A DISCRETE EVENT SIMULATION MODEL FOR THE EGRESS DYNAMICS FROM BUILDINGS

Paolo Lino, Bruno Maione
Dept. of Electrical and Electronics Engineering, Technical University of Bari, Bari, Italy

Guido Maione
Dept. of Environmental Engineering and Sustainable Development, Technical University of Bari, Taranto, Italy

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Abstract: Safe egress of people from closed buildings is a critical issue, in which modern control methodologies and information and communication technologies play a crucial role. Current research trends suggest us to profitably use wireless networks of distributed sensors and actuators. Then, a large amount of feedback from the real scenario is needed to determine control outputs. In this paper, we use a discrete event system approach to define a simulation model of a complex real scenario. The egress of students and academic staff from a lecture area in the School of Engineering in Bari was simulated, to validate the modeling approach in predicting the evacuation process. Performance indices (flows of individuals in spaces and at critical points, number of evacuated people, time to complete egress) were measured in standard conditions when no emergency or panic phenomena occurred. The results show that the model properly represents real phenomena like blocking, congestion or overcrowding, and faster-is-slower effect. Then, the same approach could be efficient to predict flows in emergency conditions, when specific control actions are taken for speeding-up egress safely.

1 INTRODUCTION

Recently, safe egress of people from large buildings in standard or emergency conditions has received considerable attention. In particular, after the the 9/11 Twin Towers terrorist attack in New York City the evacuation of complex and/or high buildings has been a focus of attention. All the world over, safety has been based on prescriptive design regulations concerning building characteristics (distances, number of exits, exit widths, etc.) which allow the occupants to evacuate the structure within a pre-defined acceptable amount of time. Hence evacuation procedures assuring acceptable, building safety standards have been a major concern for engineers. Consequently, the crowd management has been based on the assessment of the people handling capability of building spaces before using them. However, the shortcomings of this strategy is that it fails to take into account how people actually behave during the egress. Today there is a tendency to control the behavior of occupants also before, during and after the evacuation process. However, the egress control for influencing the behavior implies a research effort both in mathematical modeling and information and communication technologies (ICT).

The mathematical or simulation models can be very useful in: describing the crowd dynamics during evacuation by means of system parameters (*e.g.* crowd distribution and speed); studying critical phenomena (blocking and congestion); measuring performance indices (number of evacuated individuals, time required, speed, etc.); designing and optimizing buildings and escape routes; comparing alternative control strategies. A good control strategy to route individuals should predict and dynamically adapt itself to the different emergency conditions, the different and random distributions and behaviors of individuals (type and time of reaction to alarms, decisions taken, etc.), the random events (interruption of escape routes, doors or exits blocked, overcrowding close to emergency exits, etc.). Then, suitable control actions are based on feedback from the environment.

Sensing and communication technologies are used to measure variables which can indicate emergency and/or panic, and, at the same time, to communicate

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actions for safely escaping from the risky environment. Such communications can be directed to all people by using distributed actuators (monitors, flashing lights, automatically opening doors, acoustic signals and alarms, etc.), or to specific expert human agents, devoted to help and direct groups of people to a safe exit, by using Personal Digital Assistants (PDAs) or palmtop computers.

Recently, our research group started up a scientific project to profitably use wireless sensor networks and ICT for managing evacuation from buildings during emergencies. The main goal is reducing egress times in a safe way. After a literature review, a model suitable to develop supervisory control policies and a test-bed are currently under investigation. The model of the crowd dynamics defines the feedback information and the control actions. In particular, the time required to manage an emergency condition is $T = T_1 + T_2 + T_3$, given by the time to feel and recognize emergency (T_1), the time to elaborate sensed information (T_2), the time to route the crowd in a safe condition (T_3). Control should minimize T_3.

