Safety of users in road evacuation: modelling and DSS for pedestrian outflow

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Abstract

This paper concerns the simulation of pedestrian outflow related to the evacuation of a building. In this paper, after a literature review concerning commercial software suited for the simulation of evacuation, a simulation tool is proposed and a comparison between results obtained from simulations and data recorded from an experimentation on a test site is also presented.

1 Introduction

In those cases where a forthcoming disaster can be notified in advance, only evacuation represents a chance. During the time interval between notification and effects of the disaster a preventive evacuation can be executed, so a preventive planning of the activities to be executed in emergency conditions is fundamental for an efficient evacuation and to reduce clearance time. For this reason, evacuation calculations are an important part of performance-based analyses in order to assess the level of life safety provided in buildings.

In the last years a variety of commercial, academic and governmental tools were produced to support efficient evacuation planning. The availability of tools and the advent of (relatively) low-cost, high-performance computing platforms encourage public agencies to consider analytical methods to improve their evacuation planning or operational practices.

The tools can be classified as regards the classes of adopted models for transport simulation. They influence the computational complexity of tools and, in general, the tools' capability to facilitate decision-making ranging from real-time to planning exercises.

On the other hand there is also, in certain circumstances, a need for simple tools able to quantify, in terms of evacuation time, the effectiveness of an evacuation plan.

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In this paper, after a classification of some of the most adopted applications for the simulation of evacuation, a comparison of simulated results with those obtained during a real experimentation is conducted.

In particular, the paper is structured as follows: in section 2 it is shown an inventory of pedestrian evacuation tools, section 3 reports a short description of the models and procedures adopted to carry out simulations in a real context. Section 4 presents an analysis of results obtained with the simulations and a comparison between these results and on site experimentation data.

2 Pedestrian evacuation tools inventory

Among proposed classifications and reviews, those proposed by Gwynne et al [1], Fire Model Survey [2] and Kuligowski and Peacock [3] can be considered in order to specify a common terminology, structure and data gathering in order to approach a classification of the models.

Adopted classification method

According to definitions given in [3], egress models in this work have been classified considering:

- the perspective of model;
- the perspective of users;
- the modelling method
- the structure of supply model;
- the users' behaviour;
- measurable outputs and visualisation capabilities.

In the following definitions adopted within the classification method are shown.

Perspective of model

The perspective of the model explains how the model views the users; model views the occupants, there are two ways that a model can view the occupant:

1) *Individually*: a model with an individual perspective tracks the movement of individuals throughout the simulation and can give information about those individuals (e.g. their positions at points in time throughout the evacuation).
2) *Globally*: in this case the model sees its occupants as a homogeneous group of people moving to the exits.

An individual perspective of the occupants is more detailed, but which alternative is best depends on the purpose of the simulation. If the user is not interested in knowing the position of each occupant throughout the simulation or assigning individual characteristics to the population, then a global view can be sufficient.

Perspective of users

The perspective of users explains how the users (occupants) view the building; also in this case two ways can be identified:

1) In an *individual* view of the building, the user does not know the building's exit paths and decides his/her route based on information from the floor, personal experience, and in some models, the information from the users around him/her.

2) In a *global* view of the building the users are familiar with the building and automatically know their best exit path.

Modelling Method

Under the modelling method category, the following three labels can be individuated:

- *Movement models*: those models that move users from one point in the building to another (usually the exit or a position of safety).
- *Behavioural models*: those models that incorporate users performing actions, in addition to movement toward a specified goal (exit).
- *Partial behaviour models*: those models that primarily calculate user movement, but begin to simulate behaviours. Possible behaviours could be implicitly represented by pre-movement time distributions among the users, unique user characteristics, overtaking behaviour, and the introduction of smoke or smoke effects to the user.

Structure of supply model

This subcategory is used to assess how users move throughout the building; three categories can be introduces:

- a *coarse* supply model divides the floor plan into rooms, corridors, stair sections, etc. and the users move from one room to another;
- a *fine* supply model divides a floor plan into a number of small grid cells that the users move to and from;
- a *continuous* supply model applies a 2D (continuous) space to the floor plans of the structure, allowing the users to walk from one point in space to another throughout the building.

Using fine and continuous supply models it is possible to simulate the presence of obstacles and barriers in building spaces that influence individual path route choice, whereas the coarse supply models “move” occupants only from one portion of a building to another.

Users’ behaviour

The behaviour of the users is represented using the following labels associated with this sub category:

- *None* (N): in these models only the movement aspect of the evacuation is simulated.
- *Implicit* (I): these models attempt to model behaviour implicitly by assigning certain response delays or occupant characteristics that affect movement throughout the evacuation.
- *Conditional (rule-based)* (C): these models assign individual actions to a person or group of users that are affected by structural or environmental conditions of the evacuation (i.e. “if, then” behavioural method models).
- *Artificial Intelligence* (AI): these models attempt to simulate human intelligence throughout the evacuation.
- *Probabilistic* (P): for these models many of the rules or conditions are stochastic, allowing for the variations in outcome by repeating certain simulations.

