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HUMAN FACTORS IN SIMULATION MODELLING OF EVACUATION DURING MASS EVENTS

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Purpose: The goal of this research work is to present the possibility of applying the simulation modelling of evacuation conditions software in the preparation of a mass event management plan. These software allow the introduction of dimensional characteristics of agents, but their consideration is most often implemented in a simplified manner or ignored. Using a selected example, the methods of including the dimensional characteristics of persons during analyses are presented.

Design/methodology/approach: The paper presents the preparation stages of the simulation modelling process of crowd flows using the example of an open air event. The paper is preceded by a review of research into the determinants of crowd flows and good practices and guidelines for organising and managing mass events. The result of the research is a presentation of the application possibilities of simulation modelling taking into account human dimensional characteristics in decision support during the planning of mass event organisation.

Findings: The results of the study provide a demonstration of how to integrate the simulation modelling involving anthropometric criteria into the management process of mass events.

Research limitations/implications: The results of the research are presented using a selected example. By increasing the number of variants of event scenarios, it will be possible to identify detailed relationships between the modelled parameters and develop guidelines for managers of mass events.

Practical implications: The application of simulation modelling to the analysis of crowd movement during the organisation of mass events, makes it possible to predict the threats that may occur in emergency situations. The results of the research will expand the catalogue of criteria considered during evacuation modelling to include anthropometric data.

Social implications: Based on the analysis of the literature, there are shortcomings in the research basis of the guidelines considered during the planning of mass events. They are based in many aspects on experience and require a structured methodical and analytical approach during planning.

Originality/value: Research work on evacuation modelling has so far not emphasised the importance of the impact of changes in dimensional characteristics on simulation results. This paper presents a method of considering anthropometric data during simulation modelling.

Keywords: crowd moving, evacuation modeling, anthropometric data, crowd management.

Category of the paper: Research paper, conceptual paper.

1. Introduction

The problem of evacuation or movement of large concentrations of people (crowds) is the subject of simulation analyses involving events, facilities or areas such as:

- religious mass gatherings (Basak, Gupta, 2017; Zhao et al., 2019; Farook et al., 2020; Owaidah, 2021);
- passenger cruise ships (Hu, Cai, 2022);
- airport terminals (Yang, Tang, Wang, 2022; Jasztal, 2022);
- train and metro stations (Shiwakoti, 2020);
- stadiums (Mahmudzadeh et al., 2020; Gravit et al., 2022; Ivanusa, 2023);
- cities, neighbourhoods, streets, etc. (Zhao et al., 2021; Yoshimura, 2023; Ronchi, 2019; Onelcin, 2013).
- open air events (Strongylis et al., 2019; Still, 2000; Kapałka, 2016), itd.

Crowd movement is one element of proactive crowd management. Crowd management is a systematic plan for achieving the goal of orderly movement and gathering of people. When organising a mass event, a crowd management plan should be prepared taking into account: crowd density, behaviour and circulation (arrival, duration and departure) (Keys to Crowd Management Planning, 2020; Bishop, 2020; Eckes, 2012). The effectiveness of crowd management is impacted by (Sharma et al., 2018):

- effective event planning,
- crowd monitoring and control (crowd control refers to actions implemented after incidents get out of hands, such as responding to prevent injury, restricting or limiting behaviour or responding to an unexpected emergency (Keys to Crowd Management Planning, 2020)),
- gathering information after the event,
- reporting on lessons learnt for more effective systems in the future.

The crowd management process is often aided by techniques for automatically monitoring the number and density of people (Yang, 2022; Sottile, 2022; Herrmann, 2012; Royo, 2022). In addition, a number of models of crowd behaviour based on experiments from the biological and physical sciences can be distinguished (Kok, 2016).

When organising mass events, it is indispensable to comply with legal requirements. According to the Act of 20 March 2009 on the safety of mass events (Journal of Laws 2023, item 616), it is possible to determine the area of the land on which the event is organised based on the information contained in the definition of the area allowing for the holding of a mass event: *... a separate, appropriately marked area in the open air, complying with hygiene and sanitary conditions in accordance with the requirements provided by law and having infrastructure ensuring the safe conduct of the mass event, in which the number of places for people is determined at the rate of 0.5 m^2 per person.* The expected density is therefore a maximum of 2 persons/m^2. According to the "Guidelines for district fire brigades of the Mazovian Voivodeship", when organising a mass event in an open area, it is necessary to:

- divide it into sectors, with appropriate areas separated from each other by escape routes 4.5 m. wide, for no more than 2,000 seats and 6,000 standing places;
- mark sectors with capital letters of the alphabet A, B, C;
- sectors to be divided into 6 sections - a section may not have more than 350 seats and 1,000 standing places;
- label the sections with Arabic numerals 1 to 6;
- sections in the sectors are separated by 3 m wide aisles;
- fence off sectors - in cases where sectors are fenced off with metal fences or wooden structures, at least two exits of an appropriate width (approx. 20-40 % of the values assumed for buildings) should be provided, with the possibility of quickly clearing them - excluding the front lines of sectors and the sides of sectors adjacent to the main escape route; the rigging separating sectors and sections - attached to posts - should be easily removable;
- the main access road to the central ritual or event venue should be at least 6 m wide.

A number of research papers have analysed the relationship between crowd speeds and crowd density (Yugendar, Ravishankar, 2019; Vermuyten et al., 2016; Kang et al., 2015; Nelson, Mowrer, 2002). It has been observed that walking speed can depend on individual characteristics (own pace, independent of others) at crowd densities of up to about 0.54 persons/m2. If the crowd density exceeds about 3.8 persons/m^2, there will be a stoppage of the crowd until enough people leave the congestion and the density decreases (Nelson, Mowrer, 2002; Kang et al., 2015). In addition, age, gender, density and having luggage are important criteria affecting crowd speed (Yugendar, Ravishankar, 2019). Many classifications of crowd density are distinguished in the literature. One of them considers five categories (Farook et al., 2020):

- Very low density (VLD): ≤ 0,43 persons/m^2,
- Low density (LD): 0,43-0,72 persons/m^2,
- Medium density (MD): 0,72-1,08 persons/m^2,
- High density (HD): 1,08-2,17 persons/m^2,
- Very high density (VHD): ≥ 2,17 persons/m^2.

