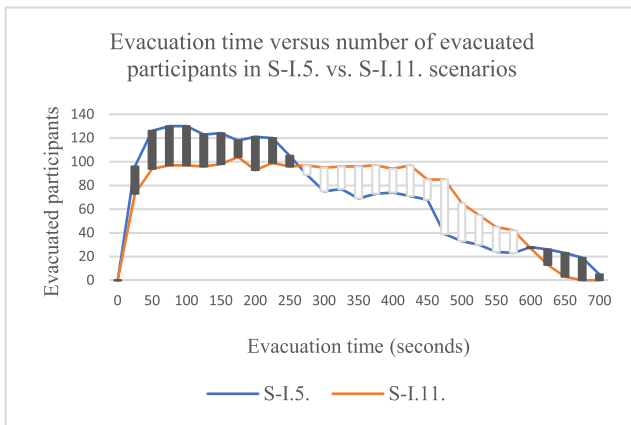

FIGURE 16. Evacuation time versus the number of evacuated participants for S-I.5. and S-I.11.

considered. The S-II.3. situation is the baseline situation as it reproduces the general audience of the event hall, the results being the same as in the S-I.1. scenario. The other three scenarios considered feature the highest number of participants that can attend an event (2500 participants, S-II.4.) and a lower number of participants (1000, respectively 1500 participants). The structure of the participants is the same in all the considered scenarios: 81.8% adults, 15.0% seniors, 3.0% children and 0.2% persons with locomotion

TABLE 7. Simulation results for scenario II.

Scenario	S-II			
	S-II.1.	S-II.2.	S-II.3. (Baseline)	S-II.4.
Number of participants	1000	1500	2000	2500

TABLE 8. Simulation results for scenario II.

Scenario	Indicator		
	Overall evacuation time (seconds)	Average evacuation time (seconds)	Average distance travelled (meters)
S-II.1.	287	104	17
S-II.2.	418	148	22
S-II.3. (Baseline)	547	192	26
S-II.4.	675	237	29

impairment, while all the four evacuation doors are available during the entire evacuation process. A number of 39 staff members add to each considered scenario.

The results obtained after 10,000 simulations are presented in Table 8, rounded to the nearest integer. Compared to the baseline scenario, S-II.3., a 50% reduction of the number of participants, S-II.1., conducts to a reduction of the *overall evacuation time* of 47.53%, with a comparable reduction of the *average evacuation time* of 45.83% and a reduction of the *average travelled distance* of 34.62%.

On the other hand, a reduction of 25% of the number of participants compared to baseline, reduces the *overall evacuation time* by 23.58%, the *average evacuation time* by 22.92% and the *average travelled distance* by 15.38% (S-II.3. vs S-II.2.), while an increasement of 25% increases the *overall evacuation time* by 23.40%, the *average evacuation time* by 23.44% and the *average travelled distance* by 11.54% (S-II.3. vs S-II.4.). Based on the recorded values, it can be stated that the changes in the number of evacuated persons impact all the three indicators, the less affected indicator being the *average distance travelled*.

As for the *overall evacuation time*, Fig. 17 presents the evolution of the number of evacuated participants over time in the four scenarios.

Based on Fig. 17, it can be observed that for a period of time ranging between 75s (S-II.1.) and 225s (S-II.4.), the number of evacuated persons per unit of time is 149 – 153 persons, decreasing until the end of the simulation. The period of time corresponds to the period in which all the four exits are used at their maximum capacity and can be easily identified by running the agent-based model and watching the evacuation
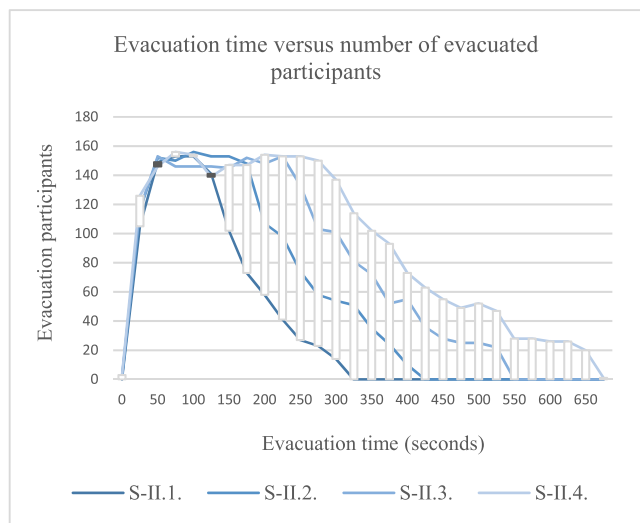
FIGURE 17. Evacuation time versus the number of evacuated participants for S-II.1. – S-II.4.

process. After this period of time, step-by-step, the agents choosing Exit A, B and C finish the evacuation. In all the situations, Exit D is the last door through which the participants are still evacuating. As a result, the evacuation time is prolonged due to the Exit D position and length, with a more accentuated impact on the situations in which the number of participants is large.

