Simplified flood evacuation simulation in outdoor built environments. Preliminary comparison between setup-based generic software and custom simulator

(Article begins on next page)

Enrico Quagliarini, Gabriele Bernardini, Guido Romano, Marco D'Orazio,
Simplified flood evacuation simulation in outdoor built environments. Preliminary comparison between setup-based generic software and custom simulator,
Sustainable Cities and Society, 2022, 103848, ISSN 2210-6707, https://doi.org/10.1016/j.scs.2022.103848.
(https://www.sciencedirect.com/science/article/pii/S2210670722001755)

Highlights.

- We investigate evacuation simulation in flooded outdoor built environments.
- We compare a generic and a custom simulation model based on a microscopic approach.
- We set a generic simulator up to reproduce flood-related behaviors.
- Simulators are applied to an idealized literature-based case study, including comparisons with real-world data.
- Results seem to encourage the proposed generic simulator setup.

Simplified flood evacuation simulation in outdoor built environments. Preliminary comparison between setup-based generic software and custom simulators

Enrico Quagliarini[1], Gabriele Bernardini[1,*], Guido Romano[1], Marco D'Orazio[1]

[1] DICEA Dept, Università Politecnica delle Marche, via di Brecce Bianche 60131 Ancona

[*]phone: +39 071 220 4246, mail: g.bernardini@univpm.it

Acknowledgments. The software license of the MassMotion simulation software was supplied to the researchers by Oaysis Ltd in the context of the Mutual Non-Disclosure Agreement "Simulating human behaviours during emergencies to improve the safety of buildings: testing and validation of the Massmotion simulation software".

Abstract. Floods are among the most destructive sudden disaster affecting worldwide communities and society. In such extremely dangerous circumstance, pedestrians can be forced to evacuate the affected areas thus exposing them to multiple risks. Therefore, outdoor built environment flood risks analyses should be performed through rapid, easy, and sustainable tools to speed up the risk assessment for safety measures. To this end, custom evacuation simulators have been developed, but are generally used in research activities, not user-friendly, and need high-level training. On the contrary, generic (e.g. commercial) software tools seem to be more suitable for low-trained technicians but should be modified to include human behaviors effects, especially considering the evacuation, when people's peculiar choices depend on interactions with floodwaters and built environment layout/composing elements. This work tries to evaluate simulation differences between a custom simulator and a generic one with a specific setup to include main peculiar behaviors (no-code modifications). The chosen simulators are based on the same microscopic approach, and applied to an idealized literature-based outdoor scenario. Simulation outcomes are compared together and with real-world data. Results show acceptable differences when applying the generic simulator with proper setup, thus moving towards a promising use also by low-trained technicians.

Keyword. Urban flood; flood evacuation; pedestrians' evacuation; behavioral model; social force model; evacuation simulation; urban built environment; risk assessment.

1. Introduction

According to the UNDRR, "a sudden-onset disaster is one triggered by a hazardous event that emerges quickly or unexpectedly"[1]. Between them, worldwide, floods are the most common and

[1] https://www.undrr.org/terminology/disaster (last access 29/10/2021)

devastating threats for our cities and society, affecting each year more individuals than any other disaster (European Commission, 2017; Gu, 2019; Young and Jorge Papini, 2020). Thus, detailed yet quick analyses and solutions are necessary to deal with such type of emergencies.

Previous works on flood risk assessment in outdoor spaces (Bernardini et al., 2017b; Fan et al., 2018; Jamrussri and Toda, 2018; Li et al., 2019; Matsuo et al., 2011; Najafi et al., 2021; Paquier et al., 2015; Piyumi et al., 2021) pointed out the necessity of simulation tools for: (1) risk assessment and mitigation strategies evaluation (e.g. rescuers' actions management, emergency planning, early warning systems); and (2) interventions on the architectural spaces and facilities (e.g. drainage and floodwater storage systems in BE, handrails and platforms to support people moving in the open spaces). These simulators should include the representation of the evacuation process in flood conditions, since the interactions between the pedestrians, the surrounding BE and the floodwater conditions highly affect casualties in such first disaster phases (Ashley and Ashley, 2008; Bernardini et al., 2017b; Dias et al., 2021; Samany et al., 2021; Shirvani et al., 2020; Takagi et al., 2016). Thus, the representation of the human factor in terms of presences (e.g. by also including spatiotemporal dynamic issues) and peculiar behaviors before and during the flood, assume a paramount role in preliminarily evaluations of the hosted community's reaction to the disaster and the effectiveness of emergency response actions (Bernardini et al., 2017b; Bodoque et al., 2016; Dai et al., 2020; Jamrussri and Toda, 2018; Jia et al., 2016; Kolen and van Gelder, 2018; Mignot et al., 2019).

According to previous works on pedestrians' risk and behaviors in flooding evacuation (Bernardini et al., 2017a; Ishigaki et al., 2008; Mignot et al., 2019; Milanesi et al., 2015; Xia et al., 2011), the most significant effects in the evacuation process are due to floodwater characterization (depth D_f [m] and speed v_f [m/s]). Firstly, it affects the evacuation speed v_i [m/s]. Equation 1 (Bernardini et al., 2017a) traces the minimum experimental-based evacuation speed for given D_f and v_f (g is the gravitational acceleration [m^2/s]) so as to adopt a conservative approach in the motion speed estimation, and so in the evacuation timing assessment. The higher D_f and v_f, the lower the evacuation speed v_i.

$$v_i = 0.52\left(\frac{D_f \cdot v_f^2}{g} + \frac{D_f^2}{2}\right)^{-0.11} \qquad (1)$$

Secondly, critical D_f and v_f induce human body instability, provoking pedestrians' evacuation stop and serious threats because of buoyancy phenomena or body failure (Cox and Shand, T.D.Blacka, 2010). General consolidated thresholds to these problems refer to $D_f*v_f \geq 1.2$ m^2/s or $v_f \geq 3.0$m/s, and, in case of still water, $D \geq 1.2$m, which provokes buoyancy.