Some models have the capability of assigning probabilities of performing certain behaviours to specific user groups. Many of the partial behavioural models allow for a probabilistic distribution of the pre-evacuation times, travel speeds, and/or smoke susceptibility.

Table 1: Background characteristics of considered models.

TOOL	COUNTRY	PERSPECTIVE OF MODEL	PERSPECTIVE OF USERS
ALLSAFE	Norway	Global	Global
ASERI	Germany	Individual	Individual
BuildingExodus	United Kingdom	Individual	Individual
CRISP3	United Kingdom	Individual	Individual
EESCAPE	Austria	Global	Global
EGRESS	United Kingdom	Individual	Individual
EVACNET4	United States	Global	Global
EXIT89	United States	Individual	Individual
EXITT	United States	Individual	Individual
FPETool	United States	Global	Global
GridFlow	United Kingdom	Individual	Individual
Legion	United Kingdom	Individual	Individual
PathFinder	United States	Individual	Global
PedGo	Germany	Individual	Individual
PEDROUTE	United Kingdom	Global	Global
SICURO	Italy	Individual	Global
Simulex	United Kingdom	Individual	Individual
STEPS	United Kingdom	Individual	Individual
TIMTEX	United States	Global	Individual
WAYOUT	Australia	Global	Global

Table 2: Main features of considered models.

TOOL	MODELLING METHOD	STRUCTURE OF SUPPLY	USER BEHAVIOUR
ALLSAFE	Partial Behaviour	Coarse	Implicit
ASERI	Behaviour	Continuous	Rule-Based / Conditional
BuildingExodus	Behaviour	Fine	Rule-Based / Conditional
CRISP3	Behaviour	Fine	Rule-Based / Conditional
EESCAPE	Movement	Coarse	None
EGRESS	Behaviour	Fine	Conditional
EVACNET4	Movement	Coarse	None
EXIT89	Partial Behaviour	Coarse	Implicit
EXITT	Behaviour	Coarse	Rule-Based / Conditional
FPETool	Movement	Other	None
GridFlow	Partial Behaviour	Continuous	Implicit
Legion	Behaviour	Continuous	Artificial Intelligence
PathFinder	Movement	Fine	None
PedGo	Movement / Partial Behaviour	Fine	Implicit
PEDROUTE	Partial Behaviour	Coarse	Implicit
SICURO	Movement / Partial Behaviour	Coarse	None
Simulex	Partial Behaviour	Continuous	Implicit
STEPS	Movement / Partial Behaviour	Fine	None
TIMTEX	Movement	Coarse	None
WAYOUT	Movement	Coarse	None

Table 3: Main measurable outputs of considered models.

TOOL	VISUAL CAPAB.	MAIN MEASURABLE OUTPUTS
ALLSAFE	None	▪ Time to fire detection, to react and to interpret the situation ▪ Time for users to decide where to escape ▪ Time to evacuate a room or corridor and the building
ASERI	2D / 3D	▪ Evacuation time ▪ Detailed information on the structure and congestion situation that lead to delay ▪ Mean egress time, along wish their corresponding variances and confidence intervals
BuildingExodus	2D / 3D	▪ A data analysis tool (askEXODUS) allows to extract specific data from the output files
CRISP3	2D / 3D	▪ Detailed information about each person at every time step ▪ Route information, fire conditions in certain locations ▪ Evacuation time ▪ Pictorial output
EESCAPE	None	▪ Total evacuation time
EGRESS	2D	▪ Visualisation of congestion points ▪ Visualisation of bottlenecks ▪ Visualisation of merging flows
EVACNET4	None	▪ Time to evacuate building, average time for evacuee to egress building, average number of evacuees per specified time period, number of successful evacuees ▪ Number of evacuees that passed through a particular exit to safety ▪ List of arcs and number of people travelling through each arc ▪ Location of queues and time length of the queue ▪ Floor and node clearing time ▪ Building and destination evacuation profile ▪ Number of people not evacuated by a specified time
EXIT89	None	▪ User movement table (track the time and corresponding node position of each user throughout the simulation) ▪ Total evacuation time ▪ Number of occupants trapped ▪ Stair and floor-clearing times
EXITT	None	▪ Number of users out of the building ▪ Number of occupant trapped ▪ Total evacuation time ▪ Action of individual users at all time periods of the simulation
FPETool	None	▪ Horizontal and stair travel time ▪ Time for all users to pass through exit doors
GridFlow	2D / 3D	▪ Outputs that can be imported into spreadsheet programs. ▪ Details about population in every space at every logging interval after each run. ▪ Detailed aspects of the buildings and users.
Legion	2D / 3D	▪ Usage maps (space, utilisation, density and speed, etc) ▪ Graphs on outflow characteristics ▪ Animations
PathFinder	2D	▪ Number of people that have used an exit ▪ Statistics on times for people to exit from a given room ▪ Time for a stair and a floor to become empty ▪ Total evacuation time
PedGo	2D	▪ Text files that can be imported into spreadsheet programs (limited documentation on this model)
PEDROUTE	2D / 3D	▪ Details of peak occupancy and average delay per passenger

