Modeling and Simulation of Crowd Egress Dynamics in a Discrete Event Environment

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Abstract— **In this paper, a queueing network model representing the main aspects of the evacuation dynamics from buildings is developed. A systematic method allows to define in few steps a queueing network representing flows of individuals during egress. In particular, different modules, whose parameters depend on statistical characteristics of motion, are defined for spaces composing the evacuated environment and properly combined. The proposed model is conceived to develop control strategies for real time management of evacuation of crowds, by means of the adaption of strategies and escape routes, depending on information collected from the real scenario. To test the method, a simulation model is implemented in the MATLAB/Simulink© environment, providing a tool suitable for designing and validating evacuation strategies.**

I. INTRODUCTION

The problem of safe egress of people in emergency conditions has received considerable attention. Sometimes, chaotic collective motions are used for searching the best positions in sport events or shows. Technology and scientific research improved design criteria of buildings and escape routes and procedures. Usually, safety is ensured by plans that are statically fixed by norms before the emergency event occurs.

But problems still exist when emergencies involve many people, many of which can be subject to panic phenomena and escaping limitations (age, physical conditions, handicap, etc.). Therefore, mathematical or simulation models can be very useful for: describing the crowd dynamics during evacuation, studying critical conditions (blocking and congestion), measuring performance indices (number of evacuated individuals, time required, speed), evaluating and improving efficiency of escape procedures. A good strategy should predict and adapt to the different scenarios, different and random distribution and behavior of individuals (type and time of reaction to alarms, decisions taken), random events (interruption of escape routes, doors or exits blocked, overcrowding close to exits), and should take consequent control actions based on feedback from the environment. Whereas, conventional building design and egress procedures are based on static assumptions on crowd distribution, characteristics, and behavior.

This work is part of the Research Project "Infrastrutture di telecomunicazione e reti wireless di sensori nella gestione di situazioni di emergenza" funded by Apulia Regional Government, Italy.

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Current scientific investigations apply modern sensing and communication technologies, to measure variables and signals which can be interpreted as indication of emergency and/or panic, and, at the same time, can communicate or suggest actions for safely escaping the risky environment. Such communications can be directed to all people in the environment by distributed actuators (monitors, flashing lights, automatically opening doors, acoustic signals and alarms, etc.), or to expert human agents, devoted to help and direct crowds or groups of people to a safe exit, by Personal Digital Assistants (PDAs) or palmtop computers.

Recently, Technical University of Bari started up a scientific project to profitably use wireless sensor networks and information and communication technologies for managing evacuation from buildings during emergencies. To this aim, all the decentralized systems and control actions are coordinated to reduce egress times and guarantee a safe dynamics of the crowd. After preliminary studies, a model suitable to develop supervisory control policies and a test-bed is currently under investigation. The model must consider the total time $T = T_1 + T_2 + T_3$ required to manage an emergency condition, starting from the generating event: T_1 is the time to feel and recognize emergency, T_2 the time to elaborate sensed information, T_3 the time to route the crowd in a safe condition. Control should minimize T_3.

Scientific literature reports flow-based models developed using graphs, cellular automata representations, agent-based systems in which each agent represents an individual, activity-based models including sociological and behavioral aspects [1], [2], [3], [4]. The flow-based models exploit the carrying capacity to predict the evacuation dynamics, by considering the topology of the location in which the emergency occurs and the evacuation policies [1]. Some models also consider the human response, thus including psychological or sociological factors and detailing individual reactions [5], [6], [7]. The two approaches differ for a macroscopic or microscopic point of view, respectively. Macroscopic models are usually employed to statically plan escape routes, by solving an optimization problem for achieving the 'quickest flow' or the 'maximum flow', and are not adapted by feedback from the real scenario. Neither microscopic models can be adapted in real time, because a dynamic optimization of escape routes and flows requires too much computational resources and time. Moreover, a detailed micro-simulation requires information that can't be acquired during emergency.