Moreover, the perception of unmovable obstacles as safe elements for pedestrians walking through floodwaters in an urban BE can alter the pedestrians' trajectories because of attraction phenomena (Bernardini et al., 2017b). Indeed, pedestrians prefer moving towards and near walls and fences (preferred distance of about 1m to 2m, with an experimental considered limit of 3m) to gain support and handle on them while walking.

In view of the above, the analysis of emergency conditions through simulation software should involve the adoption of microscopic models rather than macroscopic approaches, since they are able to represent the specific individual-scale interactions in the evacuation process (Jebrane et al., 2019). Such a microscopic approach has been adopted by several flood evacuation simulators proposed according to different modelling methodologies (e.g. cellular automata, social force models) (Bernardini et al., 2017b; Li et al., 2019; Matsuo et al., 2011; Shirvani et al., 2020), thus developing custom models for researches purposes. They try to effectively represent the aforementioned peculiar pedestrians' behaviors in flooded BEs, and they have been tested in relevant conditions to manage comparisons with real-world data and move towards the models' verification and validation (Bernardini et al., 2017b; Li et al., 2019; Ronchi, 2020; Ronchi et al., 2013a).

However, such custom software is generally characterized by a high complexity level in terms of use, functionality, and interoperability that could slow down (or impede) crucial analyses for the risk assessment, especially considering applications to different real-world BEs performed by Local Authorities technicians, who can have a low training level on the matter. Generic evacuation simulation tools, on the contrary, represent a powerful solution from these perspectives, and they are widely implemented in more user-friendly software, especially considering commercial ones. They are oriented towards general-purpose evacuation simulation, or towards fire scenarios, and use behavioral and motion quantities from related databases (Bosina and Weidmann, 2017; Ronchi, 2020; Shi et al., 2009). Their general verification and validation process has been provided according to standard testing conditions (Ronchi et al., 2013a). Nevertheless, generic software needs adequate modifications to represent flood-related behaviors. To this end, adopting a specific software setup can ensure a quick and standard-based software application, thus avoiding complexity-increasing operations on the source code or the implementation of dedicated plug-ins and additional tools. Meanwhile, reliability analyses of such a setup-based generic model should be provided (Bernardini et al., 2017b; Li et al., 2019; Ronchi, 2020; Ronchi et al., 2013a). Comparisons with real-world data could be performed to this end. Simulation results of a setup-based generic model could be also compared to custom and flood-dedicated simulators. Although this kind of analysis cannot be always defined as a fair comparison, because of the peculiarities of the modelling logics, such comparisons can roughly and preliminarily evaluate possible differences and behavioral uncertainties in simulation outputs typical of the considered disaster (e.g. evacuation timing, trends of distances between pedestrians and unmovable obstacles) in different approaches.

This work tries to compare the simulation results of two different microscopic software based on the Social Force Model (SFM) approach (Helbing et al., 2000): a custom flood evacuation simulator (Flooding Pedestrians' Evacuation Dynamics Simulator-FlooPEDS), which has been developed and preliminarily validated according to experimental data for flood evacuation purposes (Bernardini et al., 2017b); and a generic (commercial) software which is generally used for indoor evacuation analysis (MassMotion Guide, 2020), and which setup has been modified in this work to quickly represent main man-floodwaters and man-built environment behaviors.

To this end, the work and the paper are organized by following the following structure. Section 2 firstly traces the criteria for generic software setup and comparisons with custom tools and real-world data according to four main phases. The first one provides the setup criteria to quickly replicate main human flood-affected evacuation behaviors in outdoor in a generic simulator (Section 2.1). Then, a scenario is selected according to previous works (Bernardini et al., 2017b) to apply the setup-based generic simulator and the custom one (Section 2.2). This scenario is quite simple since it is a linear and flat pathway, representing a common outdoor BE such as a street, and concerns stationary flood conditions where small compact groups of pedestrians are evacuating. Nevertheless, as in the aforementioned general aims of standard testing conditions for verification and validation of evacuation simulators, if the comparison is not effective in such a simple scenario, more sensible differences between the simulators will surely appear in more complex outdoor BE or conditions. Different setup solutions of the generic simulator are tested, thus allowing us to check the factors that can alter the expected simulation outcomes with respect to the custom simulator evacuation and the real-world data (Section 2.3). Simulation results of the two software are compared through the main significant outputs to be evaluated for the flood evacuation, and additional analyses concerning real-world data are provided for the setup-based generic simulator (Section 2.4). Results are organized comparing outputs of the generic and custom simulators (Sections 3.1 to 3.3), then the comparison is extended to real-world data (Section 3.4). Finally, the generic simulator fittest setup is selected and discussed (Section 3.5).

2. Methods

2.1. Software setup criteria to replicate human behaviors

The quick setup of a generic simulator is based on the following main assumption, according to the main behavioral drivers from the literature review in Section 1. For each modelling assumption, advantages and implementation issues concerning the comparison process and the full-scale application are also discussed.