Table 3 Continued.

TOOL	VISUAL CAPAB.	MAIN MEASURABLE OUTPUTS
SICURO	2D / 3D	▪ Time to evacuate building, average time for evacuee to egress building, average number of evacuees per specified time period ▪ Flow characteristics for each arc ▪ Location of queues and time period that arc had a queue ▪ Travel times for each path ▪ Destination evacuation profile ▪ Number of people evacuated by a specified time
Simulex	2D	▪ 2D visualisation of evacuation ▪ Overall evacuation time of all users reaching the exits ▪ Number of people passing through each exit
STEPS	2D / 3D	▪ Total evacuation rime ▪ Number of users in certain areas, planes and paths ▪ Number of people that have left the different fields versus time
TIMTEX	None	▪ Total evacuation rime ▪ Individual floor clearing time
WAYOUT	2D	▪ Complete movement time ▪ Individual time when each compartment is evacuated

2.1 Model classification

In this short review a total of 20 available computer models have been considered. Many of such models can also simulate evacuation from other types of structures. The considered models, in alphabetical order, are the following: ALLSAFE [4], ASERI [5–7], buildingEXODUS [3, 8–10], CRISP [11, 12], EESCAPE [13], EGRESS [14–16], EVACNET4 [17, 18], EXIT89 [19–21], EXITT [22, 23], FPETool [24], GridFlow [25], Legion [26, 27], PathFinder [28], PedGo [29, 30], PEDROUTE/PAXPORT [31–33], SICURO [34–36], Simulex [37–39], STEPS [40, 41], TIMTEX [42], WAYOUT [43].

Results of review are summarised in the following tables. In particular in Tab. 1 background characteristics of each model are described, Tab. 2 reports main features of each considered model and in Tab. 3 are summarised visualisation capabilities and main measurable outputs available for each considered tool.

3 Applicative context

3.1 The test site

The considered building is a primary school located within the CBD area selected for the drill [18]. The school evacuation plan stipulates that everybody must gather at a site in front of the building (called *first assembly point*, see Fig. 1); according to the town evacuation plan, the school's staff and pupils will be led to the refuge area located about 2 km from the school by means of a bus service starting from another gathering place (*second assembly point*) as shown in Fig. 2. Hence evacuation of the school was schematized in following five main phases: 1) evacuation of the building reaching first assembly point; 2) roll-call of pupils at first assembly point; 3) transfer to second assembly point;

4) boarding on bus; 5) transfer to refuge area. In the application here described the analysis focuses on the evacuation of the first three phases.

Data were gathered concerning supply and demand. During the drill a monitoring system was arranged, with manual/automatic tools and 12 video cameras, in order to acquire data concerning pedestrian outflow (times, densities) both inside and outside the building until the gathering places were reached.

3.2 Mesoscopic simulation

As an application a computer simulation of the observed evacuation was performed. Paths were obtained from the school evacuation plan. As regards the cost functions adopted, for fictitious links a constant speed function was considered; for corridors and descending flights relationships between speed and specific flow specified and calibrated in [36] has been considered.

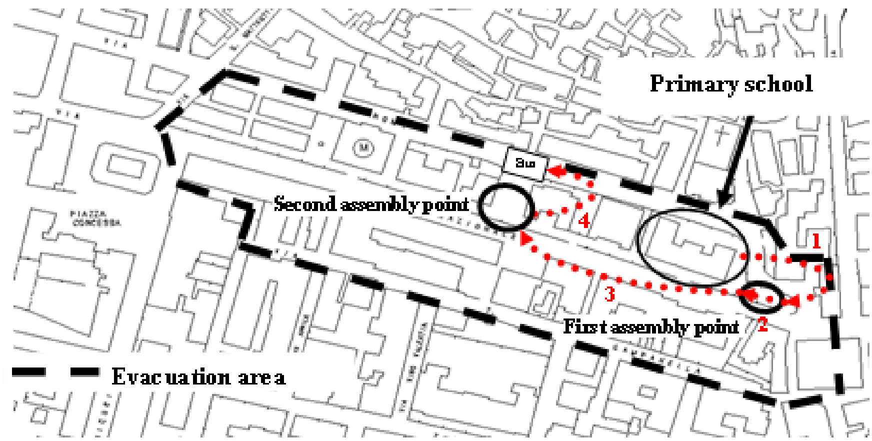

Figure 1: Phases of evacuation.