Even in the case of Scenario II it can be observed that the number of participants has an impact on the considered indicators, increasing their values as the number of participants increases. Besides this influence, the structure of the room plays an important role as the indicators might increase slowly if the position of the evacuation doors and their width are adjusted to better fit an evacuation situation.

C. SIMULATIONS RESULTS FOR SCENARIO III

As in the previous scenarios, we have held the same baseline scenario as in S-I.1. (called now S-III.1.) and we have built upon varying the elements related to the structure of the evacuation population, keeping them close to the possible real structures of the crowds of persons attending such large events. The sub-scenarios to be analyzed are presented in Table 9.

The simulations results are reported in Table 10. The first observation is that, as the number of adults decreases, the *overall evacuation time* increases. This change in the *overall evacuation time* can be due to the values of speeds set for the considered categories, with the adults being the category with the highest speed. A decrease of the adult population from 81.8% (S-III.1.) to 15.0% (S-III.6.) determines an increasement in the *overall evacuation time* of 15.54%. At personal level, the *average evacuation time* increases with 16.67%, while the *average distance travelled* is almost the same, the small changes reported in this indicator might be due

TABLE 9. Structure of the population.

Scenario	Category			
	Adults	Seniors	Children	Persons with locomotion impairment
S-III.1. (Baseline)	81.8%	15.0%	3.0%	0.2%
S-III.2.	60.0%	30.0%	9.0%	1.0%
S-III.3.	45.0%	45.0%	9.0%	1.0%
S-III.4.	35.0%	35.0%	29.0%	1.0%
S-III.5.	30.0%	60.0%	9.0%	1.0%
S-III.6.	15.0%	81.0%	3.0%	1.0%

TABLE 10. Simulation results for scenario III.

Scenario	Indicator		
	Overall evacuation time (seconds)	Average evacuation time (seconds)	Average distance travelled (meters)
S-III.1. (Baseline)	547	192	26
S-III.2.	571	200	26
S-III.3.	592	207	25
S-III.4.	596	210	25
S-III.5.	611	215	25
S-III.6.	632	224	25

to the stochastic simulation and rounding to the closest integer.

As for the S-III.4. situation, in which a quasi-balanced population (between adults, seniors and children participants plus the persons with locomotion impairment) has been considered, it can be observed that the *overall evacuation time* increases by 8.96% compared to the baseline. The *average evacuation time* increases by 9.38%, while the *average distance travelled* has almost the same value as in S-III.1.

As the speed of the population evacuating determines the values of the considered indicators, it can be said, once more, that knowing and evaluating properly the characteristics of the evacuated population and adequately introducing them in the agent-based model can improve the accuracy of the simulation results.

D. SIMULATIONS RESULTS FOR SCENARIO IV

Scenario IV refers to the case in which the children and the persons with locomotion impairment are helped for evacuation by an adult agent. The children and the persons with locomotion impairment are created in the agent-based model near an adult – as they were even in the case of the previous scenarios – but, in this case, they evacuate together with the adult, choosing the same door as the adult with whom they are evacuating, with the adult behind the child or the locomotion impairment person. The speed of the agents evacuating
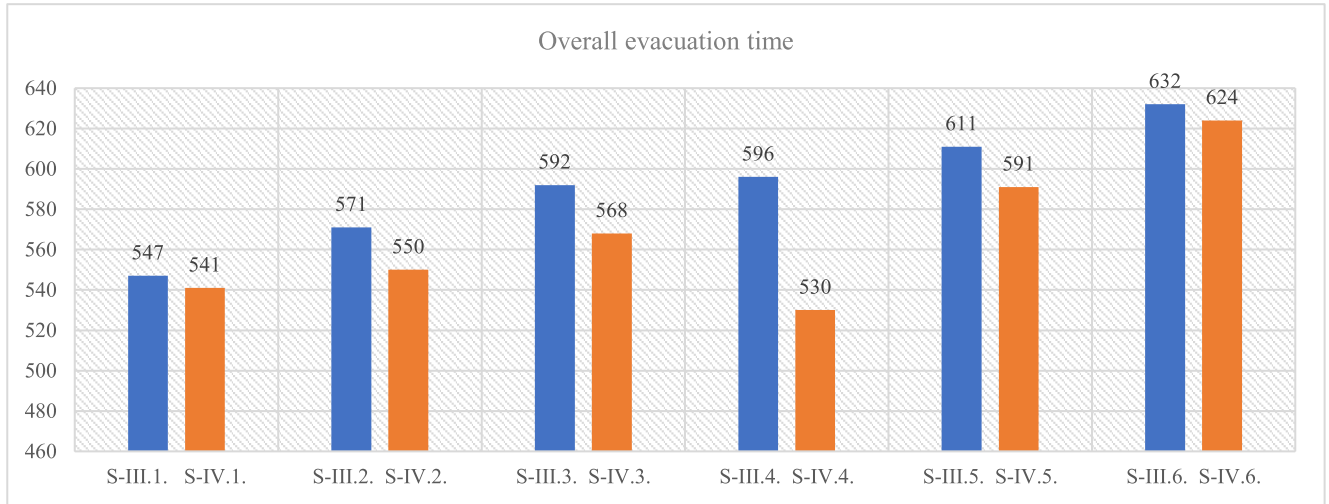
FIGURE 18. Overall evacuation time in S-III vs. S-IV sub-scenarios.

