AN APPROACH TO A SAFE EGRESS FROM PUBLIC SPACES DRIVEN BY RISK PRINCIPLES

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Abstract

The management of the crowd in public walking spaces, such as squares, stations, and commercial areas, has been a topical research theme. This is linked to the strategic need of addressing the uprising challenges on public safety, ensuring an effective crowd evacuation in emergency scenarios induced by various hazardous critical events, including malicious actions performed by individuals or groups. In designing and managing crowd places, there is the need to demonstrate appropriate levels of safety and security for people egressing, taking into account the pedestrian dynamics in and around the target place. The ultimate scope is avoiding undesirable side conditions, such as extreme crowding. Different engineering tools are available in this framework to support the analysis, planning, and management of pedestrian and evacuation movement. These tools can supplement current emergency protocols with valuable guidelines that can support emergency operators in finding the best strategy during a dynamic egress scenario. This work discusses an approach to safe egress from a public space based on concepts related to classes of risk scenarios. In detail, we simulate the egressing crowd dynamics and consider parameters that may affect the egress performance in open spaces. We show how the unavailability of escape routes, linked to obstacles or emergency needs, impacts the overall scenario in critical extreme crowding. Moreover, starting from punctual data retrieved by sensors (e.g., at the entrance of public space), we propose a method of assessing the risk level in the surrounding area. Based on a case study, we classify the resulting scenarios on a risk ranking that can be used as a support tool for emergency operations management.

Keywords: risk analysis, safety, evacuation, sensors, emergency scenario

Introduction

Evacuation modelling and models are powerful tools that can be adopted in the investigation of evacuation strategies under different scenarios [1]. Various evacuation models reviews, including those given by [2] and [3] show that such approaches are mostly developed and used for the assessment of buildings spaces, especially under fire scenarios. In fact, the study of human behavior and related models are aimed at translating into practice research outcomes to minimize the risk to people egressing from hazardous contexts.

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However, their flexibility makes it possible to adapt to other types of scenarios such as large-scale evacuation from open public spaces or evacuations in transportation contexts (e.g., railway stations, airports, …).

The role of simulation is crucial in reproducing complex egress scenarios, in light of analysing the system's performance in routine and extreme conditions. In this way, alternative and optimal strategies in a decision-making environment can be identified, including the evaluation of the performance of egress routes and the overall dynamics. In this framework, different decision-making stages originate from the initiating event. Among these, a crucial role is given by risk identification and assessment, that is at the basis of an appropriate response to any critical scenario [4]. A coupled successful warning message is critical to provide a safe, effective, and appropriate action across the decision-making stages. The message should have some qualities including, specificity about the threat involved, repetitiveness, consistency, and credibility. Therefore, an effective way to effectively tackle large egress operations in open public spaces is to implement proper methodologies for dynamically assessing the risk level in the target area, before and during egress operations [5]. A proper risk assessment is crucial in any critical scenarios to ensure an adequate resilient answer [6-7].

Risk assessment can be performed via sensors (such as cameras or microphones), but such sensors can provide a punctual data, fixed in space. However, this data does not provide any information about the area surrounding the sensors, nor how the risk assessment can be calculated by combining the data coming from different sensors. To overcome this issue, Radial Basis Functions (RBFs), introduced in [8], have been developed during the years [9].

RBFs are very flexible and useful techniques which can calculate data starting from scattered nodes [10] and have been used in many fields, such as surface modeling [11-12], image restoration [13], and rehabilitation robotics [14]. Its ease of implementation makes it appealing not only under a research point of view, but also for industrial environments. In fact, RFBs can even be used to detect obstacles or humans in collaborative applications [15].

In this paper, starting from the egress simulations, RFBs are used to capture data from sensors in a real environment and perform a risk evaluation in the area adjacent to the sensors. In this way it is possible to capture different risk sources from different sources (e.g., calculate the number of people in a plaza by counting the number of people that enters from different routes) and calculate an ideal risk evaluation on the entire are (i.e., the plaza).

Methodology

This section introduces the methodology implemented for risk assessment of egress from public spaces.