Concerning v_i, stationary floodwater conditions are considered, that is assuming that D_f and v_f do not change over the simulation time. In this work, a unique area in terms of D_f and v_f is simulated, thus creating a unique v_i value in the setup process, according to Equation1. Differences between v_i can be assigned by most of the evacuation simulators in a rapid manner, as well as different typologies of pedestrians can be generally created to this end. Hence, the representation of pedestrians' speed uncertainties can be ensured using, for example, a v_i distribution. In this work, according to the reference work (Bernardini et al., 2017b), v_i in the range 0.85±0.05 m/s (Gaussian distribution) is assigned to describe low-medium floodwater levels, e.g. being $(D_f \cdot v_f^{\,2})/g+D_f^{\,2}/2$ ≈0.01m^3/m. In a full-scale application scenario, the motion space can be divided into different areas (as for floors in case of building evacuation simulators (MassMotion Guide, 2020)), each of them having a specific floodwater level, hence a maximum (e.g. capped) motion speed v_i. Ideally, v_i can be also varied over simulation time to describe dynamic conditions in floodwaters spreading.

Non-critical conditions for human body stability are assumed in this work. Indeed, it is considered that the motion-process should be carried out in any case before major threats due to floodwater-related pedestrians' stability can occur (Opper et al., 2010). Thus, all the pedestrians can arrive in a safe area in the simulated scenario, and tests can focus on the motion tasks.

Finally, concerning the attraction towards unmovable obstacles, preferred distances pedestrians-elements are imposed, since literature works noticed that pedestrians prefer to stay closer than about 3m in any case (Bernardini et al., 2017b). To this end, simulated pedestrians are assumed to move along linear paths alongside the building walls/fences.

These criteria are implemented into MassMotion 10.6[2]. This simulator uses the SFM approach to simulate the pedestrians' movement, thus being based on the same model approach of FlooPEDS. Appendix A resumes the overall details on the setup of the software, by including both the pedestrians' data and the scenario implementation. In particular, concerning the attraction towards unmovable obstacles, this work proposes a *server*-based configuration of the outdoor spaces alongside the buildings (MassMotion Guide, 2020).

[2] Tests (randomly selected within the list of the validation scenarios in Section 2) were additionally carried out with MassMotion 9.5.2.2 to compare results with the previous version and no differences were found.

2.2. Tested scenario

The setup-based version of MassMotion (developed according to Section 2.1) and FlooPEDS (Bernardini et al., 2017b) are applied to the same typological scenario for comparison purposes. According to the previous FlooPEDS tests, this scenario is composed of a linear pathway having a width of 17.6m and a length of about 87m, with a linear plano-altimetric profile and no internal crossroads[3]. Two continuous buildings are considered placed alongside the pathway, one on each pathway side. This configuration allows focusing on the pedestrians' elementary motion conditions, since constant floodwater conditions are imposed[4]. In this sense, it is representative of a street for a simple but critical layout in urban open spaces and it is also consistent with the IMO test 1 scheme (Ronchi et al., 2013b).

The following general rules are applied according to the original work about FlooPEDS tests (Bernardini et al., 2017b). Tests are carried out by considering compact groups of 10 pedestrians per side starting the evacuation at the same time, to point out the overlapped effects between the SFM attractions between the pedestrians themselves, and between the pedestrians and the buildings. The number of simulated pedestrians is provided by considering that the average number of exposed pedestrians (coming from buildings) per square meters of outdoor BE could refer to low-density conditions (LOS A, free circulation, lower than 0.08pp/m^2 (Fruin, 1971)). Such values are consistent with previous works input data on pedestrians' densities (Samany et al., 2021; Shirvani et al., 2020). Pedestrians are generated at the starting of the pathways, being initially placed at a maximum distance of about 3.5m from the building. They move towards the end of the pathway, where the evacuation test is considered to finish.

[3] These dimensions were selected in FloodPEDS tests to represent a typical real world urban built environment, i.e. composed by orthogonal urban fabric. More details are reported in (Bernardini et al., 2017b).
[4] There is no influence due to the floodwater direction and so effects of pedestrian-pedestrian and pedestrians-obstacles interactions can be better highlighted.

2.3. Generic simulator setup criteria

Three main objects compose the simulation environment of the setup-based generic simulator, besides the pedestrians[5] (see Appendix A). The *floors* are the surfaces on which the pedestrians perform their motion, that is the street. The *portals* represent both the entrances into the simulation and the pedestrians' destinations. The *servers* are useful to model queues and, more in general, to vehiculate the pedestrians' movements and behaviors. The combination of such objects' properties and positioning defines 36 different setup possibilities, which are resumed in Appendix B. In the following, each object configuration and the related reasons are discussed:

1. *Entrance portals shape*. Two configurations are tested to represent the moment from building exit by pedestrians who try to start the evacuation together, because of group behaviors:
    a. in the *rectangular* one, entrance *portals* have a dimension of 3x1m and are adjacent to the walls. The pedestrian density is about 3pp/m^2 in order to increase the interaction between them, starting the simulation closer to each other and lesser than 3.0m away from the unmovable obstacle;
    b. in the *squared* one, where entrance *portals* have a dimension of 3x3m and are placed 1m away from the walls. The pedestrian density is about 1pp/m^2 to replicate the custom simulator starting setup.
2. *Servers number, positioning, and properties*. Servers are placed along the pathway (in the following, "first servers") and at the end of the *floor*, that is near the exit *portals* (in the following "second servers") to simulate the attraction of the pedestrians towards the buildings. Considering the *floor*'s length, each pedestrian's journey is aimed at using: 1 entrance *portal* at the beginning of the *floor*, 1 "first server" placed along the *floor*, 1 "second server" at the end of the *floor*, and finally 1 exit *portal*. The reference work distinguishes three main classes of distance from unmovable obstacles: 0 to 1m, 1 to 2m, 2 to 3m (Bernardini et al., 2017b).