Scientific literature reports flow-based models using graphs or similar tools, cellular automata, agent-based systems in which agents represent individuals, activity-based models including sociological and behavioral aspects (Schreckenberg and Sharma, 2003; Santos and Aguirre, 2004; Kuligowski and Peacock, 2005; Waldau et al., 2007). Flow-based models are mostly based on the *carrying capacity*, *i.e.* they predict the evacuation dynamics by considering the topology of the building or physical location in which the emergency occurs, and the evacuation policies (Schreckenberg and Sharma, 2003). Other models consider also the *human response*, *i.e.* the psychological or sociological factors, and individual reactions (Galea et al., 1996; Klüpfel et al., 2000; Schadschneider et al., 2008). The two modeling approaches differ for a macroscopic or microscopic point of view, respectively.

Macroscopic models are usually employed to statically plan escape routes, for achieving the 'quickest flow' or the 'maximum flow', and they are not adapted by the feedback from the real scenario. Neither microscopic models can be adapted in real time, because a dynamic optimization of escape routes and flows would require too much computational resources and time. Moreover, a detailed microscopic simulation environment could require information that can't be acquired during emergency. Basically, macroscopic models do not consider individual characteristics and behaviors, but they synthesize a common emerging behavior. On the contrary, microscopic models consider each individual as an autonomous decision making entity, moving and behaving according to both personal and general criteria.

Then, we built a model useful to control evacuation in real time, on the basis of the information needed and control outputs. Important state feedback is about: distribution and number of individuals in the evacuated areas; measured flows in critical points, and congestion or overcrowding of specific areas or points that reduce flow; binary condition (crossable/not crossable) of routes, doors, exits, transit points, which can be affected by fire, smoke, structural problems, etc.. Typical control outputs can be associated to: flashing lights showing the best direction to a safe exit; acoustic signals; automatic opening of doors to a safe exit, and automatic closing of doors to dangerous or critical areas; instructions and orders given by expert operators.

Asynchronous events occurring in emergency conditions, and the discrete nature of controlled variables and signals from actuators, justify using a discrete event system (Cassandras and Lafortune, 1999) to model, analyze, and control the evacuation of people. Typical events are sudden variation of available paths, blocking of doors, elevators out of service, automatic closing/opening of doors, etc..

In particular, queuing networks (Kleinrock, 1975) easily describe precedence relations, parallelism, synchronization, modularity, and other properties. More specifically, they can be used to statistically represent the decisions and actions affecting the evacuated crowd behavior. To this aim, a probabilistic approach may take into account several decision parameters, which depend on the current system state and are related to sociological and psychological factors. The human decision is based on elaboration of perceived signals and information, not simply on a causal *stimulus-reaction* relation. For example, consider when individuals interact and form groups, or try to rescue relatives going in opposite direction to the crowd, or the influence of leaders, expert agents, firemen, and so on. This approach simplifies the control system design, and, at the same time, considers an individual perspective to a certain extent. Moreover, escape routes can be easily recognized, and minimum time/shortest length paths can be identified.

State dependent queues in the proposed model make it difficult to find a closed form solution for performance analysis. Thus, a simulation model has been implemented in MATLAB/Simulink© environment, by means of the discrete event simulation tool *SimEvents*. Here, we report some results on a case-study used to test our approach, based on queuing networks and discrete event systems theory.

Section 2 briefly introduces the model and the assumptions made. Section 3 describes the developed simulation model. Section 4 gives the performance measured in the simulated case-study. Section 5 draws the conclusions.

2 THEORETICAL MODEL OF THE EGRESS DYNAMICS

Here, we summarize the assumptions made to build a discrete event system model of the crowd dynamics in standard or emergency conditions. We represented the phenomenon as a queueing network system, composed by different queues, each one describing the behavior of individuals in a zone of the evacuated environment. A zone could be a room, a corridor, a stairway, an exit or an entrance, a door, but also a floor or level of a building. Then, the approach can be used to model and simulate complex networked buildings and environments, by integrating and connecting different queues in a single representation.