In our research, we built a model useful to control evacuation in real time, on the basis of the information needed and control outputs. State feedback comes from: distribution and number of individuals in the different evacuated areas, measured flows in critical points, congestion or overcrowding of specific areas, binary condition (crossable/not crossable, as affected by fire, smoke, structural problems, etc.) of escape routes, doors, exits, transit points. Typical control outputs can be associated to: flashing lights indicating the best direction to a safe exit, acoustic signals, automatic opening of doors to preferred routes, and automatic closing of doors to dangerous areas, instructions 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 [8] to model and control the evacuation of people. In particular, queuing networks [9] are among the best tools for modeling, analysis, and control. Namely, they easily describe precedence relations, parallelism, synchronization, modularity, and other common properties. More specifically, they can be adopted to statistically represent emergent decisions and actions affecting the evacuated crowd behavior. A probabilistic approach may take into account several decision parameters, depending on the current system state and on sociological and psychological factors. For example, consider the case in which some individuals interact to form groups, or individuals try to rescue relatives going in opposite direction to the crowd, or the influence of leaders, expert agents, fire policemen, and so on. This approach has the advantage of macroscopic models to simplify controller design, and, at the same time, considers an individual perspective to a certain extent. Finally, escape routes can be easily recognized, and minimum time/shortest length paths can be identified.

The state dependent queues used in the proposed model make it difficult to find a closed form solution for performance analysis. Thus, the network has been implemented in MATLAB/*Simulink*© simulation environment, by means of the discrete events toolbox *SimEvents*. Simulation allows performance analysis in terms of egress times, throughput (i.e. the number of evacuees per time unit), length of queues, identification of bottlenecks and congestion. We report some results on a case-study used to test the methodology based on queuing networks and discrete-event systems theory.

Organization is as follows. Section II briefly introduces the queuing networks framework used to model egress dynamics. Section III describes the developed model, the characteristics of the parts and the connections. Section IV reports the simulation results in the case-study, and the measured performance indices. Section V gives the conclusions and some ideas for future developments.

II. QUEUEING NETWORKS FUNDAMENTALS

A building or the place in which the emergency occurs can be represented as a system of different space resources (rooms, corridors, stairs, doors, exits, etc.), interconnected with each other and playing the role of 'servers'. Individuals occupying spaces and flowing in the system are considered as the entities using resources, i.e. the 'clients'. An egress procedure is associated to a sequence of servers to be acquired by a client, from the point in which he/she is at the emergency event to one of the available exits. Each individual waits and then uses the spaces he needs. Sometimes he/she may choose between different available servers for a particular operation (two or more different ways, two or more doors or exits, alternative rooms to cross, stairs or elevator, etc.), and a routing decision is necessary. Even if unlikely, revisiting the same space for more times is also possible for psychological or social reasons affecting the behavior of particular individuals, thus generating recycling loops. Moreover, individuals may belong to different classes distinguished by age, sex, physical handicap, family or sociological relations, psychological factors, etc.. Different individuals may need different times to cross the same space (a large room, a long corridor, a steep and/or long stairway), and there can be priorities or different procedures in serving special individuals (handicapped, children, older people, etc.) according to scheduling policies.

The system can be represented as a queuing network [9], in which the space resources are the nodes and the sequence relations (flows) between resources are depicted by the directed arcs between the nodes. In particular, the number of clients entering and using an open network is not fixed, as people may enter and exit the system.

Basically, the queuing network is analyzed through its state, which means the states of the nodes in the system. If we use Markovian queues, the state is associated to a vector $X = [X_1, X_2, ..., X_{\mathrm{M}}]$, where X_i is the random discrete variable giving the individuals occupying resource R_i, for $i = 1, ..., \mathrm{M}$, with M number of distinct space resources in the environment. Each resource R_i is further characterized by its capacity C_i, i.e. the maximum number of occupants, and the queuing rule used to select the next individual to host. In a Markovian network (arrival Poisson processes, exponentially distributed service times to cross spaces, random routings), usually three main processes are assumed as Poisson: an individual leaving a resource (which is an input process for the next resource), how individuals from different spaces are composed in the same space to where they go, how to decompose a crowd in groups of individuals.

