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Modelling large-scale evacuation of music festivals

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ABSTRACT

This paper explores the use of multi-agent continuous evacuation modelling for representing large-scale evacuation scenarios at music festivals. A 65,000 people capacity music festival area was simulated using the model Pathfinder. Three evacuation scenarios were developed in order to explore the capabilities of evacuation modelling during such incidents, namely (1) a preventive evacuation of a section of the festival area containing approximately 15,000 people due to a fire breaking out on a ship, (2) an escalating scenario involving the total evacuation of the entire festival area (65,000 people) due to a bomb threat, and (3) a cascading scenario involving the total evacuation of the entire festival area (65,000 people) due to the threat of an explosion caused by a ship engine overheating. This study suggests that the analysis of the people-evacuation time curves produced by evacuation models, coupled with a visual analysis of the simulated evacuation scenarios, allows for the identification of the main factors affecting the evacuation process (e.g., delay times, overcrowding at exits in relation to exit widths, etc.) and potential measures that could improve safety.

1. Introduction

Music festivals present a set of challenges from the perspective of evacuation safety. For instance, very high people densities can be reached in proximity of the stages, thus creating potential issues associated with crushing and trampling [9,26]. Attendees are often unfamiliar with the evacuation routes, thus potentially increasing the time needed for way-finding during such incidents. Pre-evacuation behaviour itself (which can be defined as the time needed to start the purposive movement towards a safe place [19]) may be affected by several variables such as the impact of social media [5,18] or levels of alcohol consumption [6].

Today evacuation safety measures for music festivals are mostly based on guidelines (rules of thumb) discussing variables such as the width of available exit space depending on the number of people, maximum number of people per m^2, etc. [10]. Evacuation exercises to test festival evacuation plans are rarely done. Evacuation modelling to test festival evacuation plans and procedures are an easier way to evaluate and improve the safety of music festivals. However this technique is seldom used as organisers and local authorities rely on the current practice of evacuation guidelines.

Evacuation models can be used to obtain qualitative and quantitative information on evacuation times and space usage in different evacuation scenarios [7]. The behaviour of festival goers and members of staff can also be explored [16,28].

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A model study was developed in order to explore the potential of evacuation modelling for the simulation of music festival evacuation scenarios. In particular, the paper discusses the insights provided by the use of evacuation simulations tools, including what type of results can be obtained and how they can be used by event safety and public emergency response managers. A fictional music festival was created, the characteristics of which were informed by a review of several real ones by the researchers. The music festival area is able to host up to 65,000 people and includes eleven stages. Three evacuation scenarios were devised, in which different threats and available evacuation routes were assumed. The connections between variables in the model (number and location of exits, delay times, exit paths) have been investigated.

2. Method

The method employed in this study was the application of evacuation modelling techniques. The initial phase of the study was therefore the selection of an appropriate evacuation model to simulate large-scale evacuation scenarios at a music festival. A review of the characteristics needed in evacuation models to simulate this type of scenarios was performed. This included the representation of large populations and high densities. Existing research on crowd modelling in cases of large-scale evacuation is mostly based on modelling assumptions aimed at low computational cost (given the large number of people involved), e.g., macroscopic simulations [3] or cellular automata [2]. The present study sets out to simulate large-scale evacuation scenarios with a higher level of sophistication, i.e., adopting a multi-agent-based model with a continuous modelling approach. The choice of the evacuation model employed in this study was made after an analysis of the characteristics of evacuation models as stated by model developers, e.g., the model inventory available at www.evacmod.net [21] or presented in scientific reviews [7,14]. A set of simulations was performed using an agent-based continuous model—Pathfinder [27].

When possible, the input of the evacuation model was calibrated using experimental data rather than the default settings of each model. This had the effect of making the evacuation scenarios as realistic as possible, while limiting the user effect [25], i.e., results affected by the choices of the modellers during the process of input calibration.