Demand values used in the simulation were obtained from school attendance on the experimentation day, and users were located in offices and classrooms following the real distribution. The demand value to be evacuated consists of about 150 users. Furthermore, in order to simulate evacuation more realistically, a path choice model was not implemented but adopted paths were obtained directly from the school evacuation plan.

The first three steps identified previously were simulated with a dynamic approach. The assignment model implemented within the DSS built for this research project allows pedestrian outflow to be simulated with two different hypotheses on distribution of departures:

- departures uniformly distributed in a defined interval;
- departures concentrated at the start of the first simulation interval.

The Dynamic Traffic Assignment (DTA) model considered here to simulate evacuation is mesoscopic and consists of an evolution of the dynamic approach developed for evacuation purposes applied in [34] for ship evacuation and in [35] as a support for the design of evacuation plans.

The approach used refers to discrete time intervals, supposed of constant length (without any loss in terms of generality). Let δ be the length of the generic interval t and τ the current time within the interval, $\tau \in [0, \delta]$.

Outflow characteristics are calculated at the beginning of each interval (end of the previous one) and are assumed homogeneous along an arc. For sufficiently short lengths of the interval, they can be considered approximately constant for the entire duration of the interval, avoiding the need to allow for the inner fixed point problem that would arise. Once outflow characteristics on arcs for a generic interval are known, movement of users can be traced on the arc, depending on the definitions of the arc model and on the adopted movement rules described below.

3.3 Macroscopic simulation

A second application has been performed applying to the building an adaptation of the IMO guidelines [44] on evacuation analysis for passenger ships proposed in [45]. This application can be summarised in the following steps:

1. Schematization of escape routes as an hydraulic network where the pipes are the corridors and stairways, the valves are the doors and restriction in general and the tank are the public spaces.
2. Calculation of the density δ for all the escape routes.
3. Calculation of the initial specific flow q_s^0, as a function of the densities.
4. Calculation of the flow q for corridors and doors, in the direction of the assigned escape routes.
5. Calculation of the outlet calculated flows q for each transition point.
6. Calculation, from the values of M (number of persons entering a flight or a corridor) and of q, of the flow time T_F for each stairway and corridor.
7. Calculation of travel time T_D from the farthest point of escape route to the stairway.
8. Calculation, for each stair flight, of its travel time T_S. For each floor the total stair travel time is given by the sum of the travel times of all stairs flight connecting the floor with the assembly point.
9. Calculation of travel time from the end of the stairway to the assembly point.
10. Calculation of the overall time T_I to travel along an escape route to the assembly point.
11. Once the calculation is performed for all the escape routes, the highest T_I is selected for calculating the travel time as $T_T = (f_1 + f_2) \cdot T_I$ where f_1 and f_2 are correction factors used to take into account of conditions of the simulated scenario and of counterflow.

3.4 Comparison of results

Results obtained from the application of the above-described approaches have been expressed in terms of evacuation time. In Tab. 4 evacuation times for the considered phases related to experimentation and to simulations are reported.

Table 4: Comparison of evacuation time obtained from drill whit simulated ones.

Phase	*Measured time*	*Meso simulation*	*Macro simulation*
1) evacuation of the building reaching first assembly point	4’14’’	5’47’’	4’23’’
2) roll-call of pupils at first assembly point	3’05’’	2’58’’	3’00’’
3) transfer to second assembly point	2’00’’	1’43’’	4’00’’
Total time	9’19’’	10’28’’	11’23’’

Some consideration can be made on the proposed approaches. For the first one (mesoscopic approach) the main advantage consists on the possibility to explicitly simulate queues and spill backs, whilst a drawback is given from the necessity to use a specific software. The second approach (macroscopic) gives an aggregate representation of flow conditions and does not allow a detailed analysis of them, on the other hand it can be easily implemented on a spreadsheet.

4 Conclusions and perspectives

The main result of this paper concerns both the application of a mesoscopic dynamic network assignment model in a multimodal context and the specification and calibration of some cost functions adopted in this model. A comparison between experimental data and simulation results shows how the usage of appropriate simulation models can realistically reproduce user behavior. It was shown that such models could be used as a support both to verify effectiveness of existing evacuation plans without resorting to expensive drills and to draw up evacuation plans. Implementation of appropriate cost functions can make the applied methodologies suitable for any building and/or area with homogeneous characteristics in terms of activities. Further investigations on travel time functions under different operative conditions are under development.

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