TABLE 11. Simulation results for scenario IV.

	Indicator		
Scenario	Overall evacuation time (seconds)	Average evacuation time (seconds)	Average distance travelled (meters)
S-IV.1.	541	190	26
S-IV.2.	550	193	26
S-IV.3.	568	199	26
S-IV.4.	530	187	26
S-IV.5.	591	207	25
S-IV.6.	624	221	25

together is determined as the average speed between their by-default speeds. Besides these assumptions, we have kept the same structure of the population as in Table 9, with the only change that we have named the sub-scenarios using ''IV'' instead of ''III.''

The results reported in Table 11 have been determined by running 10,000 each sub-scenario and determining the average value of the indicators rounded to the first integer value. A comparison between the *overall evacuation time* in scenarios III and IV can be observed in Fig. 18.

A first observation based on Fig. 18 is that the *overall evacuation time* is smaller in the case in which the children and the persons with locomotion impairment are evacuating with an adult agent. The improvement in the *overall evacuation time* is up to 1 minute and 6 seconds. The largest difference between the considered sub-scenarios is recorded between S-III.4. and S-IV.4., both of them featuring a situation in which the children plus the persons with locomotion impairment represent a consistent part of the evacuation population (30.0%). Smaller differences are recorded for the cases in which the children and the persons with locomotion
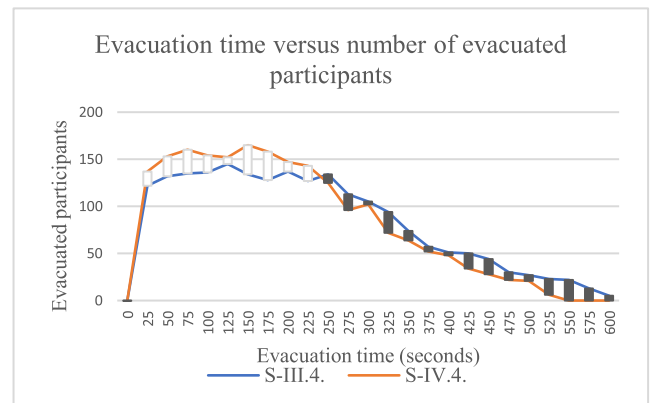
FIGURE 19. Evacuation time versus the number of evacuated participants for S-III.4. and S. IV.4.
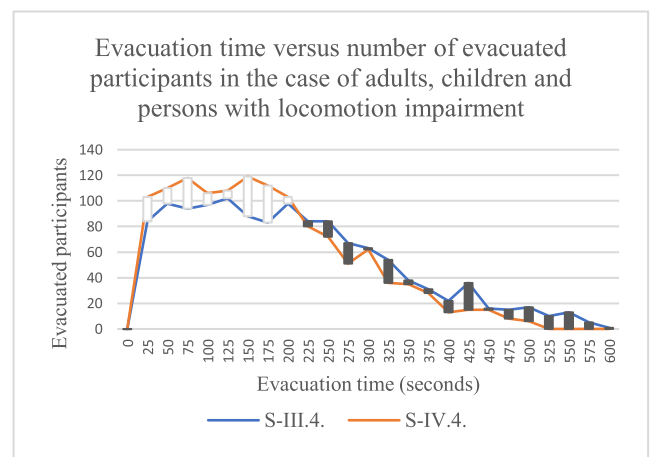
FIGURE 20. Evacuation time versus the number of evacuated participants (adults, children, and persons with locomotion impairment) for S-III.4. and S. IV.4.