With density, the evacuation rate changes. This has been presented in many literature sources (Table 1).

Table 1.

Examples of the relationship between density and speed of crowd movement

Item	Data source	Crowd density [person/m^2]	Speed of movement [m/s]
1	Kang et al., 2015	1	1,4
		2	0,7
		3	0,47
		4	0,35
		5	0,28
		6	0,23
2	Nelson, Mowrer, 2002	0,54	1,2
		1	1,03
		2	0,66
		3	0,28
		3,76	0
3	Still, 2000	0,5	1,34
		1	1,34
		2	0,91
		3	0,61
		4	0,45
		5	0,36
4	Oberhagemann, 2012	0,8	1,23 to0,84
		0,8 to 1,2	0,82 to 0,49
		1,2 to 1,7	0,52 to 0,4
		1,7 to 2,5	0,35 to 0,3
5	Vermuyten et al., 2016	Maximum free-walking speeds when the density goes to zero (data based on a review of studies of many authors)	1,3 1,61 0,6 1,4 1,25 1,34

Source: own elaboration based on: Kang et al., 2015, Nelson, Mowrer, 2002; Still, 2000; Oberhagemann, 2012.

The parameters in Table 1 were partly a result of analyses conducted in buildings but with large spaces and can also be applied to simulation modelling in open spaces.

A number of evacuation models are used in crowd evacuation analyses (Zheng et al., 2009):

- cellular automata models (CA),
- lattice gas models (LG),
- social force models (SF),
- fluid-dynamic models (FD),
- agent-based models (AB),
- game theoretic models, and
- approaches based on experiments with animals.

These models provide, among other things, the opportunity to take into account the relationship that binds groups of people in a crowd. When mapping crowd behaviour (Zheng et al., 2009):

- pedestrians are treated as homogeneous individuals or heterogeneous individuals (groups) with different characteristics;
- the behaviour of a collection of individuals results from individual interactions between multiple individuals or the collection of individuals is treated as a whole;
- crowd movement is characterised in normal or emergency situations.

The most heterogeneous models are AB (agent-based models). Their use is particularly beneficial for modelling emergency situations (Bonabeau, 2002). They make it possible to represent many individual characteristics related to evacuation behaviour. These include anthropometric characteristics. Visualisations in computer applications for evacuation modelling present people as (Dahlke, 2020; Dahlke, Idczak, 2021):

- circles (Pathfinder Verification and Validation, 2020),
- ellipses (Zou, Xu, Gao, 2010),
- combination of three mobile, flexible circles (Chooramun, Lawrence, Galea, 2012; Korhonen, Hostikka, Heliövaara, Ehtamo, 2010; Thompson, Marchant, 1995).

Many studies on evacuation models use an ambiguous description of the dimensional features. The maximum dimensions in the top view are most often based on:

- shoulder width (Pathfinder User Manual, 2020);
- shoulder breadth (Still, 2000, p. 32) - Shoulder breadth (bideltoid) – maximum horizontal shoulder width, measured to the convexity of the shoulder muscles (Pheasant, 2003, p. 37); - Shoulder breadth (biacromial) – horizontal distance between the arms, measured between the anthropometric points of the acromion (Pheasant, 2003, p. 37);
- shoulder breadth maximum (Nowak, 2000);
- elbow to elbow breadth (Gedliczka, 2001).

In the anthropometric atlases containing the dimensional characteristics of the populations of individual countries, a steady increase in values can be observed due to living and nutritional conditions, among other factors. The variability of these characteristics can have a significant impact on the results of simulation modelling. However, such studies have been conducted on the example of buildings (Dahlke, 2020). In the research presented in the following chapters, the author presented the possibilities of using an application for simulation modelling of evacuation conditions taking into account dimensional characteristics in the process of supporting the preparation of a plan for open air events. The way in which variants for the division of the site into sectors and sections can be analysed and how to create applications in a mass event management system is presented.

2. Methods

The Pathfinder application (Pathfinder User Manual, 2020; Pathfinder Verification and Validation, 2020) was used for the simulation analyses of the movement conditions of people during a sample mass event. At the outset, the primary purpose of the analysis must be assumed. This could be, for example, the dispersal of people after the mass event or evacuation after an emergency. In the second case, the scenarios would depend on a number of factors and, in an open area (undeveloped), could take into account the possibility of crowd dispersal (even in star form). This paper will present the first case, involving the exit of the crowd after the gathering. Several assumptions are made at the outset:

- an existing example of the site will be mapped, but its use will be based on theoretical scenarios;
- the site will be divided into sectors and sections respecting the recommendations of the National Fire Service: up to 6,000 people standing in sectors and up to 1,000 people standing in sections (Warunki bezpieczeństwa pożarowego…, 2003);
- during the analyses, it was assumed that 32,000 people would gather at the sample site in six sectors.;
- variants of the density of people in sectors and sections according to legal requirements and for examples of literature analyses (Table 2) will be analysed; on this basis, variants of the dimensions of the section sides were determined, assuming that one of the sides would be 30 m long;
- a sector layout extended along the central road was proposed (Fig. 1);
- there are 3 m wide roads between sections and 4.5 m wide roads between sectors; a 6 m wide road leads through the centre of the square;
- sectors and sections are fenced off with barriers and there are two exits - each 3m wide - from the section to the escape route;
- people go home using designated evacuation routes, despite the possibility of crossing;
- three routes of dispersal from the study area were considered;
- the width of the exit routes from the site, were: Exit 1: 6 m, Exit 2: 11.9 m and Exit 3: 6.03 m (Figure 1);
- the dimensional characteristics of the people and their walking speeds were adopted according to anthropometric atlases and literature data and are included in Table 3 (the analysis included an example of a random distribution of people aged between 14 and 65 years).