[5] In MassMotion, *agents*.

Therefore, three “first servers” per side of the *floor* are tested. An alternative configuration of only two “first servers” is also studied to increase the interaction between the pedestrians. In both cases, only one “second server” per side of the *floor* is tested in order to increase the attraction by the unmovable objects near the crossroads. These multiple setups are evaluated by placing servers in the middle (e.g. for the 0 to 1m class, 0.5m) or at the maximum value of each distance class (in the same example, 1m). Furthermore, the “first servers” position along the pathway is tested according to three configurations, according to a parametric approach. Tested positions are at *halfway*, at *a quarter*, and at *an eighth* of the pathway. These configurations allow investigating the impact of interferences between pedestrians at the passage points (i.e. servers), hence if behavioral uncertainties towards the unmovable obstacles exist. Finally, the probability that a pedestrian selects one of the “first servers” is assumed according to two configurations: *homogeneous*, if each element has the same probability; *by-literature*, according to the real-world data about the frequency for each class of distance from unmovable obstacles.

Figure 1 and Table 1 resume the tested setups. 36 different setups were organized by grouping them by the entrance *portals* shape (R for rectangular; S for squared) and the “first servers” position along the pathway (8 for position 1/8 of the path length; 4 for position 1/4 of the path length; 2 for position 1/2 of the path length), as shown in Figure 1. Furthermore, each group of setups is also characterized by the probability a pedestrian can choose a *server* (H: homogeneous; L: by-literature), and the *servers'* number and position in respect to the wall, as resumed in Table 1.

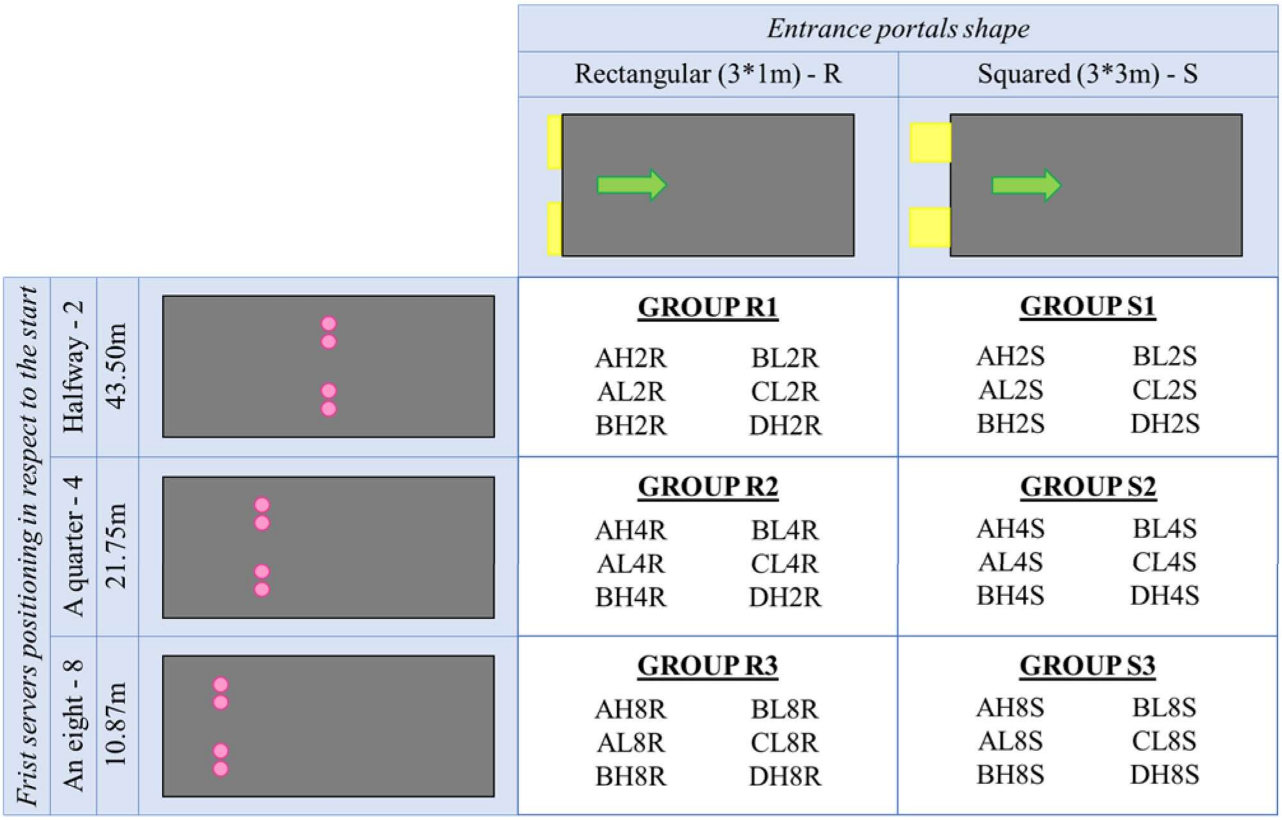

Figure 1: Setup groups organized depending on the entrance portals' shape (columns) and the "first servers" position along the pathway (rows). The setup code is composed of four characters: the number and position of the servers in respect to the wall (A-B-C-D) as in Table 1, the probability a pedestrian can choose a server (H-L), the server position with respect to the start (2-4-8), and the shape of the entrance portal (R-S).