III. A QUEUING NETWORK MODEL FOR THE EGRESS DYNAMICS

Here, we describe a systematic method to define a queueing network model of complex buildings by assembling simple modules, each one representing basic components. Since the human behavior strongly depends on the emergency conditions, some assumptions may simplify the control. The crowd behavior in different zones of a building is modeled by an elementary queue, whose parameters are derived by physical considerations related to the human behavior and characteristics (see Kendall notation [9]).

A. Preliminary Physical Considerations

The main parameter of each queue is the service rate: here, it is related to the time needed to cross corridors, rooms, stairs, and directly depends on free walking speed

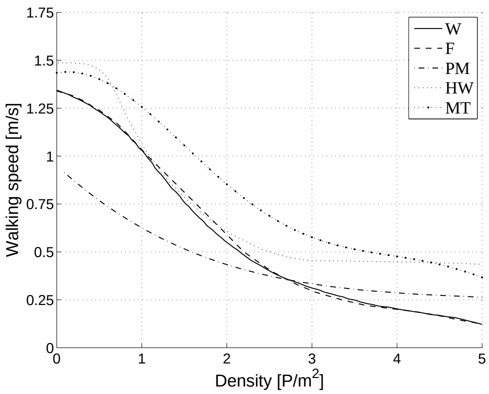


Fig. 1. Fundamental diagram of curves representing the dependance of average walking speed on crowd density; (W) Weidmann; (F) Fruin; (PM) Predtechenskii & Milinskii; (HW) Hankin & Wright; (MT) Mori & Tsukaguchi.

(i.e. the speed each individual exhibits in an open space). Such speed mainly varies with age and sex, though it can be greatly influenced by physical disabilities, trip purpose and conditions (e.g. the need to hurry or the wish to dawdle), the carry of baggages, the gradient of walking area [10]. Based on about 150 literature references, Weidmann [11] found a mean value of 1.34 m/s and a standard deviation of 0.26 for the normal distribution related to the motion of a mean population on a flat terrain in a free area.

However, the crowd density affects the walking speed, as persons adapt their speed to space available. Observations and experiments demonstrate that the average speed nonlinearly decreases as traffic density increases (traffic impeded), in terms of number persons per unit area P/m^2 [10]. In particular, density has almost no influence for values lower than 0.27 P/m^2 [10], while forward movement is halted at about 5 P/m^2 (i.e. a crowded immobile queue) [10], [16]. The latter can be considered as the maximum capacity of a unit space. For densities within the range $[0.3, 2]$, the speed decreases almost linearly. The empirical relationship between density and flow speed is described by the 'fundamental diagram' [12], [10]. Figure 1 shows some of the curves obtained through observations in different conditions, considering a uni-directional motion. In this paper, the characteristic curve presented by Weidmann is considered for motion in corridors and rooms. It can be expressed by the following formula obtained by fitting data [11]:

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

where $v(\rho)$ is the average impeded walking speed as a function of density ρ, v_0 is the average free walking speed, $\gamma = 1.913$ is a fit parameter and ρ_{max} is the maximum allowed density (i.e. 5 P/m^2).

Similar considerations hold for motion on stairways. People walking on stairways exhibit normally distributed free horizontal speeds (i.e. the horizontal component of the speed vector), with an average speed that depends on stair geometry (angle and riser height), apart the previously mentioned parameters; moreover, differences exist between short and long stairways ([10], [13] and references therein). In particular, sometimes speeds going up can be larger than speeds going down in short starways (people accelerating when walking going up), while in long starways the contrary always occurs. With reference to the case-study, we assume that long starways are traveled in the down-up directions, while short starways can be traveled in both directions. A 0.423 average speed for long starways, 0.780 and 0.830 upstairs and downstairs average speeds for short stairways are used [13]. Then, impeded walking speeds on stairways are calculated by using eq. (1). An increase of ρ_{max} is allowed on stairs because people oscillate sideways when moving up.