The following steps were taken to perform the analysis:

- selected map of the area where the mass event will be organised (www.geoportal.gov.pl);
- simulation scenarios were developed (density of people in sectors and sections (Table 2); characteristics of the population modeled during the simulation were determined for the age groups selected in the initial assumptions (gender, dimensions (according to Nowak, 2000), walking speed); percentages of each age group were adopted (Table 3));
- a map of the site was prepared in AutoCAD (site outline; division into sectors and sections; roads between sectors and sections (Figure 1)) for each scenario;
- importing maps/graphics from AutoCAD into Pathfinder;
- preparation of graphics for simulation (extraction of surfaces and introduction of persons/agents) (Figure 2);
- performing simulations and collecting data for analysis;
- data analysis.

Table 2.
Areas of sectors and sections for crowd densities selected for simulation

Scenario No.	Crowd density [persons/m^2]	Area of the sectors [m^2]	Area of the section [m^2]	Section side length in [m], with the width of the second of the side equal to 30 m
1	0.43	13953.49	2325.58	77.52
2	0.54	11111.11	1851.85	61.73
3	0.72	8333.33	1388.89	46.3
4	1	6000	1000	33.33
5	1.08	5555.56	925.93	30.86
6	2	3000	500	16.67
7	2.17	2764.98	460.83	15.36
8	3	2000	333.33	11.11

Source: own elaboration based on: Farook et al., 2020; Kang et al., 2015, Nelson, Mowrer, 2002; Still, 2000; Oberhagemann, 2012.

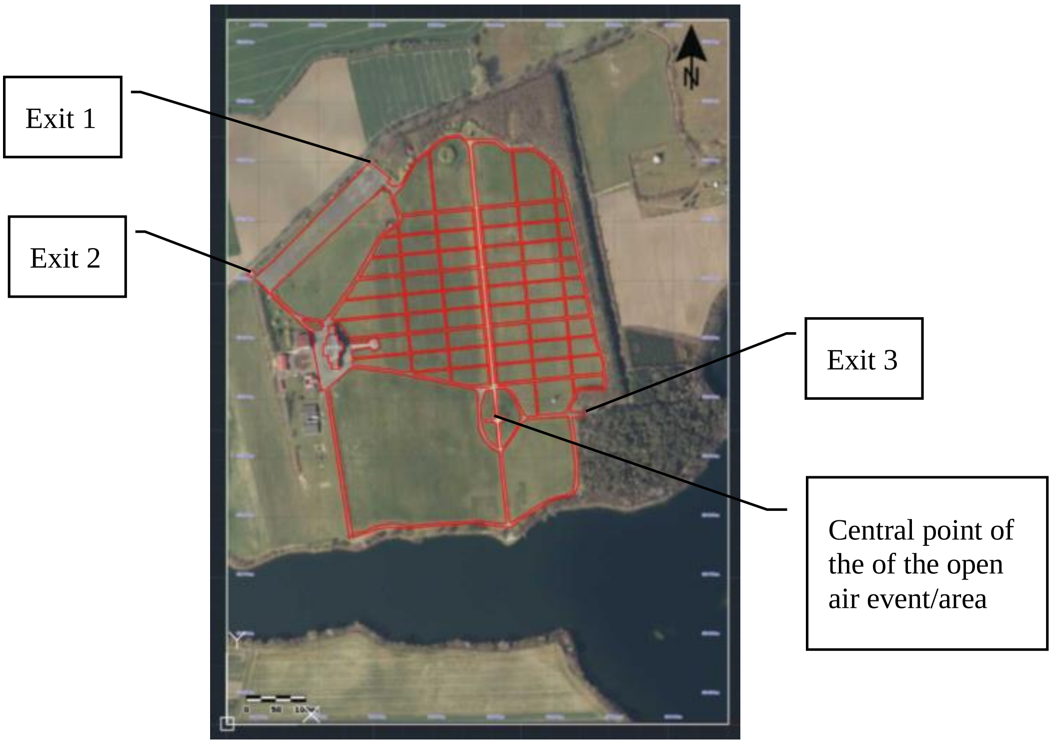


Figure 1. Example of how to divide a site into sectors and sections and how to make an outline of escape routes in AutoCAD.

Source: own elaboration based on the map from the platform www.geoportal.gov.pl.

When planning the distribution of sectors and sections on the map of the study area, a decision was made to divide it into rectangular sections. For analytical purposes, it was assumed that one side of the section would be 30 m long. At the initial stage of consideration, it was determined that the effect of crowd density in the sections on evacuation times would be investigated. Assuming different crowd density values, the areas of sectors and sections were calculated (Table 2). This made it possible to determine the length of the second side of the section. When planning the layout of the sections, it was assumed that the longer side of the section would be located on the side of the central point of the open air event (Figure 1). As the size of the sections and sectors decreased and the crowd became denser, changes were made to the row and column layout for densities of 1.0 and 1.08 persons/m^2 (Figure 2e and 2d). In each example analysed, the number of sectors was 6 (36 sections - except for scenario 1, where 35 sections were designated).

By distributing the agents in each section, the automatic ordered group insertion function was used at a given computational density. The total number of agents was 32,000.