3. Model case study

The model case study was an outdoor dance festival in an area (see Fig. 1) restricted by fences due to its close proximity to a residential area, river and main road transport infrastructure (highway and secondary roads). The area was used for music performances at different stages (eleven). The maximum number of attendees was 65,000 people, most of whom were likely to be aged between 16 and 35 years old. In case of evacuation, fences close to the exits used for the delimitation of the festival are usually open. External exits have a width in the range of 7.5–9 m, except the main entrance of the festival area (Fin_Ex2 in Fig. 1 has a width of 45 m).

Three evacuation scenarios were taken into consideration, in which different threats and available evacuation routes are assumed. The evacuation scenarios were developed in order to explore the predictive capabilities of evacuation models during such incidents:

1. A preventive evacuation of a section of the festival area containing 15,309 people due to a fire breaking out on a ship close to the festival site;
2. While the preventive evacuation is ongoing, an escalating scenario involving the total evacuation of the entire festival area (65,000 people) due to a bomb threat;
3. While the preventive evacuation is ongoing, a cascading scenario involving the total evacuation of the entire festival area (65,000 people) due to the threat of an explosion caused by the overheating of the ship engine.

Based on discussions with festival organizers, the starting average people density is assumed to be equivalent of 2 people/m^2 at the outdoor stages and 3 people/m^2 for the indoor stages. This could be due to high density in close proximity to the stages (even higher than 4 people/m^2) and a lower density in areas situated further away from them (approximately 1 people/m^2). The population placement is then adjusted in order to consider 10% of the population that is not on the stages and that the upper limit of the population allowed in the festival area is 65000 people. This results in densities lower than 1 people/m^2 in those festival areas situated far away from the stages.

Scenario 1 involved the partial preventive evacuation of a section of a festival area due to a hypothetical fire on a nearby ship. Assuming the fire occurring on a vessel on the river close to the north/north-west part of the festival area, a total of 15,309 attendees would need to be evacuated from the areas in close proximity to stages 4, 7, 10, and 11. In Fig. 1, Fin_Ex1 is the only available exit for the evacuation (the exits on the north/north-west part, i.e., Fin_Ex2, Fin_Ex3B and Fin_Ex3A are assumed not to be available due to toxic smoke from the fire) and attendees are also relocated to the central part of the festival area.

In order to provide insight into the impact of the blocked exits upon the evacuation process, a benchmark case was also considered (Scenario 1a) in which the preventive evacuation scenario was simulated again but with all exits considered available (i.e., including the exits in the north/north-east part of the festival). In addition a Scenario 1b is also considered where the exits on the north/north-east part, i.e., Fin_Ex2, Fin_Ex3B and Fin_Ex3A are assumed to be unavailable (as in Scenario 1), but an additional provisional 9 m wide exit is created in the proximity of Fin_Ex1 by removing fences.

The two more complex scenarios (Scenarios 2 and 3) involved the total evacuation of the entire festival area, containing an estimated 65,000 people. In this case, all exits were available except Fin_Ex2, Fin_Ex3B and Fin_Ex3A (see Fig. 2). Attendees were expected to move to one of the available exits in order to leave the festival area (see all exits available in Fig. 1).

Detailed information on the model case study, assumptions in use and subsequent results can be found in the full report associated with this paper [1].

3.1. Model input calibration

The physical abilities of people in the festival area were represented through their approximate unimpeded walking speed distributions (see Table 1). Two categories were used, namely "standard occupant" and people with locomotion impairments [4]. This second category was used in order to represent people with both permanent and temporary locomotion impairment. The unimpeded walking speeds were represented with truncated normal distributions in order to account for the variability of people abilities. Those values are derived from previous experimental research [4,13]. In total, 30% of the attendees of the festival were assumed to have locomotion impairments.

The studies from [20] demonstrate that an appropriate representation of delay times can be made through the use of log-normal distributions. Pre-evacuation delays are assumed based on previous real emergencies [11,15], existing literature on the impact of social media during emergencies [5] and private communication with festival organizers and first responders.