Setup code	"First servers" features		"Second server" features	
	Number [-]	Distance from the wall [m]	Number [-]	Distance from the wall [m]
A	2	1; 2	1	1
B	2	0.5; 1.5	1	0.5
C	3	0.5; 1.5; 2.5	1	0.5
D	2	1; 2	1	0.5

Table 1: Setup code for the servers' position by considering their number and distance in respect of the side of the floor (i.e., the buildings wall).

2.4. Simulation outputs and comparison criteria

Simulations are repeated 10 times due to the probabilistic rules in motion simulation (Ronchi et al., 2013b).

The evacuation curve is expressed as the percentage of arrived pedestrians [%] over the simulation time [s]. The average evacuation curve coming from the is considered for each tested condition.

The distance D_w [m] between each pedestrian and the side of the building during the evacuation process is tracked over the pathway length, thus forming a curve describing how the criteria for unmovable obstacles attraction affect the pedestrians' trajectory along the path, depending on the input setup. To elaborate this curve, D_w trend data are organized according to a quartile-based analysis, by grouping data over 3m-long pathway steps, according to the distance threshold for repulsive phenomena in motion considered by FlooPEDS and based on previous works relating to the SFM (Lakoba et al., 2005).

According to previous works (D'Orazio et al., 2015; Ronchi et al., 2013b), the following Key Performance Indicators (KPIs) are used for comparison purposes about evacuation curves and D_w trends:

- the Secant Cosine *SC* [-], to measure the differences of shape between two curves, as their first derivative (for *SC* next to 1, the shapes of the curves can be considered similar);
- the Euclidean Relative Difference *ERD* [-], to measure the overall agreement between two curves, as the norm of the difference between two vectors (for *ERD* next to 0, the curves can be considered close);
- the Euclidean Projection Coefficient *EPC* [-], to measure the scale factor, which is the best possible fit between two curves (for EPC next to 1 the curves can be considered similar);
- the Difference between the graphic Areas Under the Curves *DAUC* [%], to investigate if underestimating/overestimating contingencies exist (positive values point out that predictions for the generic simulator are over those of the custom one).

Results are discussed through KPIs mean and standard deviation values for each of the 6 setup groups identified in Figure 1, while extended results for all the 36 setups are reported in Supplementary Materials S2.

In addition, D_w results from generic and custom simulators are compared between them and with the experimental percentage distributions by considering the three literature-based main classes (Bernardini et al., 2017b): lower than 1m; from 1m to 2m; higher than 2m. Percentages differences due to the modelling logics at both microscopic and macroscopic levels are assessed to be compared with acceptability thresholds concerning real-world data, which are up to about 10%-20% (Robin et al., 2009; Schadschneider et al., 2009; Shiwakoti et al., 2008). In particular, in case of D_w overestimation, results can be considered as conservatively acceptable because risks for pedestrians' motion in critical floodwater conditions are not underestimated (i.e. flow effects in the central part of an open channel (Chow, 1959)).

Finally, pedestrians' evacuation timing analyses are performed. The maximum evacuation time t_{max} [s] is calculated to describe the overall time during which the pedestrians remain in the outdoor BE. Similarly, the maximum waiting time t_w [s] (i.e., that is the time in which a pedestrian remains stationary at a *server*) is introduced to evaluate the impact of possible queuing phenomena simulated by the generic simulator at the *servers*. It has been normalized by the maximum evacuation time t_{max}, to identify the waiting time percentage W [%] over the entire simulation. W considers how the effect of group dynamics can force pedestrians to spend time in non-movement activities because of simulator logics in respect of the input setup. In fact, in MassMotion, *servers* attract people towards the buildings but could represent deadlocks. 5-to-95th percentiles evacuation flow F [pp/s] are also calculated to estimate the speediness of the evacuation process. In this sense, the 5th and 95th percentile are measured to reduce the impact of outliers as a consequence of particular simulation aspects in crowd motion (Ronchi et al., 2013a; Schadschneider et al., 2009), such as those related to starting positions less or more favorable, neighbors behaviors, deadlocks phenomena, etc. Quartile-based analyses of t_{max}, F, and W are performed by comparing the generic simulator setup depending on the *portals* shape to describe general uncertainties for the whole set of considered input setups. Only t_{max} and *F* are compared to FloodPEDS outcomes since the custom simulator does not consider deadlocks in the building attraction, while *W* outcomes are discussed independently to evaluate the impact of the queuing phenomena on the evacuation timing in the generic simulator.

3. Results

3.1. Evacuation curves comparison

Figure 2 shows the evacuation curves for the generic and custom simulators by considering the same entrance *portals* configuration, i.e., setup groups 1 to 3 are *rectangular*, 4 to 6 are *squared,* according to Figure 1. Table 2: KPIs measuring differences between evacuation curves obtained from each setup tested on the generic simulator and the one obtained from the custom simulator. Results are shown in terms of mean and standard deviation values according to the grouping criteria shown in Figure 1.
resumes their comparisons, in respect of the custom simulator results, according to the selected KPIs, according to the same setup conditions grouping. Average results per group are provided.