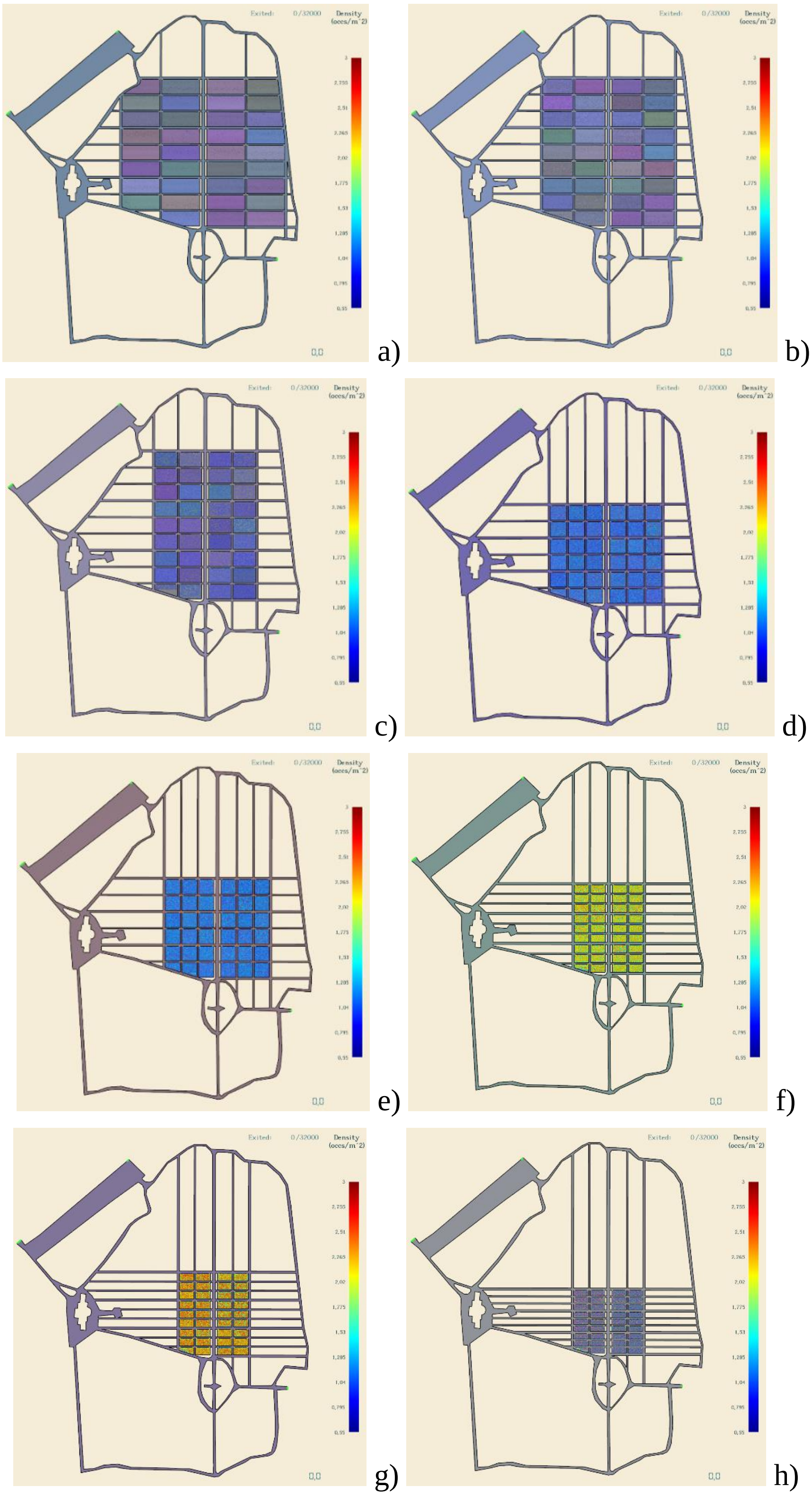


Figure 2. Variants for the distribution of sectors and sections for the analysed scenarios (Table 2); a) density 0.43 persons/m^2; b) density 0.54 persons/m^2; c) density 0.72 persons/m^2; d) density 1.0 persons/m^2; e) density 1.08 persons/m^2; f) density 2.0 persons/m^2; g) density 2.17 persons/m^2; h) density 3.0 persons/m^2.

Source: own work in Pathfinder software.

It was assumed that people would leave the square by heading to the three exits (Figure 1) via designated routes (not cross-country). The choice of exit will be made automatically.

Table 3.
Anthropometric features by simulation scenario

Item	Age group	Population percentage	Name of anthropometric feature	5th percentile female [cm]	50th percentile female [cm]	95th percentile female [cm]	5th percentile male [cm]	50th percentile male [cm]	95th percentile male [cm]	Range of speed [m/s]
1	♂: 19-65 ♀: 19-60	5	- shoulder breadth maximum: - chest depth: - stature:	39.5 20.8 153.6	45.3 25.6 163.4	52.5 31.1 174.0	45.6 21.7 166.0	51.8 26.0 177.8	58.8 30.4 189.0	0.72-1.13 0.61-0.853
2	♂: 14 ♀: 14	19	- shoulder breadth maximum: - chest depth: - stature:	34.9 14.2 154.9	39.7 16.6 164.5	44.1 18.9 174.4	33.8 15.5 152.8	41.0 18.0 167.3	48.2 20.5 181.0	0.932-1.5 0.89-0.99
3	♂: 15 ♀: 15	19	- shoulder breadth maximum: - chest depth: - stature:	35.1 14.5 155.9	40.3 16.8 166.4	45.2 19.1 177.2	35.6 15.9 161.0	42.4 18.7 174.1	49.2 21.5 187.5	0.932-1.5 0.89-0.99
4	♂: 16 ♀: 16	19	- shoulder breadth maximum: - chest depth: - stature:	35.2 14.7 156.7	40.7 17.2 167.6	45.4 19.7 179.7	38.3 16.5 165.5	44.2 19.4 178.3	50.1 22.3 188.5	0.932-1.5 0.89-0.99
5	♂: 17 ♀: 17	19	- shoulder breadth maximum: - chest depth: - stature:	35.9 14.9 158.0	40.8 17.3 168.1	45.4 19.9 180.4	38.5 16.7 167.7	44.9 19.6 179.9	50.8 22.3 191.7	0.932-1.5 0.89-0.99
6	♂: 18 ♀: 18	19	- shoulder breadth maximum: - chest depth: - stature:	36.9 15.4 159.2	41.2 17.4 168.6	46.2 19.9 181.1	40.8 16.9 170.8	45.8 19.6 181.2	51.5 22.5 192.1	0.932-1.5 0.89-0.99

Source: Own work based on: Dahlke, 2020; Gedliczka, 2001; Nowak, 2000; Yugendar, Ravishankar, 2019.

In the simulation model implemented in the Pathfinder application, agents were assigned dimensional characteristics and speed (Table 3) randomly according to a normal distribution.

3. Results

For each deployment scenario (Figure 2), simulation results were obtained:

- total time to leave the area (Table 4);
- graphs of the flow of people through the various exits (Figure 4);
- animation with surface plots of crowd density variation over time (Figure 3).