The methodology consists of three main steps and starts with the simulation of an egress scenario from the public domain previously mapped (Figure 1). This work used Thunderhead Pathfinder® as the simulation engine to model the occupant movement to exits from the public space. More in detail, Pathfinder® provided support for importing the public space geometry, which is the preliminary step to set the simulation according to the proposed methodology. The imported geometry represented the walking space for the evacuation model. Relevant information includes the following:

- Extension of the public space
- Number, size, and availability of egress routes
- Presence of obstacles along the egress routes

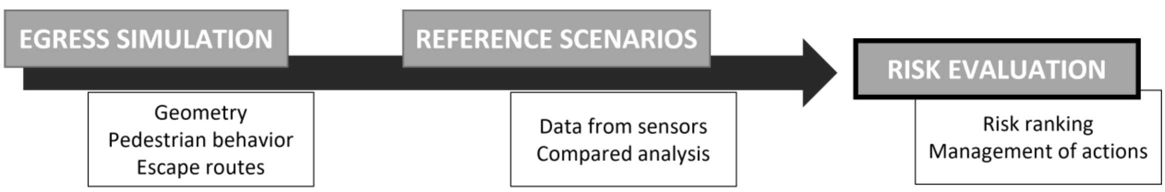


Figure 1: Approach to risk evaluation in egress scenarios from public spaces.

The simulation of egress included the modelling of occupants' movement to available exits in which each agent uses a combination of parameters dynamically to select the path to an exit. In other words, each occupant responds dynamically to changing queues during simulations without necessarily considering the closest exit or avoiding long queues. The approach included options where an occupant's movement conflicts with another due to geometry limitations or approaching an egress route. The analysis considered a flow-limiting condition while moving through a constrained egress route, and the contraction at a wide exit (i.e., the egress route) was analysed.

We selected the occupant features according to the specific simulated scenarios; in this way, we allocated age profiles according to a statistic distribution for a general scenario. The resulting effective egress velocity resulted from a maximum velocity (also depending on the age profile) and the occupant density in the public space. Selected maximum velocities are given in Table 1. The critical density of occupants in the open space (3 p/m^2) was considered among relevant indicators for a risky scenario, while an optimal density for egress operations was set at 1.9 p/m^2.

Table 1: Maximum speed for different age profiles of occupants.

Age profile	16-25	26-40	41-65	66-90
Maximum velocity [m/s]	2.22-2.87	2.25-2.6	1.92-2.25	1.92-2.25

We used the egress simulations to identify a limited number of reference scenarios on a specified geometry, classified according to an increasing criticality level. We ranked the criticality of a given scenario according to the following parameters:

- number of people that need to evacuate,
- egress performance, including the time required for a safe egress operation, and the occurrence of situations of critical congestion
- availability of egress routes.

In our approach, the reference scenarios can be compared to real-time or almost real-time data coming from sensors like people counters mounted in the target area. The recorded total number of occupants moving within the target area before an initiating event that requires egress can be used to rank the related scenario.

The impact of the availability of egress routes was analysed in arranging the reference scenarios. As a base case scenario, all egress routes departing from the public space were considered available, letting people use them to evacuate without limitations except for hydraulic constraints. However, the present work was also focused on the rational analysis of the impact of egress routes unavailability. The unavailability can be connected to physical obstacles but also specific management strategies in an emergency. Selected egress routes can be designed as priority passages for rescue teams, especially in complex layouts, but this requires a detailed design. This work deals with the design of such scenarios, supported by numerical simulations.

The following parameters are linked to the complexity of a layout in terms of the availability of egress routes:

- overcrowding, with the maximum, allowed number of people in daily scenarios or during planned events, or the number of people instantaneously insisting on the public space served by the available egress routes
- availability of egress routes, this parameter depends on the actual number of egress routes and their width, but also on their position
- smart lighting, if available to support egress operations
- emergency plan.

In planned events, the number of people also includes the staff working at the event. The instantaneous number of people in a public space can also be quantified with people counters.

The availability of egress routes, as indicated, is also determined by geometric parameters. Ideally, an egress route should have a constant width to avoid localized overcrowding, but this feature requires assessment when dealing with real scenarios in open public spaces. It should also be noted that people involved in critical scenarios are characterized by different degrees of familiarity with egress routes and the general condition. It is the same situation in transit areas, including railway and subway stations and airports. These aspects modify the exit choice in an emergency evacuation because of the influence given by exit familiarity and neighbour behaviour on the egress dynamics.

Smart lighting can affect the egress dynamics, especially the effectiveness of egress operations. The present work does not cover this topic. However, proper smart lighting can steer the flow of people toward the desirable exits while lowering the burden on selected escape routes used for emergency access.