The results highlight that, when the "first servers" position is closer to the entrance *portals*, that is for setup groups R3 and S3, the generic simulator outputs seem to be more similar to those of the custom simulator. In fact, in these cases, *SC* increases and *ERD* decreases. As expected, *EPC* seems non to be affected by the setup, as it tends to 1 in all the cases. In general, the generic simulator seems to underestimate the safety conditions considering the first arrived pedestrian by about 30% (see, for instance, Figure 2). Anyway, the *DAUC* always assumes positive values regardless of the proposed setup, meaning that the generic simulator slightly overestimates the entire evacuation process speed, as values range from 1 to 24%.

Considering the specificities of the setup groups, R2, R3, and S3 are the only ones with $SC>0.8$ and $ERD<0.2,$ thus improving the similarities between the evacuation curves indeed. These groups are characterized by smaller distances between the entrance *portals* and the *servers*. Slight differences can be noticed considering the number and positioning of the *servers* in respect to the side of the pathway, as the standard deviation values of all the KPIs point out, ranging between 0.01-0.03. On the other hand, assigning the probability that a pedestrian selects one of the "first server" by-literature, seems to move towards better *SC*, *ERD,* and *DAUC* values, thus increasing the shape similarity (see extended results for each setup in Supplementary Materials S1).

Setup	***Values***	***SC***	***ERD***	***EPC***	***DAUC***
R1	**avg**	**0.777**	**0.170**	**1.038**	**13%**
	st. dev.	*0.031*	*0.025*	*0.016*	*2%*
R2	**Avg**	**0.849**	**0.102**	**1.008**	**7%**
	st. dev.	*0.035*	*0.024*	*0.011*	*2%*
R3	**avg**	**0.857**	**0.084**	**0.997**	**4%**
	st. dev.	*0.029*	*0.011*	*0.016*	*2%*
S1	**avg**	**0.710**	**0.260**	**1.073**	**22%**
	st. dev.	*0.021*	*0.016*	*0.009*	*2%*
S2	**avg**	**0.764**	**0.208**	**1.053**	**17%**
	st. dev.	*0.032*	*0.013*	*0.005*	*1%*
S3	**avg**	**0.822**	**0.157**	**1.035**	**12%**
	st. dev.	*0.028*	*0.021*	*0.013*	*2%*
OVERALL	**avg**	**0.796**	**0.164**	**1.034**	**13%**
	st. dev.	*0.060*	*0.063*	*0.028*	*6%*

Table 2: KPIs measuring differences between evacuation curves obtained from each setup tested on the generic simulator and the one obtained from the custom simulator. Results are shown in terms of mean and standard deviation values according to the grouping criteria shown in Figure 1.

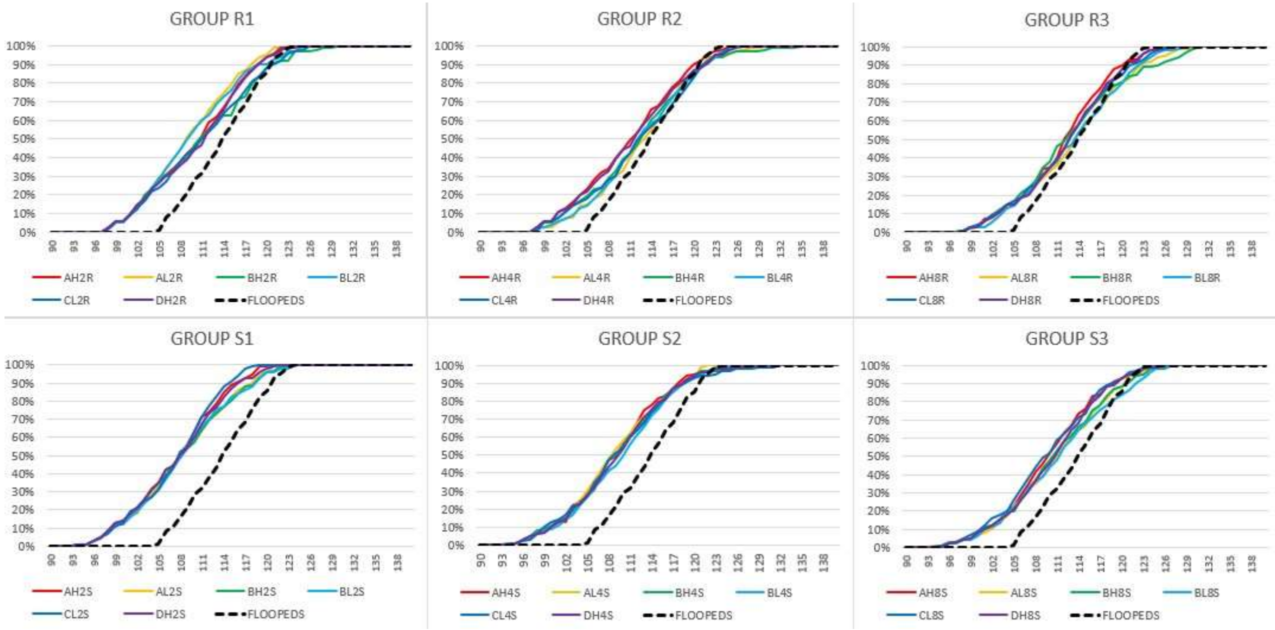

Figure 2: Custom simulator evacuation curve (black dashed lined) compared to those of the generic simulator grouped according to the criteria shown in Figure 1(straight lines).0-90s are omitted as no pedestrians complete the evacuation in this timespan.