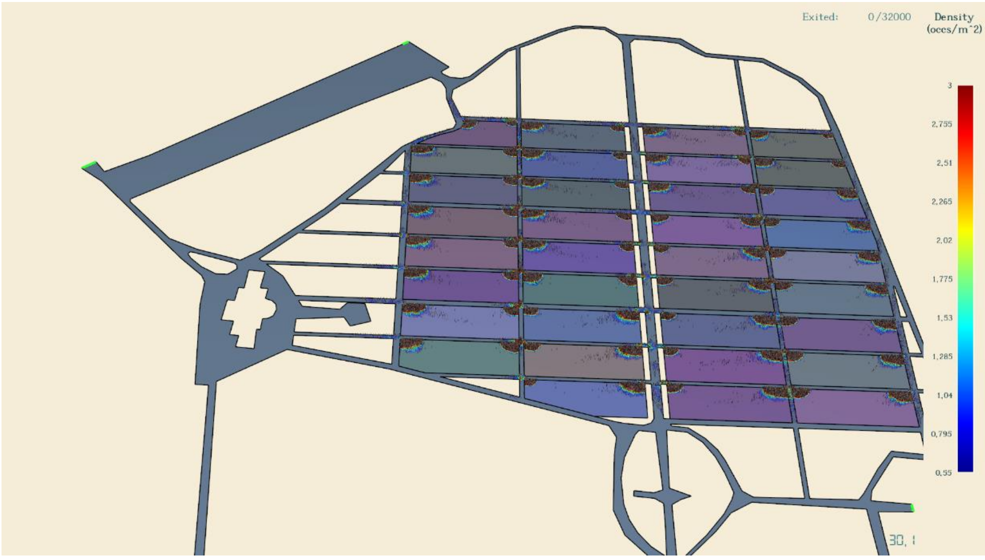


Figure 3. View of an example simulation with area plots of the variation of crowd density in the area under analysis over time.

Source: own work in Pathfinder software.

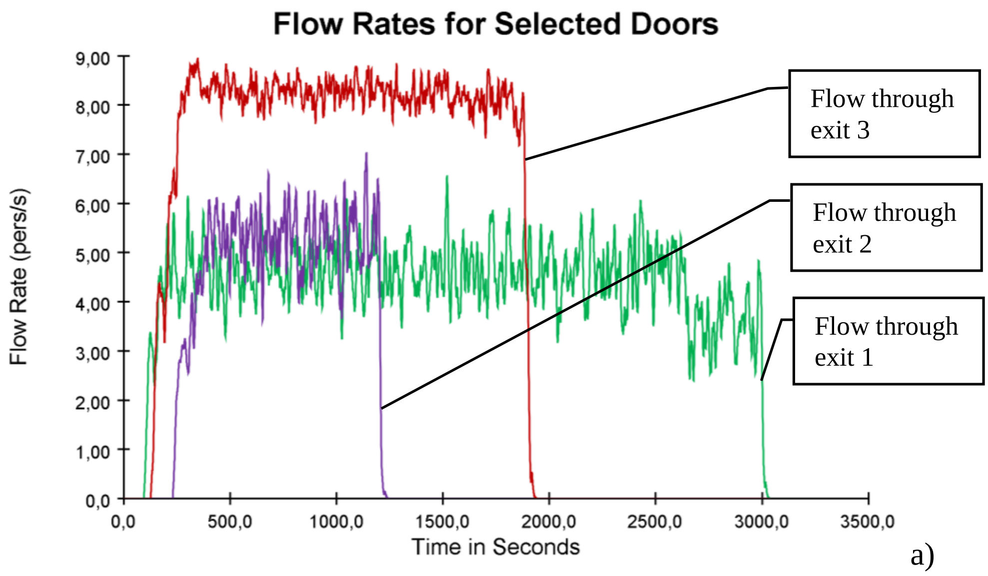
Table 4

Total crowd exit times

Scenario No.	Crowd density [persons/m^2]	Number of section rows along the central road	No. of exit through which the flow takes the longest	Total time to leave the open air event site [s]
1	0.43	4	1	3036.3
2	0.54	4	1	3015.8
3	0.72	4	1	3125.8
4	1	6	3	2606
5	1.08	6	3	2648.3
6	2	4	3	3180.3
7	2.17	4	3	3196.3
8	3	4	3	4065.8

Source: Own work.

The results of the crowd exit times presented in the table above (Table 4), facilitate the selection of the sector density variant. The shortest leaving times were obtained for a density of approximately 1 persons/m^2. The results of the two cases analysed were influenced by the different arrangement of the sections (six vertical rows instead of four). However, the remaining data show an increasing trend - as the crowd density in the sections increases, the time to leave the area increases.


Flow Rates for Selected Doors
Flow Rate (pers/s)
9,00
8,00
7,00
6,00
5,00
4,00
3,00
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1,00
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0,0
500,0
1000,0
1500,0
2000,0
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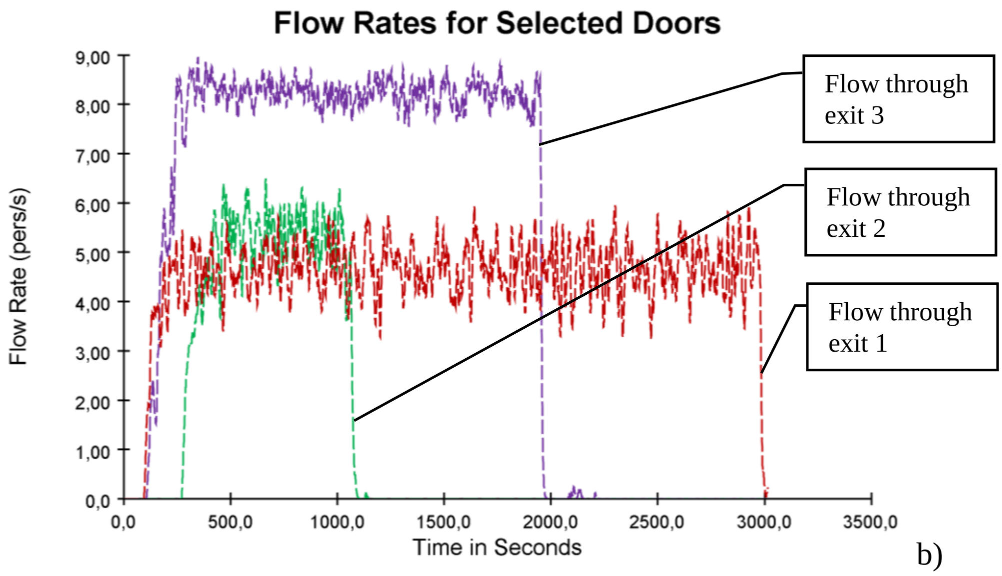
3500,0
Time in Seconds
Flow through exit 3
Flow through exit 2
Flow through exit 1

a)