Egress modelling

The egress scenario was modelled with Thunderhead Pathfinder® v. 2021.3 on a realistic map imported as a DWG file. According to the considered scenario, the total number of people was set from 1000 to 5000. The maximum velocity was set according to Table 1 and the statistical age distribution.

The egress dynamics were based on the action that causes an agent to take the fastest perceived route to a set of exits without any assistance.

We tracked the following parameters during the simulation:

- the density of people expressed in p/m^2,
- speed of each person and average information in m/s,
- time to exit in min,
- level of service,
- time profile of the number of people egressed.

Risk analysis

To assess the risk analysis in an area, it is necessary to combine the data coming from various sensors. In this sense, RFBs are very promising due to their simplicity in modelling nonlinear relationships using a linear combination of the weights of the variables. In fact, given a 2D space (e.g., the map of a square), the RFBs is defined as the combination of multiple subfunctions as follows [9,11]:

$$f(x,y) = \sum_{i=0}^{n} w_i \phi(\|\mathbf{P} - \mathbf{C}_i\|) \quad (1)$$

Where n is the number of subfunctions, w_i is the weight of the i-th subfunction an $\phi(\|\mathbf{P} - \mathbf{C}_i\|)$ is the basis, or the basic form of the subfunction, with $\mathbf{P}$ the point on the 2D space (with coordinates x and y) and $\mathbf{C}_i$ the center of the basis.

Virtually, any function can be used as the basis. In our work, the basis is described by a Gaussian function as follows:

$$\phi(\|\mathbf{P} - \mathbf{C}_i\|) = e^{-\frac{\|\mathbf{P} - \mathbf{C}_i\|}{2\sigma^2}} \quad (2)$$

Following Equation 1, $\mathbf{C}_i$ are the coordinates of the center of the i-th Gaussian function and σ is the standard deviation.

In a real case scenario, $\mathbf{C}_i$ are the coordinates of the sensors (e.g., cameras, microphones, people counter), σ is a tuning variable (that identifies how the Gaussian function “spreads” in the adjacent space) and the weights w_i are retrieved from the sensors data and the egress simulations.

Indeed, sensors can identify how many people are in a specific area, and from the egress simulation, it is possible to identify where the risk is higher. Moreover, if the people mostly use a specific route to enter or exit a certain area, it is possible to use different people distributions to assess different risk degrees. In other words, if a specific sensor counts an unusual number of people passing through a specific route, the risk on that route increases due to a higher concentration of people in the surrounding area.

Case study, results and discussion

The egress simulation is applied to the open public space reported in Figure 2. It consists of a public square with the size 98 x 53 m at the widest. Under normal circumstances, six egress routes are fully available, represented by public streets opened to pedestrians and vehicles.

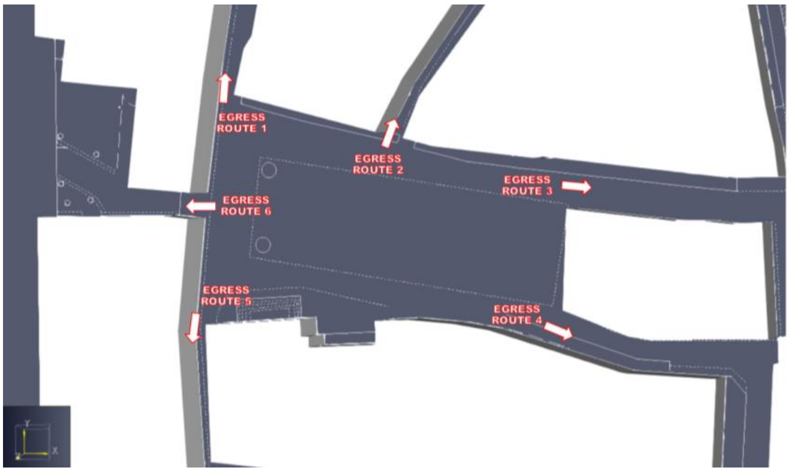


Figure 2: Open public space geometry and normally available egress routes (six).

According to the proposed methodology, the egress of 1000 people under normal circumstances is modelled, as an example. Egress parameters are derived accordingly, and this refers to the base case scenario. Different frames of an egress simulation are reported in Figure 3.