In this framework, we described the behavior of people as an elementary queue with parameters determined by physical human peculiarities, according to the Kendall notation (Kleinrock, 1975). The queue service rate is interpreted as the time necessary to cross rooms, corridors, stairs, and depends on the *free walking speed*, *i.e.* the speed an individual may reach in an open space. This speed is function of age, sex, physical conditions and abilities, external pressure to hurry, dawdling, baggage carried, gradient of walking area (Fruin, 1971; Tregenza, 1976). An average value $v_0 = 1.34\ m/s$ and a standard deviation of 0.26 for a normal distribution are commonly accepted (Weidmann, 1993). But actual walking speed is nonlinearly affected by density ρ of individuals. Experimental studies showed that the *average impeded speed* v decreases as the number of persons P per unit area increases (Fruin, 1971; Tregenza, 1976): ρ has almost no influence up to $0.27\ P/m^2$, and motion is stopped when $\rho_{max} = 5\ P/m^2$ (Tregenza, 1976), which is taken as maximum space capacity. A linear relation can be assumed between v and ρ, if $\rho \in [0.3, 2]$. Here, we assume the motion of individuals in rooms and corridors as described in (Weidmann, 1993), according to the following formula:

$$v(\rho) = v_0 \left[1 - e^{-\gamma\left(\frac{1}{\rho} - \frac{1}{\rho_{max}}\right)} \right], \qquad (1)$$

where $\gamma = 1.913$ is a fit parameter.

For motion on stairways, we consider the free 'horizontal' speed, *i.e.* the horizontal component of the speed vector, as normally distributed. The average is function of the previously cited parameters and of the stair geometry (angle and riser height). Short and long stairways can be distinguished (Fruin, 1971; Kretz et al., 2008): the first exhibit higher speeds when walking down-up, the latter when going up-down. In this paper, we assume short stairways traveled in both directions (average free up-down speed $0.780\ m/s$, average free down-up speed $0.830\ m/s$), and long stairways only down-up (average free speed $0.423\ m/s$). These v_0 values (Kretz et al., 2008) are used for the impeded actual speed in (1).

Moreover, interactions between individuals increase with ρ, especially in bottlenecks (Helbing et al., 2000). Frictions occur when people wish to move faster than the currently achieved speed, a typical panic behavior. Then, arch-like clusters form and grow at doors, exits, or other critical points, if desired walking speed v_d exceeds the critical free walking speed (Helbing et al., 2000; Parisi and Dorso, 2007). The consequence is a *faster-is-slower* effect which delays the egress. Then, two different outflow regimes exist depending on v_d: the first is when outflow depends linearly on v_d (the faster individuals want to move, the faster they evacuate); the second is when outflow decreases with v_d, due to interactions.

Queues with null queueing space and a certain server capacity are used to represent rooms, corridors, stairways, doors, exits, entrances and gateways. Each queue can accommodate as many people as the capacity of the modeled space (Jain and Smith, 1997). If a unit space has a capacity of $5\ P/m^2$, an area of length L and width W has a capacity $C = 5 \cdot L \cdot W$. The service time is normally distributed, with an average value given by $L/v(\rho)$. Differences between the modeled spaces are obtained by specifying a different v_0 for each type of space. Arrivals to queues are exponentially distributed, as it is commonly assumed and also observed. Summing up, we obtain state dependent $M/G/C/C$ queues.

In particular, doors, exits, entrances, and gateways are modeled by queues with a server capacity equal to the width W of the passage (more precisely the maximum number of individuals that can flow through). If the way is filled at its capacity, then the queue of the antecedent space is blocked.

The queue service rate is determined by taking into account the faster-is-slower effect, as described in the following. First of all, it is supposed that the desired walking speed of individuals crossing a bottleneck varies as proposed by (Helbing et al., 2000):

$$v_d(t) = [1 - p(t)]\, v_d(0) + p(t) v_d^{max}, \qquad (2)$$

where $v_d(0)$ is the initial desired speed, v_d^{max} is the maximum desired speed, and $p(t)$ specifies the crowd impatience (Helbing et al., 2000), with:

$$p(t) = 1 - \frac{\overline{v}(t)}{v_d(0)}, \quad (3)$$

being $\overline{v}(t)$ the average speed of individuals in the crowd. Then, we assume that the queue desired service rate $\mu_d(t)$ and the average service rate $\overline{\mu}(t)$ relate to the desired and average speeds according to $\mu_d(t) = W v_d(t)$ and $\overline{\mu}(t) = W\overline{v}(t)$, respectively. Finally, the actual service rate μ is normally distributed with an average value given by (Wang et al., 2008):