Flow Rates for Selected Doors
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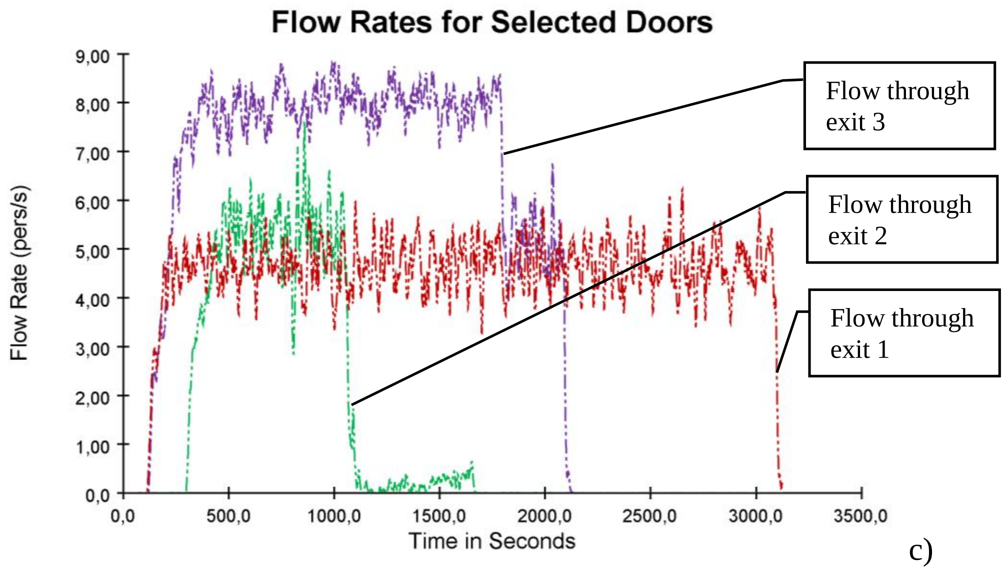
Time in Seconds
Flow through exit 3
Flow through exit 2
Flow through exit 1

b)


Flow Rates for Selected Doors
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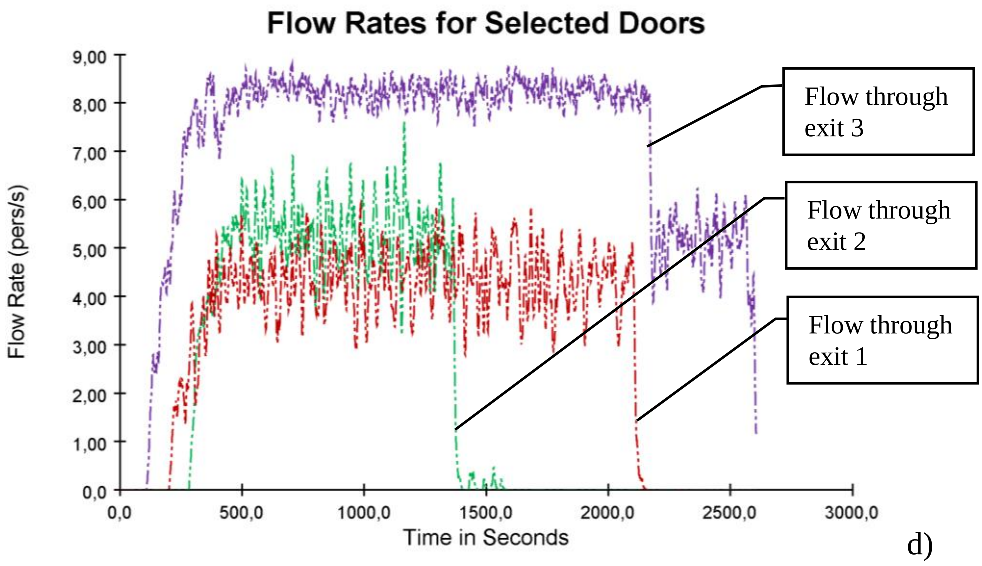
Time in Seconds
Flow through exit 3
Flow through exit 2
Flow through exit 1

c)



Flow Rates for Selected Doors
Flow Rate (pers/s)
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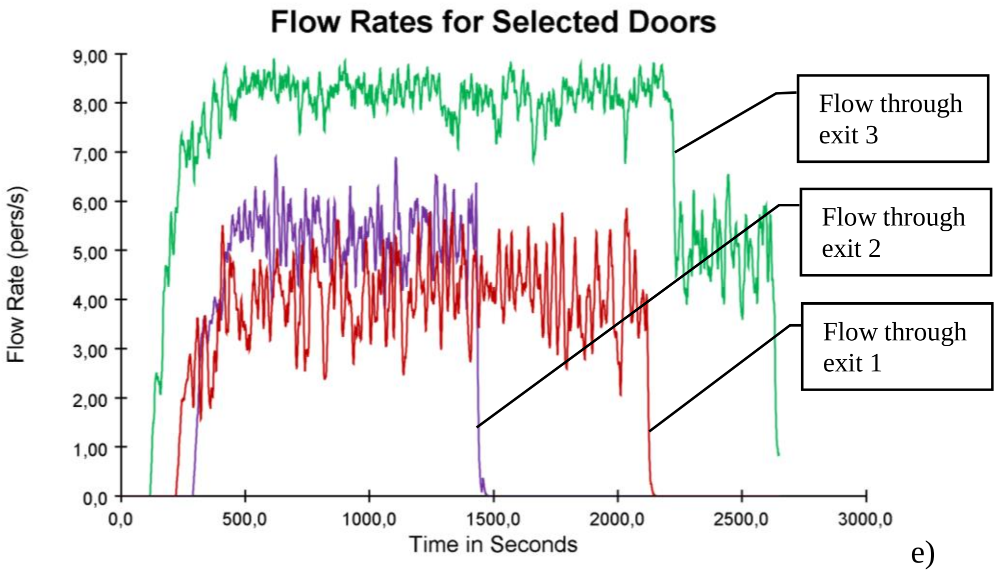
Time in Seconds
Flow through exit 3
Flow through exit 2
Flow through exit 1

d)