3.2. Comparison between D_w trend along the pathway

Table 3 resumes the analysis of the D_w trend according to the KPIs and considering the median distribution on a 3m resolution along the pathway. Results are grouped according to Figure 1 criteria, while data for the 1st and 3rd quartile are available in Supplementary Materials S2. Average and standard deviation values per group are provided.

As for Section 3.1 results, setup groups characterized by smaller distances between the entrance *portals* and the *servers* seem to lead to more similar results in respect of the custom simulator, as shown by the median D_w trends in Figure 3. This result is mainly remarked by the *SC* values for groups R3, S2, and S3 ranging between 0.45-0.54, which is significantly higher if compared to other setup groups, thus implying that the *server* constraint should be placed closer to the start to effectively attract pedestrians near the unmovable obstacles (i.e., to reduce the curve subtended area). In this sense, such results seem to confirm those on the evacuation curve. However, the *SC* variability between the setups in the groups demonstrates some differences in D_w trends, as standard deviation values range from 0.07 to 0.12, while they are up to 0.20 considering the overall sample. Nevertheless, it is worth noticing that a limited correspondence between all the setups and the custom simulator outputs on D_w appears according to the other KPIs, as shown by Table 3 samples.

Setup	***Values***	***SC***	***ERD***	***EPC***	***DAUC***
R1	**avg**	**0.048**	**0.579**	**1.293**	**37%**
	st. dev.	*0.070*	*0.064*	*0.076*	*9%*
R2	**avg**	**0.316**	**0.448**	**1.203**	**27%**
	st. dev.	*0.073*	*0.062*	*0.082*	*10%*
R3	**avg**	**0.447**	**0.446**	**1.173**	**25%**
	st. dev.	*0.108*	*0.070*	*0.089*	*10%*
S1	**avg**	**0.170**	**0.510**	**1.278**	**34%**
	st. dev.	*0.096*	*0.060*	*0.067*	*8%*
S2	**avg**	**0.542**	**0.416**	**1.214**	**27%**
	st. dev.	*0.083*	*0.077*	*0.085*	*10%*
S3	**avg**	**0.506**	**0.409**	**1.166**	**23%**
	st. dev.	*0.121*	*0.074*	*0.093*	*11%*
OVERALL	**avg**	**0.338**	**0.468**	**1.221**	**29%**
	st. dev.	*0.203*	*0.090*	*0.096*	*11%*

Table 3: KPIs measuring differences between curves tracing the Dw trend for each setup tested on the generic simulator and the one obtained from the custom simulator (2nd quartile data). Results are shown in terms of mean and standard deviation values according to the grouping criteria shown in Figure 1. Extended results for each setup are in Supplementary Materials S3.

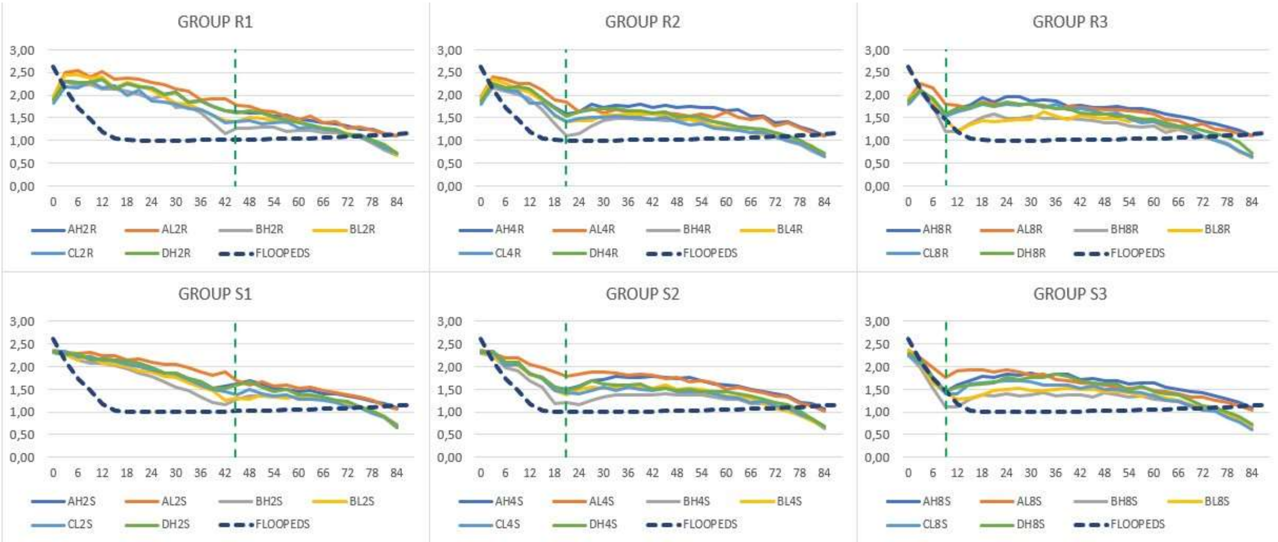

Figure 3: Custom simulator 2nd quartile D_w trend (blue dashed line) compared to those of the generic simulator grouped according to the criteria shown in Figure 1 (straight lines). The green dashed line indicates the position of the "first servers" along the pathway.