$$E[\mu \mid \mu_d] = \begin{cases} \mu_d & if \quad \mu_d \leq \mu_c \\ 1 - e^{\frac{\alpha}{\mu_d - \mu_c}} & if \quad \mu_d > \mu_c \end{cases} \quad (4)$$

where $E[\mu \mid \mu_d]$ is the expected value of the service rate μ, μ_c is the flow capacity of the passage, and α is a negative constant. To sum up, firstly μ_d is computed and compared to μ_c, then $E[\mu \mid \mu_d]$ is used to generate μ.

3 THE SIMULATION MODEL

The proposed model represents the main aspects of the evacuation process, and can be exploited to carry out performance analysis in terms of egress times, number of evacuees per time unit, length of queues, existence of bottlenecks and congestion. Unfortunately, a closed form solution giving the steady state probabilities of the network cannot be easily found, as service times depend on the system state. Moreover, the real time management of evacuation can take advantage from the knowledge of the transient dynamics, which cannot be analytically determined. Thus, a queueing network simulation model providing a tool suitable for implementing and validating evacuation strategies is developed in the MATLAB/Simulink© environment. In particular, we exploit the discrete event system toolbox *SimEvents*. Just like other software tools like Arena, Extend, Witness, etc., it allows the representation of complex discrete-event systems by a network of queues. Moreover, the integration with MATLAB and Simulink simplifies the modeling process of hybrid dynamical systems, which include continuous-time, discrete-time and discrete-event subcomponents, such as sensor networks and distributed control systems.

Figure 1 depicts the block scheme of the queue which models wide areas, like rooms and corridors. We assume the flow in one direction. The main elements of the scheme are a *FIFO queue* representing the queueing space and a *N-server*, consisting of a number of servers matching the available capacity.

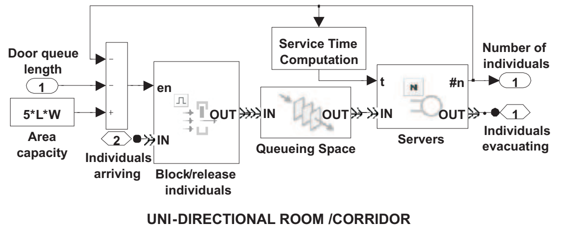


Figure 1: *SimEvents* implementation of rooms, corridors, and stairways.

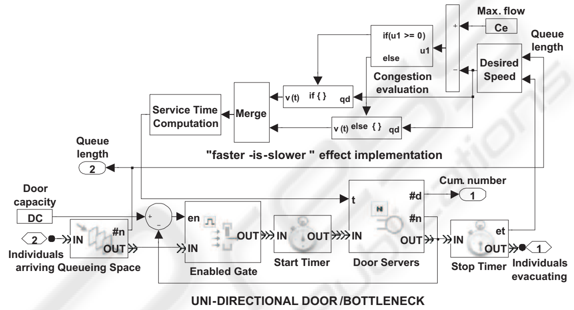


Figure 2: *SimEvents* implementation of bottlenecks.

The function *Service Time Computation* computes the service time depending on the area congestion. It consists of two functions: the first derives the current speed from (1) by considering the number of people crossing the area; the second computes the service time as the path length divided by the speed. The *Block/release* element prevents individuals to enter area, if the maximum capacity $5 \cdot L \cdot W$ has been reached.

For stairways we use the same scheme in Figure 1: free walking speeds specified in Section 2 are used in (1) to compute the current speed in congestion conditions. More precisely, the individual space occupancy is suitably increased for upward motion, because people oscillate sideways when rising stairways, which reduces the available space.