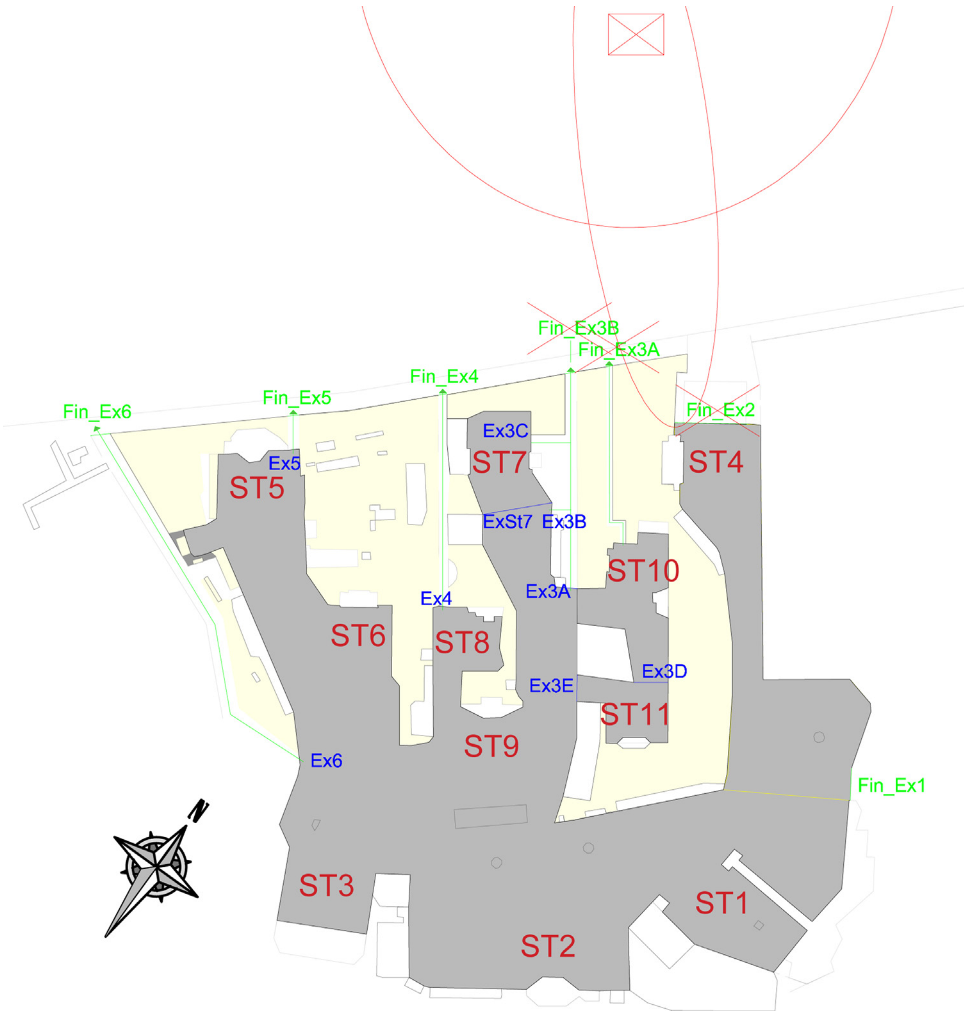

Fig. 1. Schematic two-dimensional representation of the festival area. Legend: STX = stagenumber, ExX = exit of stage number *x*, Fin_ExX = final exit number *x*. The area in grey represents the area where people are initially located. The lines pointing north represent the exit paths. The rectangle indicates the starting location of the threat and the blocked exits due to the threat. Stages 1, 2, 4, 5, 9 and 10 are outdoor with an initial population density of 2 people/m^2, stages 3, 6, 7, 8 and 11 are indoor and they have an initial population density of 3 people/m^2.