In [14], it is shown that interaction among individuals increases with traffic density, more evidently near bottlenecks, where physical interaction generates inter-personal friction forces. This phenomenon is more significant when individuals wish to move faster than current speed, which is a typical behavior in panic situations. In particular, arch-like blockings can be found at doors, if desired walking speed overcomes a critical value equal to the free walking speed [14], [15]. These blockings produce inefficient outflow and delays, and the consequent increase of desired speed reduces the egress speed. This 'faster-is-slower' effect determines two different outflow regimes depending on desired speed v_d. The first one implies that the faster individuals want to move, the faster they evacuate, so that the outflow depends almost linearly on v_d. The second one implies a nonlinear decrease of evacuation efficiency with v_d due to interaction forces.

B. Modelling the Egress Dynamics as a Queueing Network

Two different queue modules are used: the first is for rooms, corridors, and stairways, the second is for doors, exits, entrances, and gateways.

As in [16], simple queues represent corridors. The same representation is applied to rooms and stairways, by properly considering the differences in the crowd behavior. Each queue is composed of a queueing space of null capacity, and a number of servers equal to the capacity C of the associated area. Given the maximum capacity of a unit space equal to 5, the capacity of the area of length L and width W is $C = 5 \cdot W \cdot L$. Then, the queue fills up if the number of individuals occupying servers matches the area capacity. The service time depends on the speed of individuals, which is determined by eq. (1). In more details, we assume that the service time is normally distributed, with a mean value $1/\mu(\rho) = L/v(\rho)$, being μ the average service rate. It is worth to note that different service times can be obtained for rooms, stairways, and corridors by considering the relevant free walking speeds, which affect the shape of curves in Figure 1. Finally, the arrivals process follows an exponential distribution. Under these assumptions, the resulting queue is a state dependent M/G/C/C queue, as the number of individuals in the area affects the service rate, resulting in a general distribution of service times.

To represent bottlenecks (i.e. doors, exits, entrances, and gateways), a queue with a queueing space of null capacity and a number of servers equal to its capacity is used. In this case, a capacity of $W\ P/m$ is assumed. If some individuals completely occupy the passage for the time needed to cross it, the preceding queue associated to a room, corridor, or stairway is blocked. To consider the faster-is-slower effect in the service rate computation, the expected value of flow rate q, given the desired flow rate q_d, is obtained by means of the relationship proposed in [17]:

$$E[q \mid q_d] = \begin{cases} q_d & if \quad q_d \leq q_c \\ 1 - e^{\frac{\alpha}{q_d - q_c}} & if \quad q_d > q_c \end{cases} \tag{2}$$

where α is a negative constant and q_c is the flow capacity of path, i.e. the maximum number individuals who can pass per time unit. To compute $E[q \mid q_d]$, we assume that q_d is related to v_d and exit width W through the equation $q_d(t) = W \cdot v_d(t)$, where desired speed increases according to [14]:

$$v_d(t) = [1 - p(t)]\, v_d(0) + p(t) v_d^{max}, \tag{3}$$

being $v_d(0)$ the initial desired speed and v_d^{max} the maximum desired speed. The function $p(t)$ is a measure of crowd impatience given by [14]:

$$p(t) = 1 - \frac{\overline{v}(t)}{v_d(0)}, \tag{4}$$

where $\overline{v}(t)$ is the average speed in the desired direction of motion. We assume that the queue service time is normally distributed with a mean value given by eq. (2). More precisely, firstly q_d is computed and compared to q_c, then $E[q \mid q_d]$ generates q by means of a probability function.

IV. COMPUTATIONAL EXPERIMENTS

A. The Case-Study

As a case-study, we consider the area of large lecture rooms at Technical University of Bari, consisting of 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 2).

The Hall is 294 m^2 large, with a maximum capacity of 270 persons. Three rooms (A, C, D in Figure 2) are 294 m^2 large, with a maximum capacity of 270 persons. Two smaller rooms (B, E in Figure 2) are 207 m^2 large, with a maximum capacity of 180 persons. Sitting desks in the Great Hall and in large lecture rooms are vertically distributed from a lower to an upper level, an internal corridor separates desks in two columns and two external corridors are available. Small rooms have one column of desks and two external corridors.