The block scheme implementing bottlenecks like doors is represented in Figure 2, and it suitably models the faster-is-slower effect. The model is composed of a *FIFO queue*, whose space will be defined in the next subsection, and a *N-server* with as many servers as the individuals that can cross the bottleneck at the same time. The service time is determined by (4), (2) and (3), provided that an estimate of the average service rate $\overline{\mu}(t)$ is available. If ΔT is the time interval taken by the last individual to cross the door, as measured between blocks *Start Timer* and *Stop Timer*, its reciprocal $\mu = 1/\Delta T$ represents the current service rate. Thus, since the number n of individuals waiting to be served has a zero service rate, the overall aver-

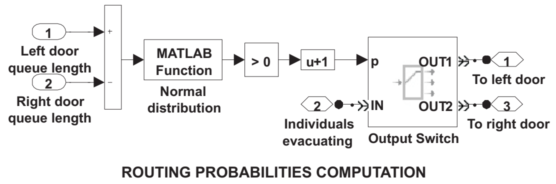


Figure 3: Transition from corridors/rooms to multiple doors.

age service rate can be computed as:

$$\overline{\mu} = \frac{\sum \mu_i}{(n+1)} = \frac{1}{(n+1)\cdot\Delta T} \quad (5)$$

Then, the *Desired speed* block calculates $p(t)$ according to (3) and $v_d(t)$ according to (2). If the resulting value overcomes the door maximum flow capacity, a congestion occurs. Finally, the *Service time computation* block outputs a service time obtained from a normal distribution with a mean equal to the reciprocal of the service rate.

When rooms/corridors and doors share the same queueing space, we must guarantee that the number of individuals in the system does not overcome the overall capacity. Then, the door queueing space capacity is set equal to the room/corridor capacity. So, after connecting the elementary sub-models, the number of individuals waiting in front of the door is used to reduce the number of available servers in the room/corridor. As an example, individuals arriving at the end of a corridor enter the door queue and wait for a free server. At the same time, they reduce the corridor available space, but do not affect the walking speed of individuals crossing the corridor. To implement this condition, the signal *Door queue length* representing the number of individuals in the door queue is fed back (see Figure 1).

For rooms/corridors with more than one door an *Output switch* block connects the area to exits. The routing probability is set for each possible direction (Figure 3). We assume that probability to choose each door is inversely affected by its crowding condition. To introduce a sufficient level of uncertainty in the choice, we generate a number from a normal distribution having the length of each queue as its average. Then, the selection comes from comparing the results.

4 SIMULATION RESULTS

As a case-study, we consider the area of large lecture rooms at Technical University of Bari, *i.e.* 5 lecture rooms and a Great Hall, all connected to a main corridor, which has an entrance/exit point 2.73 *m* wide and a maximum flow of 3 persons at a time (Figure 4).

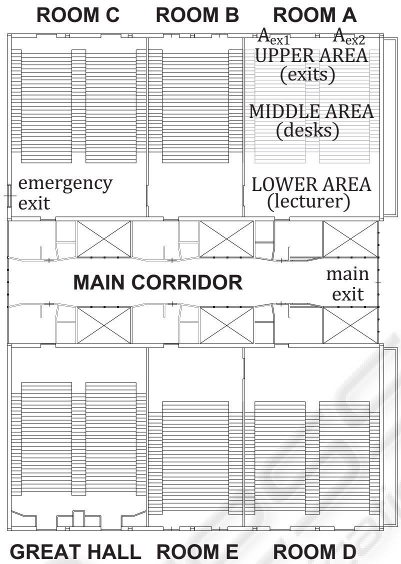


Figure 4: The case-study.

The Hall is 294 m^2 large, with a maximum capacity of 270 persons. Three rooms (A, C, D) are 294 m^2 large, with a maximum capacity of 270 persons. Two smaller rooms (B, E) are 207 m^2 large, with a maximum capacity of 180 persons. Sitting desks in the Great Hall and in A, C, D are vertically distributed from a lower to an upper level, an internal corridor separates desks in two columns and two more external corridors are available. Rooms B, E have only one column of desks and two external corridors. All rooms have one single access/exit point at the lower level (1.6 *m* wide, maximum flow of 2 persons at a time), used by academic staff, and two access/exit doors at the upper level (2.3 *m* wide, maximum flow of 2 persons at a time), used by students. The lower level doors link rooms to the main corridor, which is 235 m^2 large. Each room communicates with its adjacent room(s), except for the Great Hall: the three communication doors are 2.3 *m* wide. Room C has also a further emergency exit (see Figure 4).