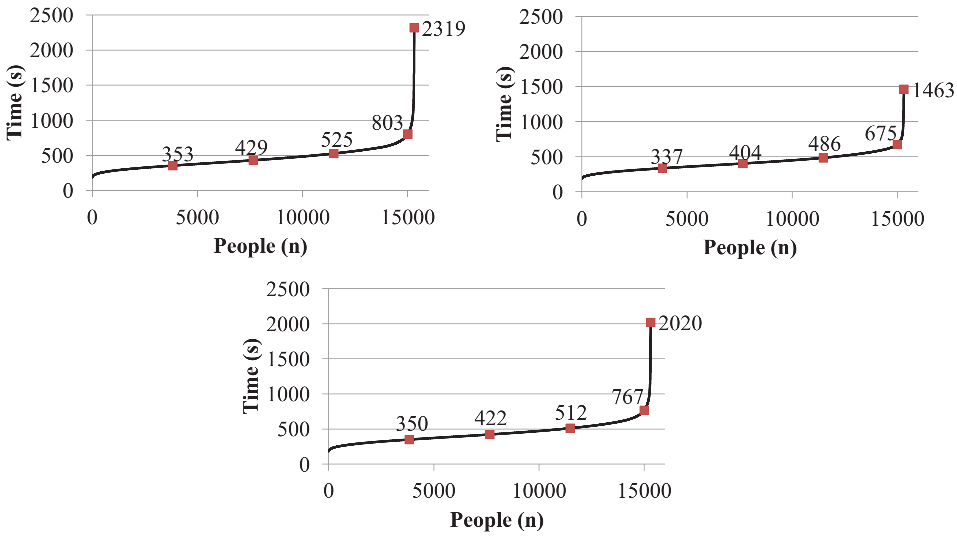

Fig. 2. People-evacuation time curve and percentages (25%, 50%, 75%, 98% and 100% in the squares) of evacuated population in Scenario 1 (top-left), Scenario 1a (top-right) and Scenario 1b (bottom). The x axis indicates the progressive number of people evacuated, while the y axis indicates the corresponding evacuation times.

In fact, other large-scale emergencies (e.g., the terroristic attack at the World Trade Center in 2001) have shown that delay time distributions in those types of large emergencies can have a maximum time in the order of 10–15 min (600–900 s) [14] and that the news of such type of large scale emergencies can appear in the media within 3 min, e.g., in the Boston Marathon bomb [5]. Agents were represented in space assuming an agent shoulder width equal to 45.58 cm. This value is in line with the average shoulder width of an adult [13].

In Scenario 1 (and sub-scenarios 1a and 1b), only a part from the festival population (15,309 people) was evacuated (see Fig. 2). Since this was a preventive evacuation scenario managed by the staff of the festival, the delay times were assumed to be within 600 s (10 min) (see Table 2 for the exact time distribution employed). In scenarios 2 and 3, while the preventive evacuation was ongoing (i.e., the same delay time distribution is assumed in the portion of the festival area where the preventive evacuation scenario takes place), a total evacuation was also triggered in the remaining part of the festival area for two different causes (bomb threat in Scenario 2 or the overheating of the ship engine in Scenario 3). Given the direct visibility of the smoke coming from the ship in Scenario 3, it was assumed that the delay time would be shorter (maximum of 750 s, i.e., 12 min and 30 s, see Table 2) than that of the bomb threat scenario, where the threat was not directly visible. In Scenario 2, the delay time was assumed to not exceed 900 s (15 min) (see Table 2). It should be noted that delay time distributions are used to represent pre-evacuation. For this reason, in some cases, the delay times of the "late responders" in the preventive evacuation may overlap with the "quick responders" in the total evacuation.

People movement was represented within Pathfinder adopting the embedded multi-agent-based approach in which each agent has its own individual properties. Route choice is simulated using the default algorithm of the model in which a *locally quickest* path planning approach is used, i.e., routes are ranked hierarchically using local information about people location and queuing times at exits.