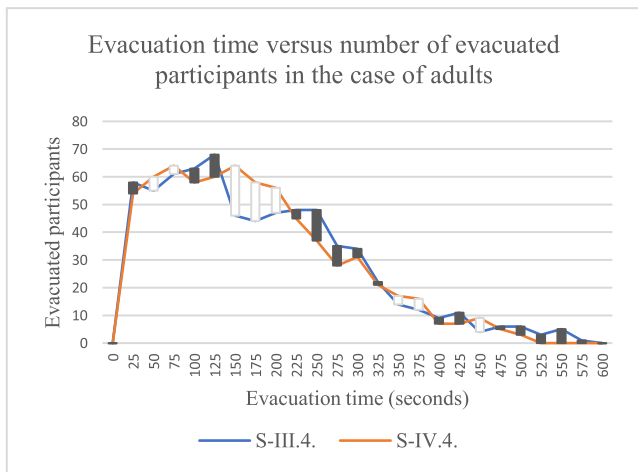impairment persons represent a small percentage of the population (e.g. 3.2% in S.III.1. and S.IV.1.).

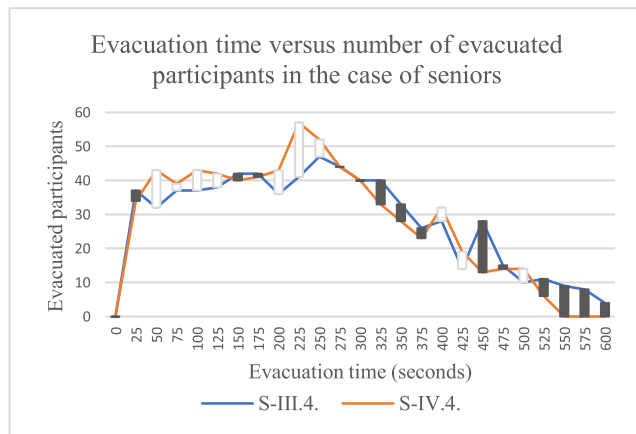**FIGURE 21.** Evacuation time versus the number of evacuated adult participants for S-III.4. and S. IV.4.

FIGURE 23. Evacuation time versus the number of evacuated senior participants for S-III.4. and S. IV.4.
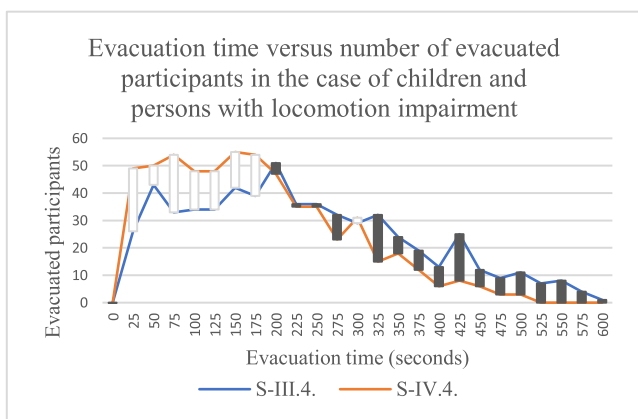

FIGURE 22. Evacuation time versus the number of evacuated children and persons with locomotion impairment participants for S-III.4. and S. IV.4.

Studying more in depth the S-III.4. vs S-IV.4. evacuation process by watching step-by-step the agent-based simulations, it can be observed that an increased number of agents are evacuating in the first 250 seconds in S-IV.4. case than in the S-III.4. (based on simulations the number of evacuated agents is approximatively 1494 in S-IV.4. vs. 1330 agents in S-III.4.) - Fig. 19.

Considering the category of agents evacuating together (namely the adults, children and persons with locomotion impairment) and comparing the evacuation time versus the number of evacuated persons, it can be observed that the S-IV.4. is favorable compared to S-III.4. as in the first 200 seconds of the evacuation process 897 agents evacuate in S-IV.4. compared to 744 agents in S-III.4. – Fig. 20.

By dividing the category represented in Fig. 20 into adults (Fig. 21) and children and persons with locomotion impairment (Fig. 22), it can be observed that the situation in which the children and persons with locomotion

impairment evacuate with adults is a beneficial one for this vulnerable category as in the first 175 seconds of evacuation a number of 358 children and persons with locomotion impairment evacuate in S-IV.4. compared to 251 persons in S-III.4.

It can be observed that even the adult category has benefits from the situation in which they evacuate with other agents as it has been observed that by helping the other agents, the entire evacuation process speeds up. As a result, after 200 seconds since the start of the evacuation process, in S-IV.4. a number of 494 adult agents have evacuated compared to 442 adult agents in S-III.4. – Fig.21.