All rooms have entrance/exit doors on the two different levels: lower points are usually used by academic staff, upper points by students. All rooms have one single access/exit point at the lower level (1.6 *m* wide, maximum flow of 2 persons at a time) and two access/exit doors at the upper level (2.3 *m* wide, maximum flow of 2 persons at a time). The lower level doors link rooms to the main corridor, which is 235 m^2 large. Each room communicates with its adjacent

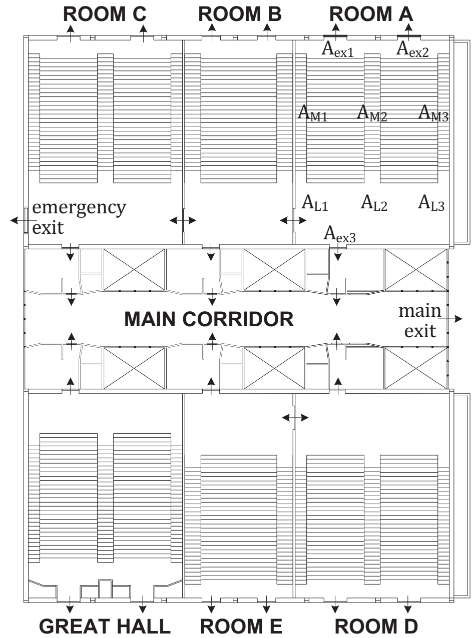


Fig. 2. The case-study

room(s), except for the Great Hall, which is not connected with any other room: the three communication doors are 2.3 *m* wide. One lecture room has also a further emergency exit located in the left part of the lower level (see Figure 2).

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 exit doors at the lower level, the corridor and then its exit. People staying in room C can use the added emergency exit, which is an opportunity also for people in the Great Hall, in special cases (e.g. when the exits from the Great hall are blocked or unavailable).

Each lecture room is divided into 3 main areas, representing the lecturer (lower), the desks (middle), and the exit (upper) areas, respectively. Then, 3 queues are associated to the first area, 2-3 queues to the second one, depending on the number of staircases, 3 to the last one.

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 to represent more chaotic behaviors.

As an example, Figure 3 shows the resulting sub-network model of room A, not connected to other rooms.

In particular, queues A_{L1}, A_{L2}, and A_{L3} are associated to the lower area, while left, central, and right staircases are represented by queues A_{M1}, A_{M2}, and A_{M3}. A_U represents the landing area close to exits, while A_{ex1} and A_{ex2} model the queues at exits. It is assumed that individuals arriving to the upper landing area can choose to evacuate through A_{ex1} (A_{ex2})

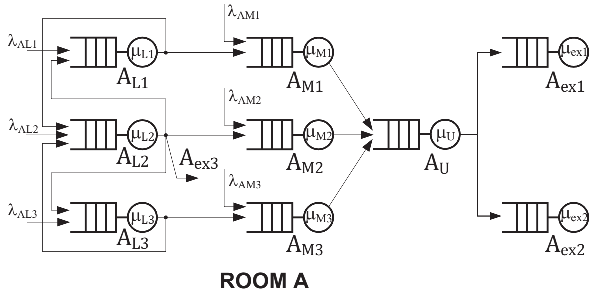
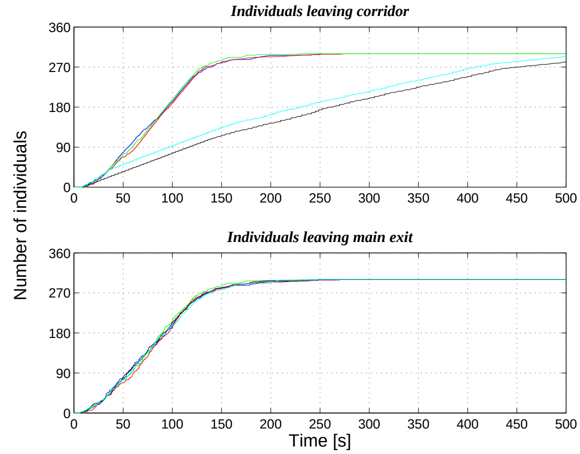
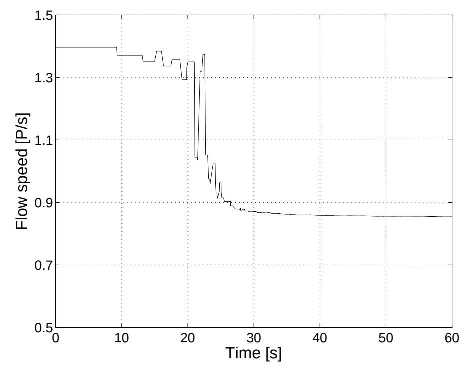