The evacuation model in use embeds distributions to reproduce human behaviour during evacuation, e.g., delay time distributions, unimpeded walking speed distributions, etc. For this reason, it was necessary to define the appropriate number of runs to be simulated in order to avoid the results of the models being affected by the number of simulations performed [23,24]. A convergence method (convergence in mean) was therefore employed to study the variability of model results due to the use of random sampling in the distributions. In the present work, the runs were stopped when the error was lower than 1% for 5 consecutive runs, i.e., an additional run would change the results of less than 1% for five consecutive runs. A minimum number of 15 runs for each scenario was also considered.

Table 1
Unimpeded walking speeds for standard occupants and people with locomotion impairments based on [4,13].

"Standard" occupant (m/s)			Occupants with locomotion impairments (m/s)		
Mean	Standard deviation	Range	Mean	Standard deviation	Range
1.29	1.00	0.29–2.29	0.8	0.37	0.1–1.68

Table 2
Assumed delay time distributions.

Scenario	Avg (s[min])	St Dev (s[min])	Min (s[min])	Max (s[min])
1–1a–1b (preventive)	360[6]	120[2]	180[3]	600[10]
2 (bomb threat)	480[8]	150[2.5]	240[4]	900[15]
3 (engine overheating)	420[7]	135[2.25]	210[3.5]	750[12.5]

3.2. Results

Results are presented using the people-evacuation time curves. In addition, a set of key percentages of evacuated population are highlighted, namely 25%, 50%, 75%, 98% and 100% of the total number of attendees in the festival area. The choice of the percentages under consideration is based on the need to study the trend of evacuation with an interval of 25% of the population as well as the analysis of the most sensitive part of the evacuation, the tail of the occupant-evacuation time curve (i.e., 98% vs 100%). The analysis of the people-evacuation time curves together with the selected percentages of evacuees allowed understanding the evacuation process and having a global picture on the impact of different scenarios during the passage of time. It should also be noted that this analysis has also been coupled with the visualization interface embedded in the evacuation model Pathfinder, which visualizes the trajectories of each individual during the passage of time.

Results of Scenario 1 are presented in Fig. 2. It should be noted that the difference in evacuation times of the last 2% of the festival population (from 98% to 100%) is significantly higher than the difference between other percentages. In fact, 98% of the population of this section of the festival area was evacuated within 803 s (approximately 13 min), while the average evacuation time of the entire population (i.e., 100% of the population corresponding to 15,309 people) was 2319 s (approximately 39 min). A similar trend is observed in Scenario 1a, although the total evacuation time is significantly reduced (1463 s, approximately 24 min). Scenario 1b presents a total evacuation time in between Scenarios 1 and 1a (2020 s, approximately 34 min).

Fig. 3 shows the results of Scenarios 2 and 3. Scenario 2 and 3 refers to the total evacuation of the entire festival area, corresponding to a total of 65,000 people. The entire festival population is evacuated in an average time equal to 5025 s (approximately 84 min) in Scenario 2 and 5009 s (approximately 84 min) in Scenario 3. The evacuation curve is almost linear after the 25% of the population is evacuation in both cases and no significant differences can be found between the 98% and 100% of the evacuated population.

A relative comparison of all results helps identify possible issues associated with different evacuation scenarios at music festival scenarios. The first evident conclusion from the comparison between Scenario 1, 1a and 1b is that the number of available exits severely affects the total evacuation times and this difference can be quantified with evacuation models. In fact, as expected, the average total evacuation time increases by approximately 37% when Fin_Ex2, Fin_Ex3B and Fin_Ex3A are not available (Scenario 1) when compared to the benchmark case where all exits are available (Scenario 1a). Similarly, comparing Scenario 1 and 1b, the additional provisional exit in Scenario 1b causes a reduction of total evacuation time of approximately 5 min in Scenario 1b (2319 s vs 2012 s, see Fig. 2). This is the result of a re-distribution of exit usage given different available exits.