Moreover, the senior category, even though it does not contribute directly to the new situation as they evacuate as single persons, has to gain from the fast evacuation process resulted from the fact that the children and persons with locomotion impairment evacuated with an adult agent – Fig. 23. As a result, after the first 200 seconds since the start of the evacuation, 434 senior agents have evacuated in S-IV.4. compared to 389 senior agents in S-III.4.

Based on the simulations results it can be concluded that when the children and locomotion impairment agents are evacuating with another adult agent the overall evacuation process is improved by minimizing the *overall evacuation time*. As for the *average evacuation time*, a 23 seconds improvement has been recorded in S-IV.4. compared to S-III.4., with smaller improvement times in the other considered cases. The average distance travelled remains almost the same and it is due to the rules regarding the random initial placement of the agents within the environment and to the fact that the agents choose all the time the closest evacuation door.

E. SIMULATIONS RESULTS FOR SCENARIO V

For Scenario V it has been assumed that not all the agents are choosing the closest evacuation door. The situation might

TABLE 12. Simulation results for scenario V.

Scenario	S-V				
	S-V.1. (Baseline)	S-V.2.	S-V.3.	S-V.4.	S-V.5.
Number of participants choosing the closest door	100%	95%	90%	85%	80%

TABLE 13. Simulation results for scenario V.

Scenario	Indicator		
	Overall evacuation time (seconds)	Average evacuation time (seconds)	Average distance travelled (meters)
S-V.1. (Baseline)	547	192	26
S-V.2.	558	194	27
S-V.3.	567	197	28
S-V.4.	581	202	29
S-V.5.	613	209	30

arise when the participants to the event are not familiar with the environment or in the cases in which due to the low visibility, they are not able to localize the closest exit. Not selecting the closest door can be also a result of panic or a result of a decision to go to a specific area in which one expects to find a relative or a friend. As Haghani and Sarvi [70] mentioned in their study, even though in normal times the proximity to a destination is the most prominent factor when selecting an exit, it has been proven to be completely irrelevant in emergency decisions. The reasons for not choosing the closest exit can be numerous, and one might envision some more considering the psychological aspects involved by being in an emergency situation. We will not discuss them in this part, as the focus is on the changes in the evacuation time when this situation might arise.

The envisioned sub-scenarios are presented in Table 12. As in the previous cases, for the baseline case, S-V.1., we have considered the same conditions as is S-I.1., while for the S-V.2. – S-V.5. sub-scenarios we have reduced the percentage of the agents choosing the closest door.

As expected, not choosing the closest door leads to increasement in all the three indicators – Table 13.

Comparing S-V.1. with S-V.5., it can be observed that a reduction of 20% of the participants choosing the closest door conducts to an increasement in the *overall evacuation time* of 1 minute and 6 seconds (12.07%), increasing the average
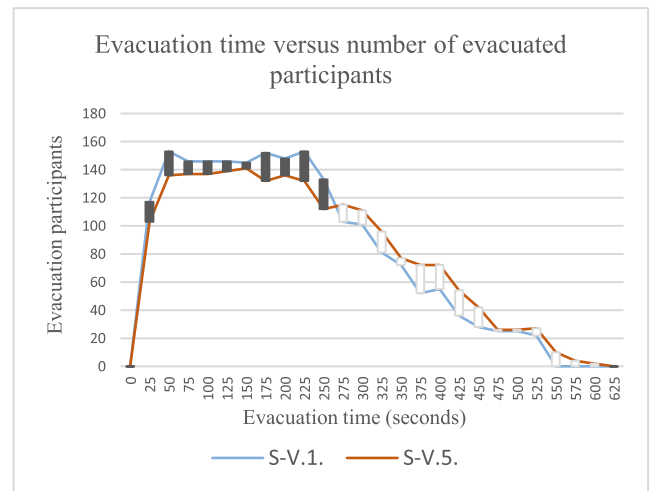

FIGURE 24. Evacuation time versus the number of evacuated participants for S-V.1. and S-V.5.

TABLE 14. Simulation results for scenario VI compared to S-I.1.

Scenario	Indicator		
	Overall evacuation time (seconds)	Average evacuation time (seconds)	Average distance travelled (meters)
S-I.1. (Baseline)	547	192	26
S-VI	875	325	41

evacuation time with 17 seconds (8.85%) and the average distance travelled with 4 m (15.38%).

In terms of evacuated persons versus the evacuation time, when comparing S-V.1. with S-V.5. (Fig. 24), it can be observed that in the first 250 seconds since the evacuation started, the when the agents are selecting the closest door, a number of 1439 agents are evacuated, while when only 80% of them are choosing the closest door, a number of 1305 agents are evacuated (with approximatively 9.31% agents less).