To sum up, there are 14 points of exit: one from the main corridor, 12 from the upper level doors, one from room C. Then, the main and natural flow of students during evacuation is through the upper doors, otherwise through the corridor, especially the ones sitting in the first lines of desks. The teaching staff can use the room lower exit doors, the corridor and then its exit. People in room C can use the added emergency exit, which is an opportunity also for people in the Great Hall (e.g. if the exits from the Great hall are blocked or unavailable). Each room is divided into 3 main areas, representing the lecturer (lower), the desks (middle), and the exit (upper) areas, respec-

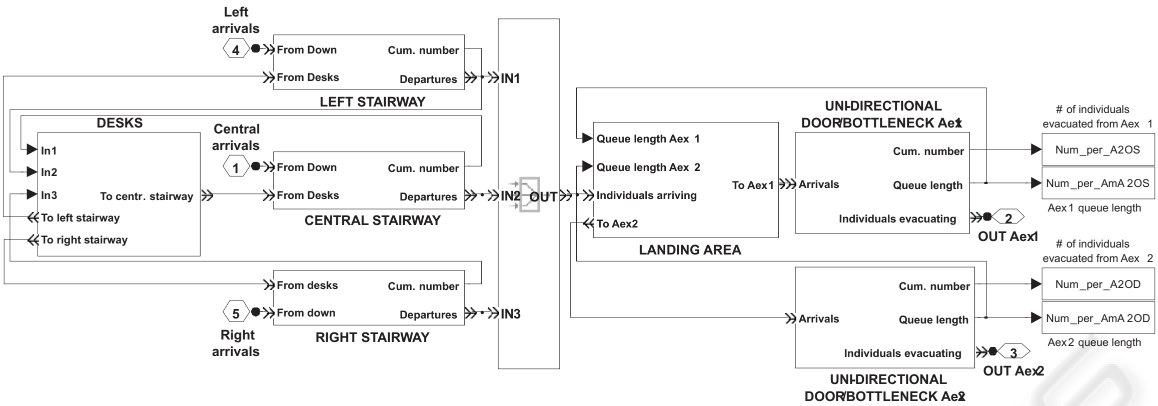


Figure 5: SimEvents model for upper and middle areas in room A.

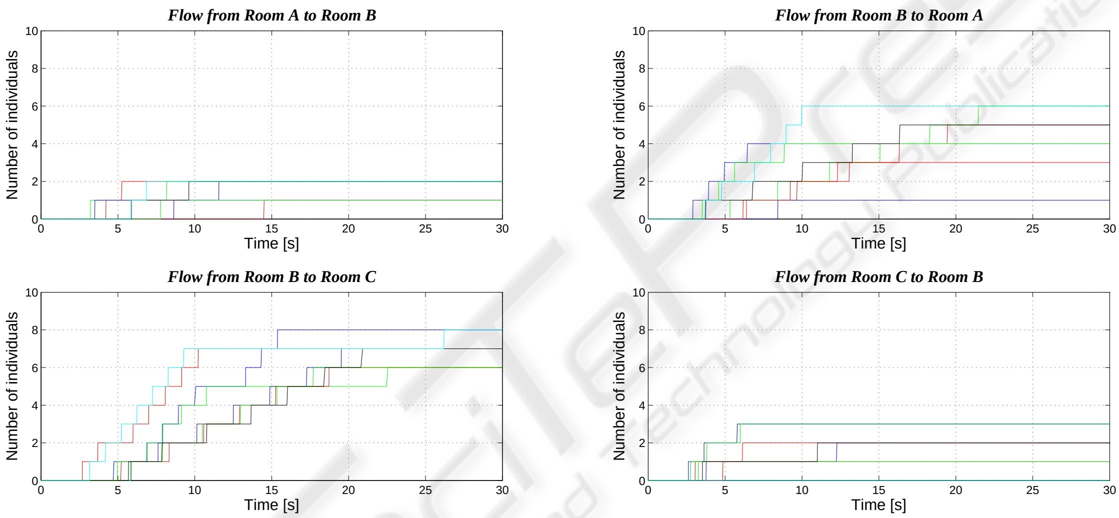


Figure 6: Cumulative number of individuals crossing doors connecting Rooms A, B and C.

tively. The exit area consist of a landing space receiving individuals from stairways and includes two exits. Then, 3 queues are associated to the lower area, 2-3 queues to the middle area, depending on the number of staircases, and 3 to the last area, *i.e.* two for exits and one for the landing space.