Another factor which may have an impact on the evacuation results is the average walked travel distance to the exit. This is also positively affected by the availability of more exits. The differences in terms of evacuation times for Scenarios 2 and 3 appear to be negligible (see Fig. 4). This leads to the conclusion that if the cause of the evacuation scenario affects only the delay times, this would not lead to significant differences in the global people-evacuation time curve in large music festival scenarios in which the evacuation time is mostly dominated by flow constraints. In addition, if different initiators are represented through their impact on the same variable, the type of initiator itself would not be important, i.e., it is the effect of the initiator that matters rather than its nature. This can be further investigated analyzing the people-evacuation time curves. In fact, the people-evacuation time curves for Scenario 1, 1a and 1b have a different trend if compared with the

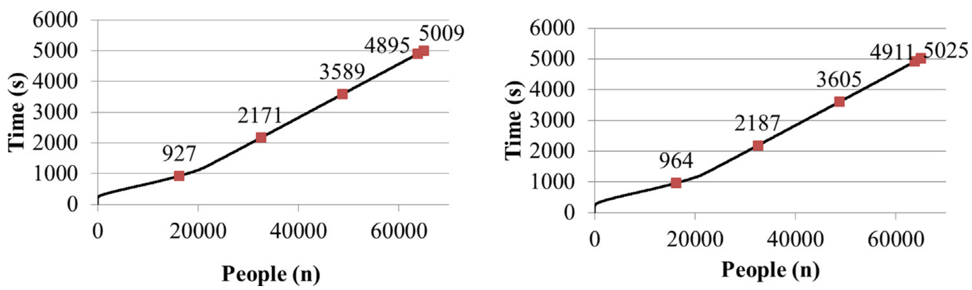

Fig. 3. People-evacuation time curve and percentages (25%, 50%, 75%, 98% and 100% in the squares) of evacuated population in Scenario 2 (left) and Scenario 3 (right). The *x* axis indicates the progressive number of people evacuated, while the y axis indicates the corresponding evacuation times.

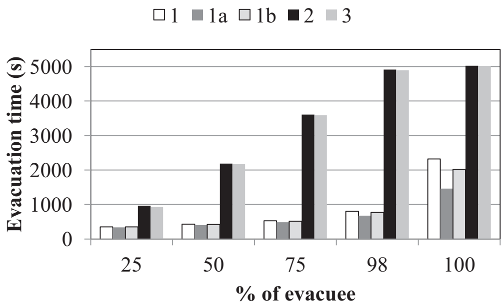

Fig. 4. Comparison of evacuation times for different scenarios and different % of evacuees.

corresponding curves for Scenarios 2 and 3. The curves of Scenario 1, 1a and 1b have an almost linear trend up to the point in which 98% of the population is evacuated, where instead the evacuation times increase significantly. The evacuation time of 100% of the population is approximately 2.9 times, 2.2 times and 2.6 times the evacuation time of 98% of the population in Scenarios 1, 1a and 1b, respectively. This could be due to the impact of slow responders with high delay times, as well as people with temporary or permanent locomotion impairments (i.e., slow walking speeds), on the people-evacuation time curves. In contrast, the corresponding curves have an approximately linear trend in the Scenarios 2 and 3 during the whole evacuation process, and present similar results although the delay distributions adopted for the population of the two scenarios are different (given the different causes of the escalating and cascading scenarios). This may be due to the fact that the flow through the exits is a predominant factor in the people-evacuation time curves, especially when compared with Scenarios 1 and 1a (where the delay times and walking speeds have a higher impact than flow constraints).

4. Discussion

This study provides evidence of how to use multi-agent evacuation models based on a continuous approach for large-scale evacuation scenarios at music festivals. This approach has been used in the past for other type of scenarios such as stadia or high-rise buildings [22].