Based on the simulation results for this scenario, it can be stated that as the agents do not choose the closest door, the *overall evacuation time*, *average evacuation time* and the *average distance travelled* increase. As a result, the interested parties in offering a safe evacuation process should consider applying the proper means through which during such an emergency the population is guided to the closest exit, which results in diminishing the evacuation time and life savings.

F. SIMULATIONS RESULTS FOR A COMBINED SCENARIO

A combined scenario has been set up in this section, in which elements from the individual scenarios have been considered in order to demonstrate once more that the cumulus of
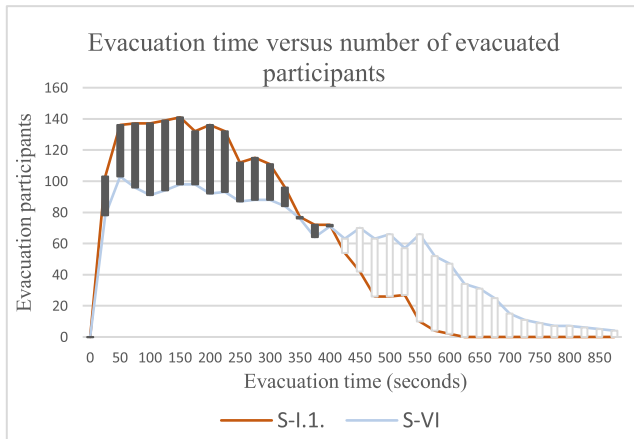
FIGURE 25. Evacuation time versus the number of evacuated participants for S-I.1. and S-VI.

factors that might appear in an evacuation can conduct to a completely different result than the one considered in an "ideal" case in which all the things go right. As the purpose was not to set up values for the variables that are hard to be encountered in an emergency, a "mild" scenario has been considered. In this scenario, S-VI., we have started from the baseline scenario S-I.1., in which we have altered some of the assumptions. As a result, it has been assumed that one of the emergency exit doors is not available to be used in the evacuation process (Exit C), while one of the main exits can only be partially used for evacuation (Exit B), that the children and the locomotion impairment persons evacuate with an adult and that only 80% of them are choosing the closest door.

The results obtained are summarized in Table 14. It can be observed that for this scenario, S-VI, the *overall evacuation time* is 14 minutes and 35 seconds (with 59.96% higher than in the S-I.1.), while the *average evacuation time* is 5 minutes and 25 seconds (with 69.27% higher than in the S-I.1.), while an *average distance travelled* of 41m (with 57.69% higher than in S-I.1.).

As for the evolution of the evacuation process in S-I.1. compared to S-VI, Fig. 25 presents the number of evacuated agents versus time. It can be observed that in the S-VI scenario the number of agents evacuated in the first 400 seconds is 1401 agents, compared to 1848 agents in the S-I.1.

Once more, it can be stated that for ensuring a proper evacuation process, the knowledge related to the location to be evacuated is of utter importance, along with the characteristics and the behavior of the evacuated persons. As shown in the cases presented above, small changes in different indicators can conduct to various changes in the result, while the combination of the different categories of changes can produce totally different results than expected.

As a result, the proposed agent-based model can serve as a tool through which the different aspects related to the

modeled event hall are represented in a simplified manner and the characteristics of the evacuees are better shaped. Through the increased number of simulations one can conduct in a short amount of time and through the visual interface offered by the agent-based model, one can better understand which are the elements to be considered and what can be done in order to improve the values of the considered indicators, with a direct result in improving the entire evacuation process.

The model has some limitations related to the elements considered in the evacuation process and can be further improved by including different states in which the agents can be as a result of the feelings they have during such an event, states that can determine a specific behavior for each agent.

VII. LIMITATIONS OF THE STUDY

A potential limitation of the study is related to the fact that the validation of the model has been made only on an adult population. This limitation has not been further investigated in the present paper as, through the validation made on the adult agents, it has been observed that the differences between the *overall evacuation time* in the case of the adapted agent-based model and the on-site simulations have been below 5%. As a result, it is expected to have the similar differences between the real-life simulations and the agent-based model in the case of the other categories of people considered in the model. Even more, the agents' speed is a parameter in the model, so anyone interested in conducting his/her own simulations on a population already known, can easily introduce the speeds of the considered categories of persons and observe the behavior of the evacuees and the values of the resulting variables.

Another limitation is given by the number and types of variables used in the agent-based model. We acknowledge that with the increasement of the number of variables considered in the study, the incidence of each variable can be better shaped. Even more, it would be interesting to observe the result of the cumulated factors on the evacuation time. Additional statistical analysis can be conducted on the obtained results in accordance with the specific of the study one decides to conduct.