Flow Rates for Selected Doors
Flow Rate (pers/s)
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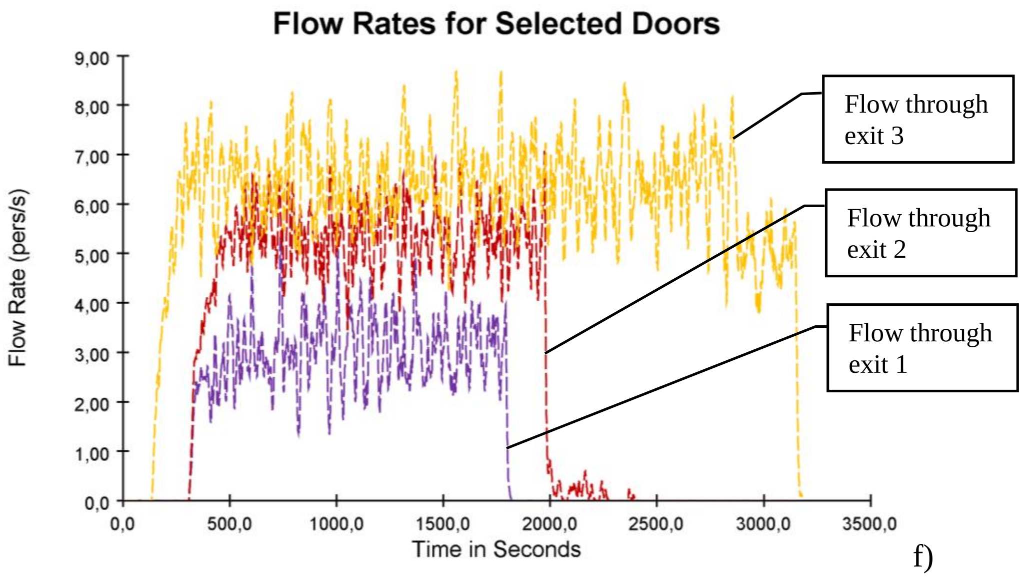
Time in Seconds
Flow through exit 3
Flow through exit 2
Flow through exit 1

e)



Flow Rates for Selected Doors
Flow Rate (pers/s)
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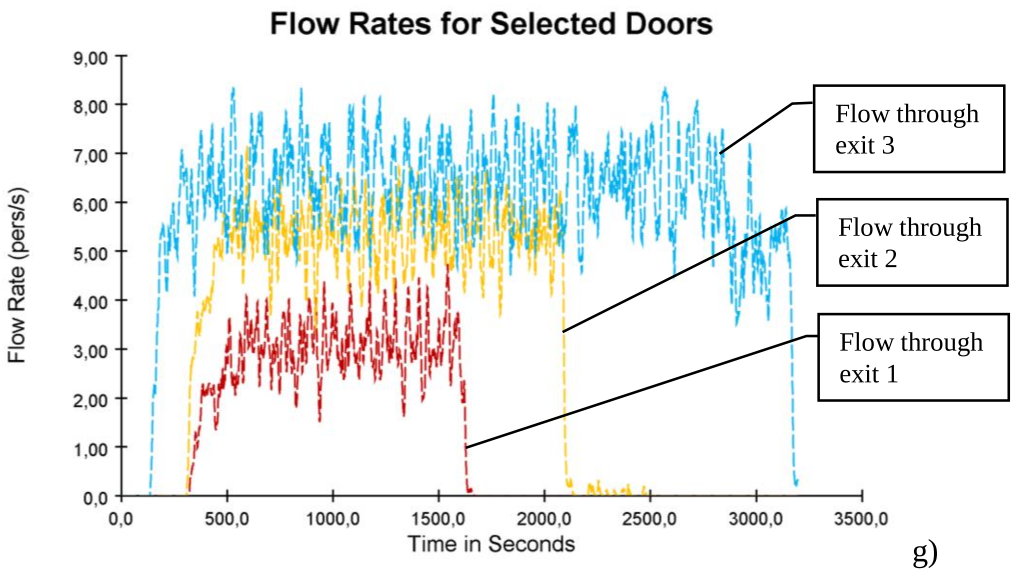
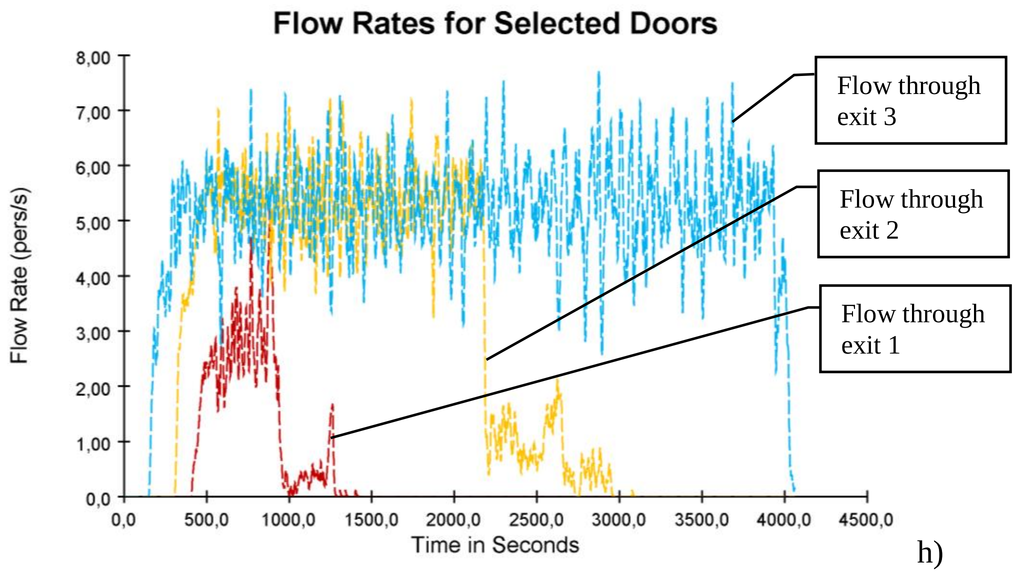
3500,0
Time in Seconds
Flow through exit 3
Flow through exit 2
Flow through exit 1

f)



g)



h)