This case study shows how multi-agent evacuation modelling tools are able to represent – either explicitly or implicitly – the behavioural factors that affect people's decision making at music festival during complex evacuation scenarios. The impact of different initiators can be simulated in evacuation models representing different behavioural responses (e.g., delay times) and adopting a gradual increasing of the area affected by the threat and the population involved. Nevertheless, evacuation models have limited capabilities in explicitly representing complex behavioural variables such as propagation of information or social influence. This can generally be represented implicitly by modifying variables such as delay times or assigning specific behaviours to groups.

Evacuation modelling can be used to identify the critical factors that affect evacuation processes under different conditions. This information can be used to help the relevant authorities and festival organizers adopt appropriate measures that reduce evacuation times and avoid critical conditions during escalating and cascading scenarios at music festivals. The present case study includes the analysis of some of the key variables affecting the evacuation process characterising the variability of possible behaviours in case of emergencies (e.g., different simulations adopting random sampling from distributions of delay times, possible people exit paths, etc.) which could not be fully considered using general guidelines or algebraic equations. Examples include the adoption of random sampling from distributions to represent delay times, possible people exit paths, etc. For instance, in order to consider these variables within the commonly used hydraulic flow model [8], the model should be modified e.g., to consider distributions of delay times for the flow calculations or to generate random distances walked by people based on distributions to account for these behaviours.

Evacuation modelling allows a systematic evaluation of different evacuation scenarios, identifying the impact that different threats may have on the evacuation process. In this context, these models can also be used to evaluate different evacuation strategies, including the simulation of different levels of controls on the evacuation process (from a spontaneous people evacuation triggered by people’s perception of a risk and social media to an evacuation procedure completely controlled by the music festival staff). Evacuation modelling tools allow for the evaluation of different strategies in which for instance there is a dynamic availability of exits (as demonstrated by Scenario 1b in which an additional provisional exit has been assumed).

The model case study also demonstrated the effectiveness of evacuation models in investigating the impact of different number of exits upon the evacuation process. This information can be used at different stages of the crowd management process, such as the design stage (i.e., in order to optimize exit number and location) or for decision support (i.e., the negative impact of reducing the number of exit available in case of an emergency scenario can be predicted and actions can be taken accordingly). In addition, evacuation models allow evaluating the impact of an additional exit option made available during the evacuation. The use of evacuation modelling during the design of crowd safety of a festival gives the possibility to make thorough evaluation of the possible safety issues associated with evacuation if compared with the use of guidelines which generally provide running meters per number of attendees.

This paper suggests that the evaluation of the results of an evacuation model in a music festival should include the entire people-evacuation time curves (and studying specific flows at different exits when deemed necessary) rather than just the total evacuation time (as it is generally done in buildings). The reason is that the study of those curves can provide a more complete understanding on the evacuation process and give useful insights for possible counter-measures to avoid critical conditions (e.g., overcrowding in certain areas, estimating the time in which people will queue at exits, etc.).

This type of analysis of evacuation model results allows for the differentiation of the scenarios in relation to the factors affecting the evacuation process (e.g., flow through doors, congestion levels, delay times, walking speeds and travel distances, etc.). This can have positive implications for the counter-measures employed to solve critical conditions. For instance, scenarios in which flow constraints at doors are found to be crucial (e.g., Scenarios 1 and 1a in the model case study presented in this paper) can be addressed by intervening on the number, width and location of the exits (as shown in Scenario 1b of the present model case study). The implementation of these modifications to the exits is fairly straightforward in music festival scenarios (especially when compared to buildings) since the delimitation of the space is (at least partially) generally done through movable fences. This applies also to scenarios in which walking distances to the exits are found to be important. In addition, this issue may lead to consider the option to adopt modifications on the crowd management strategy.

In contrast, different types of intervention may be needed for those scenarios in which the delay times of the population play a key role in the total evacuation time. For example, these measures may require some modifications to the emergency notification strategy, changing the staff procedures for communicating with the festival attendees.