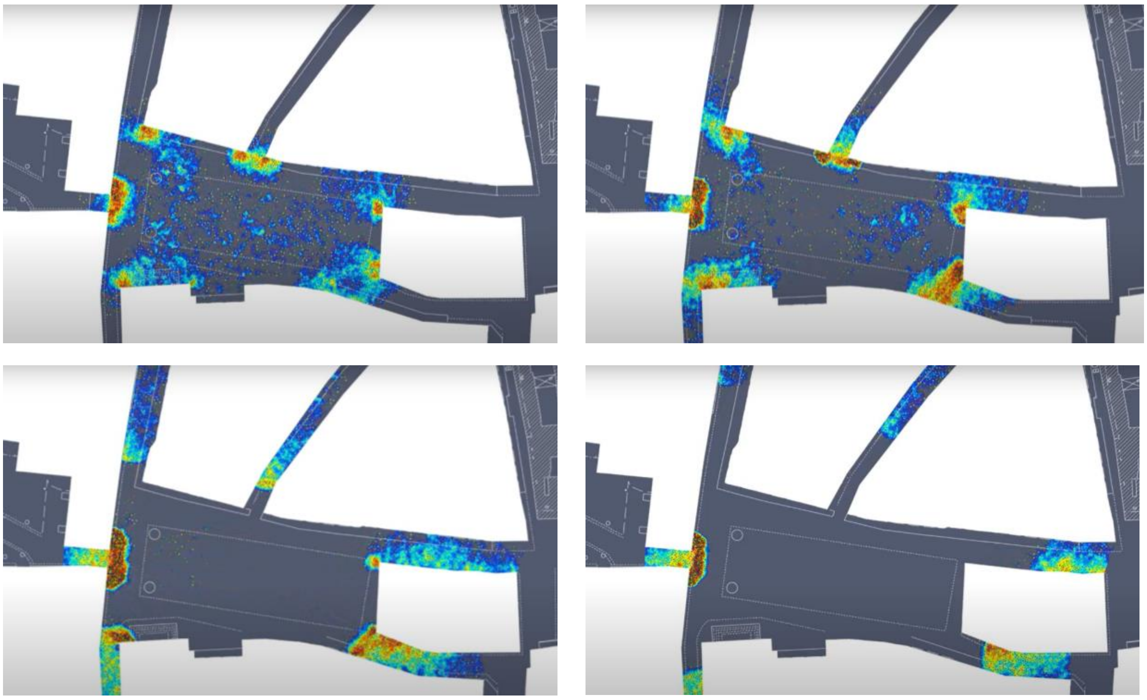


Figure 3: Different time frames of people evacuating from the open public space considered. In this simulation, the operations consider all egress routes available.

Relevant results correlated to the base-case scenario are reported in the first row of Table 2. We report the average and maximum simulated time to egress and the respective distance to be covered for egress purposes. According to the results, in ordinary scenarios with all egress routes available, the most used egress is n. 4 (Figure 3). A minor number of people egresses through gate n. 1.

Table 2: Results of the base-case egress scenario of Figure 3.

	Average / maximum egress time [s]	Average / maximum distance [m]	Prevalent egress route used	Available egress routes
Base-case scenario	28 / 38	61 / 96	Egress route 4	All
Scenario with limitations on egress routes	37 / 58	90 / 136	Egress route 4	Egress routes 2-3-4

In the same Table, we compare the base-case scenario with a different context characterized by the unavailability of egress routes identified as n. 1, 5, and 6 (Figure 2).

The unavailability of selected egress routes has different impacts, including:

- A variation in the instantaneous number of people present in the area during egress operations (Figure 4), therefore increasing the total egress time (Table 2);
- A severe effect on the flow rate of people that egress through available gates (Figure 5). In the present case, egress routes n. 2 and 4 see a relevant increase in the people flow rate because they accommodate a large part of occupants located nearby the hindered egress routes (n. 1, 5 and 6). According to the simulated scenario, egress route n. 3 does not experience substantial variations in this parameter. This means that people egress preferably from the gates identified as 2 and 4, leading to critical overcrowding. In any case, people tend to use the egress route n. 4 to leave the public space considered.

From an operational perspective, in the base case scenario, overcrowding is observed nearby egress route n. 6 (Figure 3), which is also the most vulnerable during the egress dynamics. According to the simulation, people prefer the egress route n. 6, although the level of service (Fruin and Strakosch, 1987) related to queuing experiences a progressive reduction from A to D.