The *SimEvents* block scheme for the upper and middle areas of room A is in Figure 5.

An extensive simulation analysis has been executed to predict the evacuation dynamics. Only relevant results are presented. Without loss of generality, we assume evacuation in normal circumstances, *i.e.* panic or environmental conditions do not affect the behavior. Representation of evacuation under panic conditions simply needs a tuning of model parameters, which is under investigation.

We suppose that egress starts at the end of a lecture session, so that all the rooms are evacuated simultaneously. As initial condition, an average population of 150 individuals occupies each room, mainly distributed in the desks area, while the lower and upper areas are sparsely populated. The Great Hall and the main corridor are initially empty. We assume that individuals occupying the desk and upper areas evacuate from exits in the same room, while those in lower areas evacuate from the starting room or toward an adjacent room or the corridor.

All results refer to 5 different simulation runs. Figure 6 represent flows trough doors connecting rooms A and B, and B and C, respectively. The flow is composed of individuals initially occupying the lower areas.

It is evident that only few of them try to evacuate from larger rooms A and C toward room B, because routing probabilities depend on the current crowding. In fact, the initial crowd density is larger in the smaller rooms. Finally, the cumulative number of individuals go from a room to another one changes at each

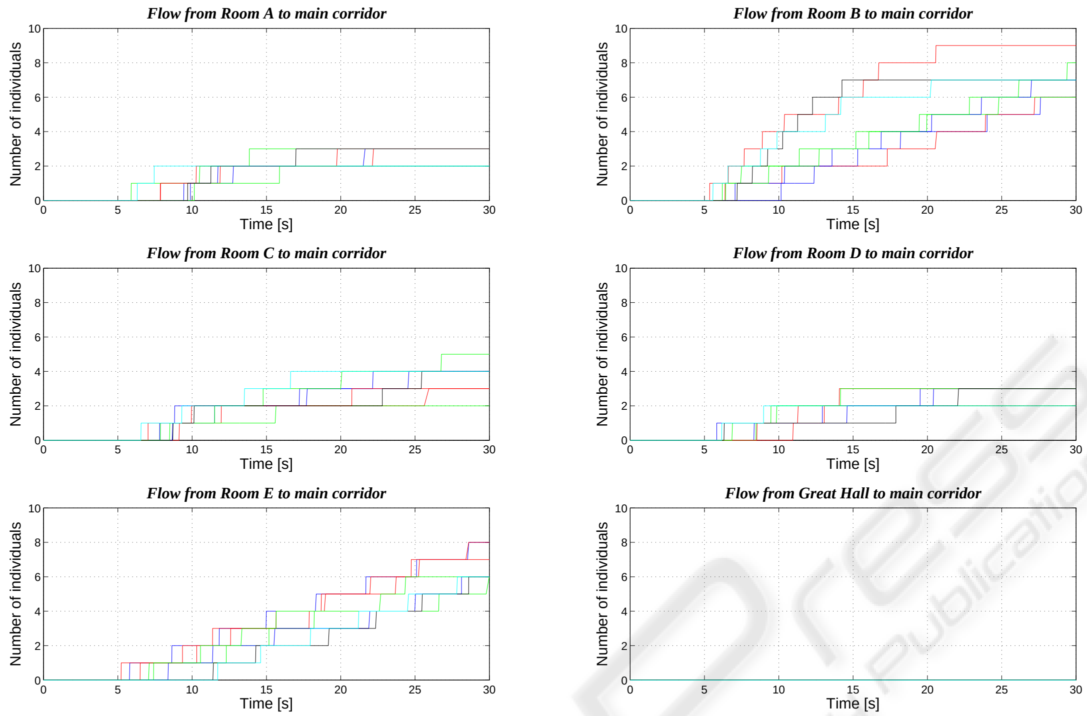
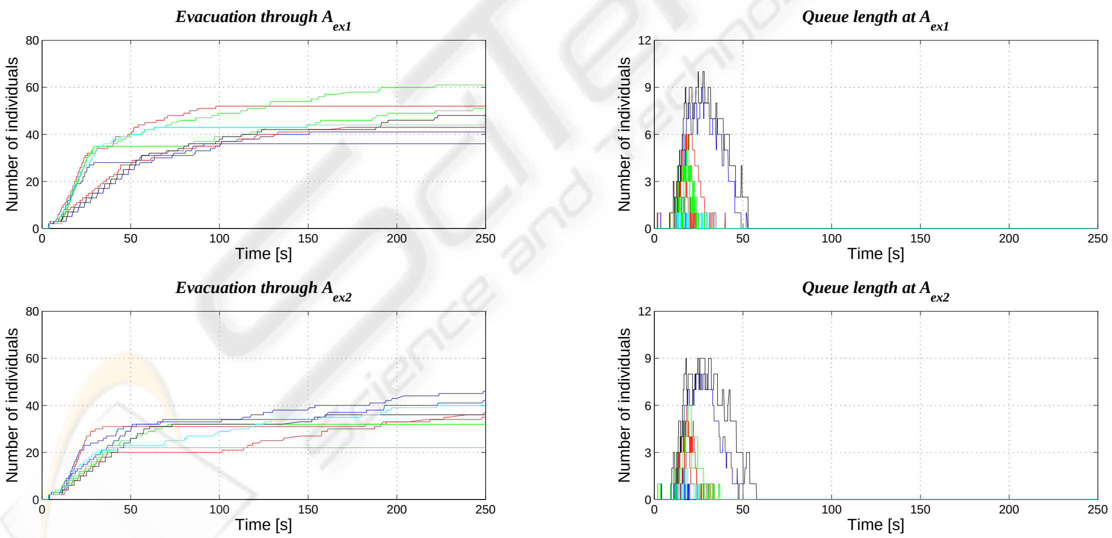