The use of an evacuation strategy that reduces the average total evacuation time does not necessarily lead to an increased level of safety. The overall exposure to a threat may increase even if the total evacuation time is shorter, i.e., a critical zone of the festival area could become more exposed to a threat for a longer time. Evacuation models generally do not produce only numerical outputs concerning the evacuation times, flows and people densities, but they allow for the 2D or 3D visualization of the entire evacuation process. This qualitative information (together with the people-evacuation time curve) can be used to identify the variation in threat exposure in light of different factors such as the adopted evacuation strategy, exit and route availability, behavioural assumptions, etc. In this context, the graphic visualization of the evacuation process represents an important benefit of using evacuation modelling tools over algebraic models or rule of thumbs.

In general, music festivals have different characteristics in terms of people density compared to theatres or stadia, where each person has its own location assigned. It is therefore very important that the allowed maximum density of each area is estimated for the purposes of evacuation safety. Additionally, the use of evacuation model predictions of people densities allows for the consideration of the level of comfort experienced by the festival attendees at the site.

This case study demonstrates that the case of a large-scale evacuation scenario involving multiple sub-scenarios associated with evacuation safety can be investigated with evacuation modelling tools. Pre-planning with evacuation simulation tools can improve successful safe egress might inform event management and allow estimating the impact of staff actions or non-actions on successful safe egress. The present work represents an example of an effective use of evacuation modelling tools for assisting decision making in case of incidents of different complexities, including cases in which escalating and cascading effects take place. For instance, the comparison between Scenarios 1 and 1b demonstrates the possibilities of evacuation modelling for the evaluation of possible counter-measures to an evacuation incident and how an effective decision making of emergency responders (Scenario 1b in which an additional temporary exit has been provided) can positively affect evacuation safety. This work exemplifies this issue for the specific case of music festival scenario, but it is possible to extend the same principle to a variety of contexts in which large-scale evacuation may occur.

5. Future research

The present work analyses the use of evacuation models to produce estimates of the people-evacuation time curves in relation to different evacuation scenarios. Future research could focus on the merging of this analysis with the study of the possible impact of the threat itself. For instance, if the threat has a direct impact on the evacuating population, e.g., the presence of a toxic cloud affecting people behaviour, there would be the need to directly simulate the impact on the evacuation process. In other words, the coupling of dispersion modelling, i.e., the prediction of gas concentrations caused by an explosion or a toxic release [17], and people movement simulation should be the focus of future research, following existing examples for evacuation in enclosures [13].

The results of this paper show that there is a need to analyse in more depth the possible impact of the behaviours of the evacuees in the case of escalating and cascading scenarios. In this context, several variables merit further analysis, such as the training received by staff, their availability, population types (e.g., different percentages of people with locomotion impairments, people with different types of disabilities, etc.) and the number of attendees at festivals.

Some of the input values used for the model variables have been based on scarce literature, thus future experimental data or on-site observations would significantly improve the reliability of model results. For instance, scarce information is available on the response times of both festival organizers and attendees in case of evacuation scenario. This is also associated with the low frequency of this type of emergencies [12], which often leads to extrapolate information from different types of events or drills. This problem can be partially solved by organizing large-scale (announced or unannounced) evacuation drills, although they are not common for such type of large-scale events.

6. Conclusion

This work explored the use of a multi-agent continuous evacuation modelling approach to simulate a case study of large-scale evacuation scenarios at music festivals. Evacuation models had sufficient flexibility to represent the behavioural aspects affecting the evacuation process during escalating and cascading scenarios. In particular, the study of the people-evacuation time curves produced by evacuation models, coupled with the visual analysis of the evacuation process, allowed for the identification of the predominant factors affecting evacuation (e.g., delay times, flows through exits, etc.) and potential measures that could improve safety levels. Future research should focus on data collection on human behaviour, the inclusion of level of comfort analysis within evacuation models, a more advanced representation of vulnerable populations, and a coupled analysis of the impact of gas concentrations produced with a dispersion model and people movement and behaviours.

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