Lastly, the paper focuses on a general evacuation process, as described above. Considering some specific evacuation processes (e.g. fire broken out in fixed points of the room), one can observe that the impact of the considered factors might change. This limitation refers to the results obtained for the output variables. As for the agent-based model, it can be adapted to better fit the situation one needs to simulate.

VIII. CONCLUDING REMARKS

The paper discusses the use of agent-based modeling and simulation in the context of large event hall evacuation for better understanding the overall evacuation process and for

observing the elements that can contribute to a prolonged evacuation process.

On this purpose, an agent-based model is built in NetLogo 6.2.2 and an "adapted cone exit" approach is proposed, which is useful in guiding the agents to the closest exit. A series of scenarios have been envisioned and simulated for better observing how the changes in different aspects of the evacuation process can influence the *overall evacuation time*, the *average evacuation time* and the *average distance travelled* by the agents.

Specifically, for the selected event hall, it has been observed throughout the simulations that when the number of participants attending an event is increased, Exit D is the last door through which the evacuation takes place. As a result, it is recommended, that in the future, if possible, the width of this exit to be increased in order to reduce the evacuation time. Even more, as Exit B plays an important role in the evacuation process, it is advisable for the persons in charge to take all the measures for keeping it available for the emergency situations by checking the space around the door and making sure that the door is not blocked or accidentally locked.

As choosing the closest door by the evacuees has a positive impact on the evacuation time, it is advisable that the persons in charge should take all the measures to ensure that the attendees to the event are familiar with the positions of the evacuation doors – this can be made by placing a small map on the back of the ticket or by playing a small video on the screen just before the start of the event. Nevertheless, helping other persons to evacuate should be among the elements to be kept in mind for decreasing the evacuation time. As a result, increasing the awareness for helping other in-need persons can be made through short videos or messages posted in the surrounding area of the event.

Given the flexibility of the agent-based model, the behavioral aspects of the evacuees and the environment characteristics of the evacuated space can be effectively represented in the model. In particular, given the simulation results and the visual analysis that can be conducted individually on each scenario, the predominant factors affecting the evacuation process can be identified and the potential measures can be properly evaluated prior to be implemented in practice. As a result, the evacuation process safety levels can be improved.

Future research can expand the model by including more information related to the vulnerable population, the feelings and reactions one might experiment in an evacuation process with effect on the evacuation behavior or the impact of specific events (e.g., different levels of gas concentration, the occurrence of multiple fire points within the event hall) on people's behavior and evacuation process. The impact of each newly considered element can be further put in connection with the resulting variables in order to better observe which of these elements are the ones leading to the greatest changes in the resulting variables. For this type of analysis, grey systems theory can be used, by computing several degrees of grey incidence, pointing in this manner the hierarchy of the elements with the highest incidence on the evacuation time.

APPENDIX A
Table of NOMENCLATURE

TABLE 15. Table of nomenclature.

Name of variable	Meaning
average distance travelled	Average distance travelled by each turtle agent
average evacuation time	Average evacuation time for each turtle agent
category	Category of each turtle agent
chosen-exit-index	Exit chosen by each turtle agent
current-speed	Current speed of each turtle agent
display-energy	Displays the distance from the current patch to the closest exit
display-path	Enables the draw of the path of each turtle agent from its initial position to its current position
exit-energy	Energy of the exit
exit-index	Index of the exit
my-teammate-ID	Identifier of the turtle agent evacuating with the current agent
object	Type of patch
overall evacuation time	Time needed for the entire population to evacuate
patches	Agents used for building the environment
pcolor	Color of each patch agent
plabel	Label of the patch
speed	Speed of each turtle agent
travelled-distance	Distance travelled by each turtle agent
turtles	Evacuating agents
with-assist	Evacuation situation in which the agents evacuate together with other agents
%-children	Percent of children in all the evacuation population
%-with-locomotion-impairment	Percent of persons with locomotion impairment in the evacuation population
%-participants-choosing-the-closest-exit	Percent of participants choosing the closest exit
%-seniors	Percent of seniors in the evacuation population