Figure 7: Cumulative number of individuals flowing from Rooms and Great Hall to main corridor.



(a) (b)

Figure 8: Evacuation from Room A: (a) cumulative number of individuals evacuating from A_{ex1} and A_{ex2}; (b) queues length at A_{ex1} and A_{ex2}.

run, due to the randomness of the transitions. Similar flows are obtained for other rooms.

Flows of individuals choosing the main corridor are shown in Figure 7.

Cumulative numbers of individuals increase almost linearly in all cases, being the doors capacities sufficient to handle the traffic. Just after 30 *s* all individuals have abandoned lower areas.

Finally, Figure 8 depicts evacuation from Room A through the two upper exits.

The flow is mainly composed of individuals leaving the desk area. Figure 8(a) shows that most of people leaves after a delay of about 10 *s*, which is nearly the time necessary to cover half of the stair length. During the initial transient, the individuals reaching exits can immediately evacuate with a minimum service time, as doors are initially free. Conversely, slopes of curves in Figure 8(a) reduce with overcrowding of queues in the upper area, which delay individuals. Figure 8(b) shows that individuals reaching the upper area direct themselves almost uniformly towards A_{ex1} and A_{ex2}, as the choice is affected by the doors crowding. After 60 *s*, the queues of upper area and exits are nearly empty, so that arriving individuals are promptly served. The overall evacuation takes 120-160 *s* on average.

5 CONCLUSIONS

In this paper, a simulation model describing the evacuation dynamics from buildings has been presented, considering the queueing network theory as a modeling tool. The model is suitable for implementing and testing control strategies for managing emergency situations. Results from a simulation model implemented in the Matlab/Simulink© environment, by using the discrete events simulation toolbox *SimEvents*, have shown the feasibility of the approach. Without loss of generality, simulation represents evacuation dynamics in ordinary conditions. Parameters tuning for panic situations is under investigation. A further validation is under development by comparing preliminary results with those obtained using commercial tools.

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