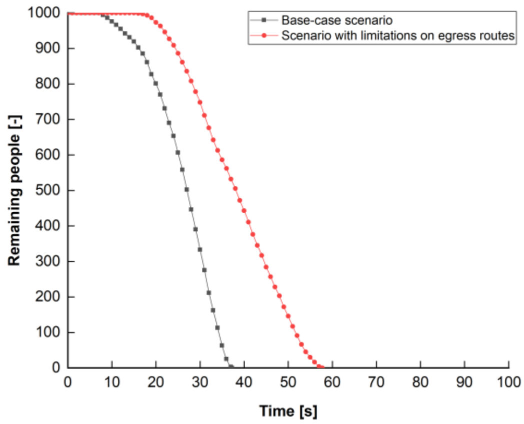
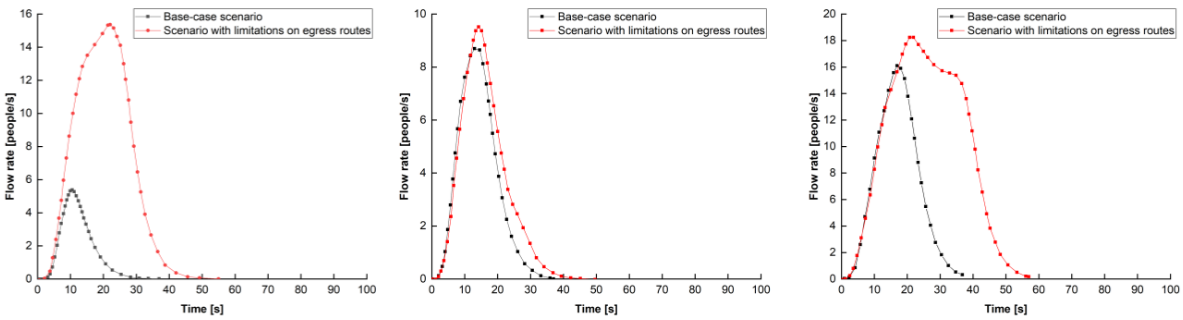


Figure 4: Time trend of the open public space occupants during the base-case scenario (full availability of egress routes) and limited egress routes (gates 1, 5 and 6 not available).



(a) (b) (c)

Figure 5: Flow rate of people egressing across selected egress gates: (a) egress route n. 2; (b) egress route n. 3; (c) egress route n. 4. Comparison between the base case scenario (full availability of egress routes) and limited egress routes (gates 1, 5 and 6 not available).

Table 3: Simulation parameters

Parameter	Base-case scenario (full availability of egress routes)	Scenario with limitations on egress routes
σ	1	1
n	6	3

From the egress simulations, it is possible to calculate the RFBs. Figures 6, 7 and 8 show the results. Since the egress simulations provide a time-dependent movement of people, so are the RFBs. For example, in Figure 6 a simulation with 1000 people in an area is shown (parameters in Table 3). At first, all the participants are located within the area, so the maximum risk index can be located at the centre of the area (Figure 6, to the left). Then, the people flow through the exits, so a high concentration of people can be found at these exits (Figure 2, to the right). RFBs weights w_i are calculated as the number of people moving through an exit or still within the area.

Due to their intrinsic nature, RFBs can be used to "spread" the risk around the centre of the Gaussian functions. In this way, even if sensors are placed in a specific position to retrieve real-time data, at a glance, it is possible to identify the area surrounding the sensor with a higher risk and deploy the resources strategically.

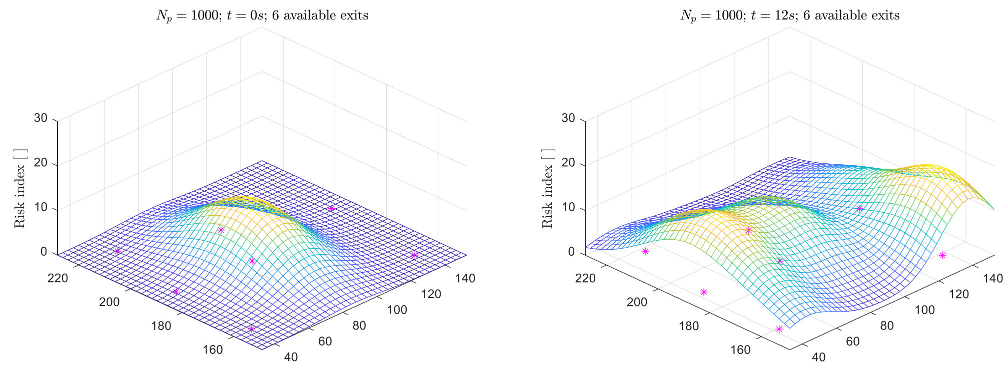


Figure 6: RFBs of the studied area with 1000 people at different timestamps ($t = 0s$ to the left, $t = 12s$ to the right). The simulation gives RFBs heights based on the number of people crossing an exit (outer points) or remaining in the area (central point).