Fig. 3. Queuing network representing lecture room A



(a)



(b)

Fig. 4. Simulation of the main corridor-main exit system: (a) cumulative number of individuals crossing the corridor and main exit, respectively; (b) actual flow speed through main exit.

with a probability depending on the crowding conditions at each door. Also, flows on staircases are considered unidirectional, while individuals in the lower area can decide to move to staircases or to adjacent lower areas with probabilities affected by overcrowding and familiarity. In fact, during normal evacuation conditions, students tend to use upper exits for leaving, almost ignoring lower exits reserved to instructors, because no panic is assumed. Individuals entering staircases from desks are associated to external arrivals exponentially distributed.

The network modeling the whole system is composed of sub-networks similar to the one described above, suitably connected according to doors and corridor displacements.

B. Simulation Results

Three set of tests were performed to assess the model validity, considering the corridor, a single lecture room, and the whole lecture rooms system, respectively.

Firstly, the main corridor connected to the external exit is considered (Figure 4). It is modeled by two different queues connected in series: the first represents the corridor and is characterized by a null queueing space and a number of servers n equal to its capacity, i.e. $n = 5 \cdot 235 = 1175$; the second models the main exit and consists of a null queueing space and 3 servers, i.e. equal to the number of individuals that can pass thorough the door at the same time. We assume that 300 individuals leave the rooms to enter the corridor with a Poisson arrival rate. The service time depends on the total number of individuals in the corridor.

Figure 4(a) shows the cumulative number of individuals passing through the corridor and reaching the main exit, obtained for 5 different runs of the simulation model. In all cases the walking speed is almost constant during evacuation, as the corridor has enough space to accommodate all the arriving individuals. On the contrary, overcrowding of the main exit (Figure 4(a)) causes a sensible slowing down of the evacuation process due to the faster-is-slower effect, as shown by the two qualitatively different, i.e. slower, curves. As shown in Figure 4(b), an increase of the desired flow speed, which is related to the number of individuals waiting to evacuate, causes a reduction of the actual flow speed through the door. Note that the peak in the flow speed after 20 seconds is originated by particular random favorable conditions in exiting the door.

A second set of 5 simulations considers room A only, so that individuals can evacuate through the two upper exits or the lower one (Figure 5). The resulting network is depicted in Figure 3. 80 individuals are initially uniformly distributed in room A. Conversely, the lower and upper areas, and the corridor are initially empty. Each simulation starts at the end of the lecture session, so that all the individuals try to exit the room simultaneously.

Figure 5(a) shows that people starts to leave staircases after a delay of about 10 seconds, 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 and no queues obstruct the flow (Figure 5(b)). Moreover, slopes of curves in Figure 5(a) reduce with overcrowding of queues on the upper area (Figure 5(c)), which keeps individuals to proceed on. It is worth to note that individuals reaching the landing area direct themselves almost uniformly towards A_{ex1} and A_{ex2}, as the choice is affected by the doors crowding condition. From time instant 60 s on, the queues of landing area and exits are nearly empty (no one occupies the queuing spaces), so that individuals arriving are promptly served without any additional delay. The overall evacuation takes 120-160 s on average.