Figure 4. Graphs of agent flows through the three exits of the analysed site for crowd density scenarios (Table 2) made in the Pathfinder application; a) density 0.43 persons/m^2; b) density 0.54 persons/m^2; c) density 0.72 persons/m^2; d) density 1.0 persons/m^2; e) density 1.08 persons/m^2; f) density 2.0 persons/m^2; g) density 2.17 persons/m^2; h) density 3.0 persons/m^2.

Source: own work in Pathfinder software.

In the graphs presented in the figure above (Figure 4), it can be seen that the time taken to pass through exit 3 increases in succession. The width of this exit is similar to that of exit 1. The concentration of the crowd around the central part of the square has made exit 3, as the nearest exit, the preferred exit for leaving the open air events area.

4. Discussion

The analysis of the conditions for crowd dispersal after the end of open air events and the conclusions drawn from it presented usefulness for decision support in the planning of the various stages of mass event management (infrastructure preparation, crowd control and dispersal after the end). Depending on the initial assumptions, the results of the analyses of the hypothetical example analysed may change. Conditions may change when, for example:

- we will consider emergency evacuation;
- we will allow moving off designated ways;
- we will enable the rapid removal/opening of barriers between sectors and sections;
- we will take into account the capacity of the roads outside the study area;
- we will include a plan for the activities to be performed by participants in open air events in sectors and sections;
- we will take into account crowd control measures, such as order announcements controlling dispersal to exits from the mass event area.

Each of the above conditions needs to be mapped in a scenario and modelled in a computer application.

The timing of the crowd leaving the area was mainly influenced by the (Figure 5):

- positioning of the sectors in relation to the exits of the area;
- Pre-density of the crowd, which caused congestion to occur more quickly and slowed down the flow of people.

Attempting to justify the decrease of evacuation times at initial crowd densities of around 1 persons/m^2, by differing sector distribution, may not be the only argument. Many research papers report maximum crowd flows at densities exceeding 1 persons/m^2 and reaching a maximum for around 1.8 persons/m^2 (Oberhagemann, 2012; Nelson, Mowrer, 2002).

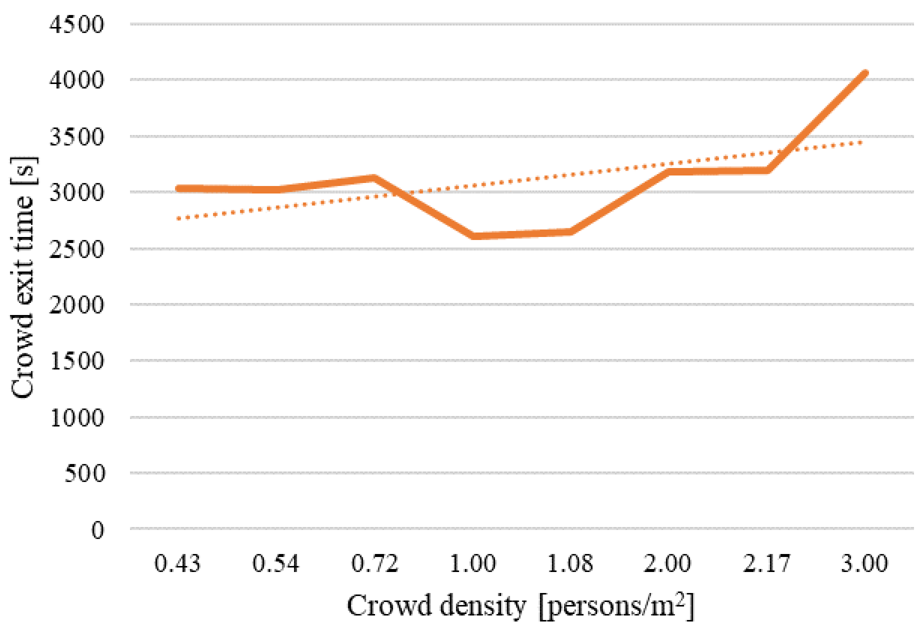


Figure 5. The correlation of the time of the crowd exiting the square to the initial density of people in the sections (the dotted line in the graph indicates the trend line).

Source: Own work.

In the modelling process, an important aspect is also the consideration of the dimensional characteristics of the crowd (Dahlke, 2020). Therefore, it is necessary to identify the target group of the mass event during simulation studies. Anthropometric atlases of the population contain data categorised by age group, enabling data applications in simulation modelling. Dimensional data of individuals have been included in many research works, but in a rather simplified form (Oberhagemann, 2012).

5. Summary

The research results presented in the previous chapters were obtained using agent-based modelling. Tools of this type are characterised by time-consuming (many hours) generation of simulations for a crowd of many thousands (Kountouriotis, 2014). The examples presented are characterised by the complexity of the criteria to be considered during modelling. These criteria are related to the mapping of crowd behaviour, architectural and infrastructural aspects in the simulators (Sharma, 2018). The multivariate nature of the scenarios requires multiple simulations to be prepared in order to draw conclusions about ensuring the safety of participants at mass events. One additional criterion to be considered is anthropometric.

Modelling results are an important decision-support element in crowd management. They provide data that facilitate emergency preparedness planning.

Findings from the research have enabled directions for further research to be observed. These include:

- analysis of the criteria considered in scenarios of events requiring evacuation due to emergencies;
- analysis of the impact of the width of sector and section exits and terrain on evacuation times;
- analysis of crowd dispersal conditions after leaving the open air event site;
- analysis of crowd control activities during evacuation or leaving the area after an open air event (directing crowds to exits based on behavioural observations).

These activities will help to improve security and crowd control measures at open air events.

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