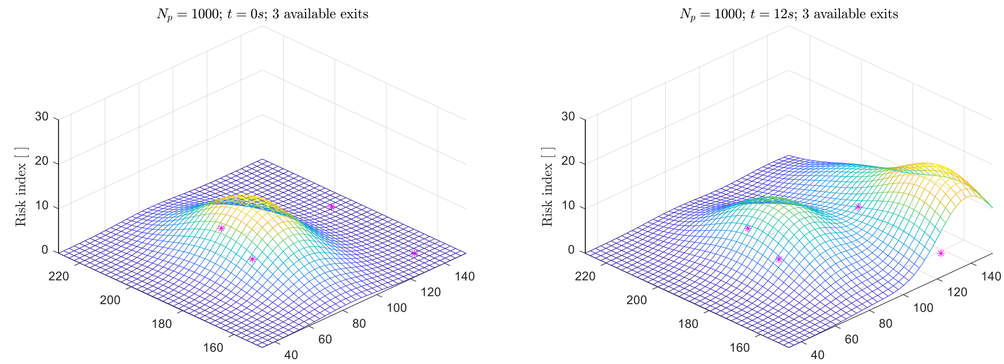


Figure 7: RFBs of the studied area with 1000 people at different timestamps and only 3 available exits ($t = 0s$ to the left, $t = 12s$ to the right). The simulation gives RFBs heights based on the number of people crossing an exit (outer points) or remaining in the area (central point).

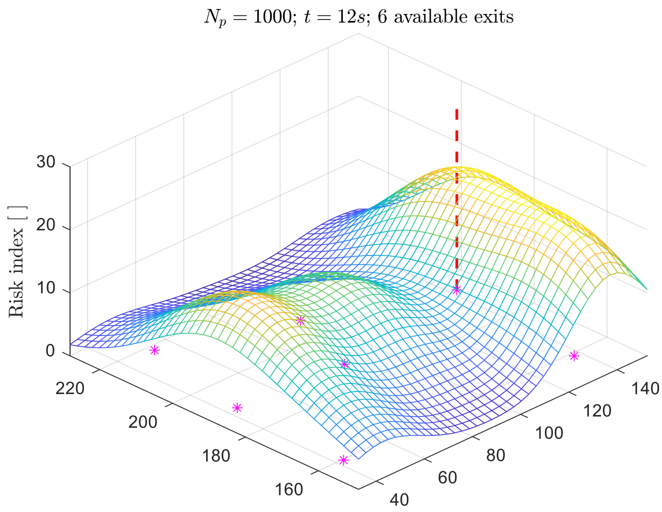


Figure 8: RFBs as of Figure 2 ($N_p = 1000;\ t = 12s$) with an anomaly at one exit (red line) that increases the risk value locally.

Moreover, with RFBs, it is possible to identify all areas that are of no risk. In Figure 7, the same simulation of Figure 6 is run, but with only 3 exits of 6 available for the egress. It is clear how a part of the area (the one where the exits are closed) is now of no risk ($w_i = 0$) since there are no possibilities for the people to group in that area.

Finally, RFBs can also be used to detect anomalies: in fact, if a sensor measures a discrepancy between the simulation and the real-time data, a higher risk value w_i can be given at the sensor location, increasing the risk value around that area (Figure 8). This can be due to uneven people distribution, which may lead to different egress behaviour.

Conclusion

The present work has proposed a structured and dynamic risk-based approach to evaluate the performance of an egress scenario from an open public space. Given some basic information related to the open space features, the number of people involved, and features of the egress routes, a base-case scenario has been identified. The impact of the unavailability of selected egress routes has been measured and linked to relevant parameters that sensors at specific locations would record, also in light of early warning.

The proposed method has shown how the risk assessment can be performed on the area adjacent to the sensors. In particular, this approach can be used to identify the area of the public space a in which the risk is higher, and, as a result, where the resources should focus on preventing any violent action. Moreover, RFBs can be linked to egress simulations to highlight whenever the real scenario differs from the simulation by looking at anomalous flows through egress routes.

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