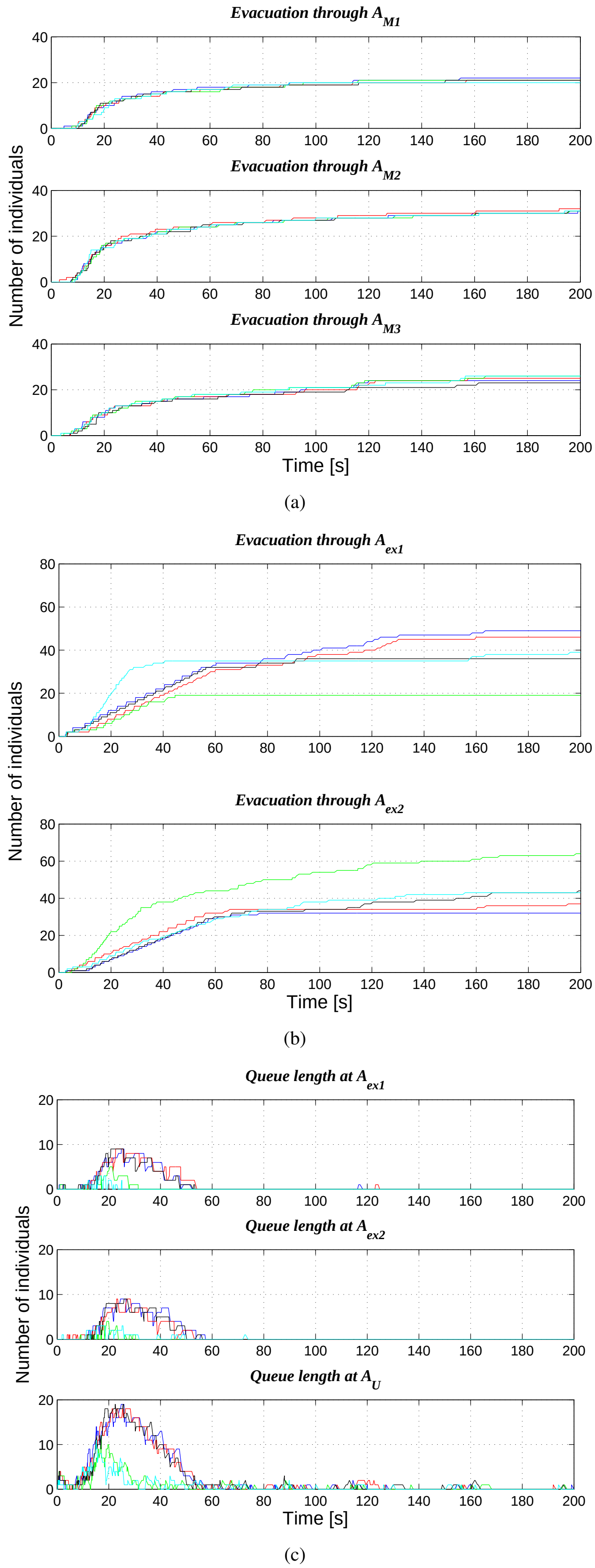


Fig. 5. Simulation of evacuation from room A: (a) cumulative number of individuals crossing left, central and right staircases; (b) cumulative number of individuals evacuating from A_{ex1} and A_{ex2}; (c) queues length at upper exits and landing area.

Results concerning the simulation of the whole system are omitted for the sake of brevity, but confirm the validity of the method, because the evacuation time recorded after simulation in standard conditions matches what is expected and overcrowding effects are observed.

V. CONCLUSIONS AND FUTURE WORKS

This paper introduced a queueing network representation of the egress procedures from a building. The systematic method is modular and can be extended to more complex buildings. Simulation tests validated the model with respect to observed evacuation processes in standard conditions. A further analysis is under development by comparing preliminary results with those obtained using commercial tools. Future improvements will introduce the influence of panic on the crowd behavior and will consider the design, implementation, and test of control strategies for managing emergency. Namely, the model and the simulation environment are suitable to adapt control strategies to different buildings, scenarios, and human behaviors.

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