APPENDIX B
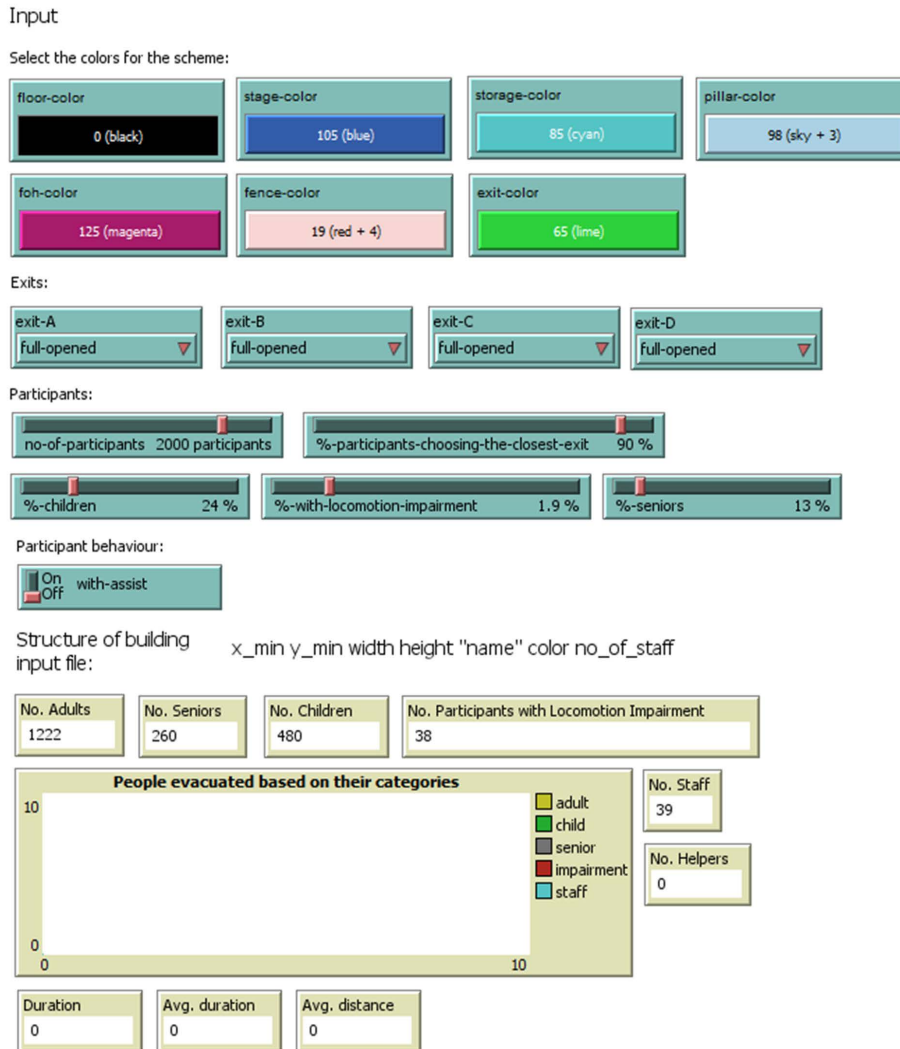## CLOSE-UP ON AGENT-BASED MODEL GRAPHICAL
USER INTERFACE

FIGURE 26. Close-up on graphical user interface – left side.
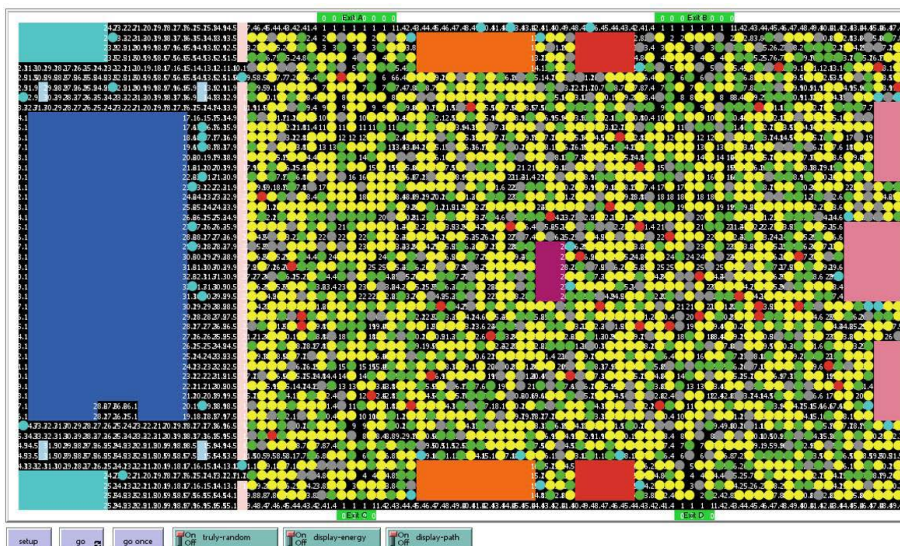

FIGURE 27. Close-up on graphical user interface – right side.

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