3.3. Quartile analysis of trends in pedestrians' evacuation timing

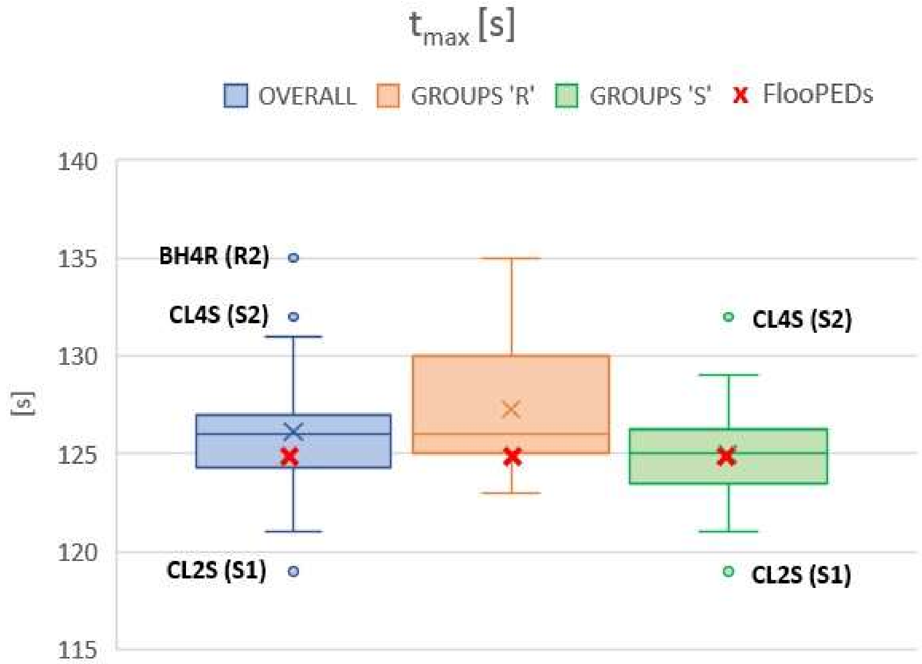

Figure 4: Comparison between the maximum evacuation time t_{max} of the custom simulator (red cross) and the generic simulator distinguishing overall (blue box) and groups data (orange and green boxes). Outlier setups are marked as follows: "Setup name (Group name)". Extended results for each setup are in Supplementary Materials S4.

Overall outcomes about the maximum evacuation time t_{max} (Figure 4) show similar results between the two simulators (1s difference between the custom simulator and the generic one mean value). Concerning the distinction by setup, the percentage differences range between -4% and 4% considering all the setup tested but the outliers (blue box). Differences between squared and rectangular portals seem to be negligible (<5%), even if groups 'R' (i.e., rectangular *entrance portals*) register slightly higher t_{max} values. This result seems to be affected by repulsion forces between pedestrians in those entrance areas, and their effects are increased by the high-density conditions (about 3 pp/m^2) in the rectangular portals. As a consequence, these conditions imply the pedestrians' trajectories are farther from the pathway sides while they are approaching the "first servers" (as shown in Figure 3).

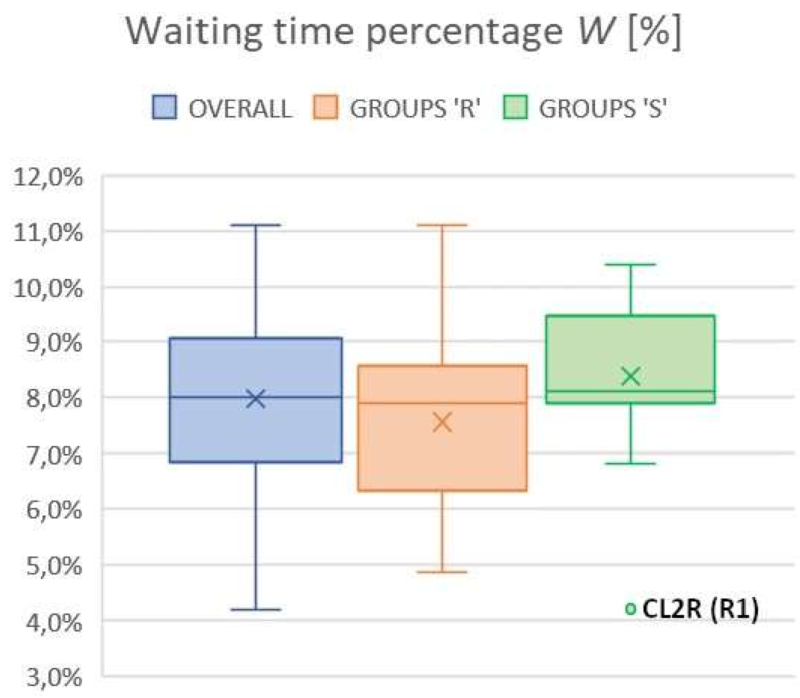

Figure 5: boxplot representation of the maximum waiting time percentage W, distinguishing overall (blue box) and groups data (orange and green boxes. Outlier setups are marked as follows: "Setup name (Group name)".

In general, a queue formation trend can be noticed because all pedestrians start at the same time and place, and they are "forced" to pass by the *server*. Some pedestrians could be forced to stop the evacuation for some time. Thus, regarding the maximum waiting time percentage *W*, the comparison between all the setups in Figure 5 shows how pedestrians behave similarly regardless of the shape of the *entrance portals* and the *servers'* features (i.e., their position and number), as differences between maximum and minimum values are only of about 7% (blue box). Anyway, absolute waiting times are in the range between 5-15s, which is reasonable for flood outdoor evacuations where circumstances like social attachment, group phenomena, and difficulties in motion and stability can force pedestrians to stop (Bernardini et al., 2019).

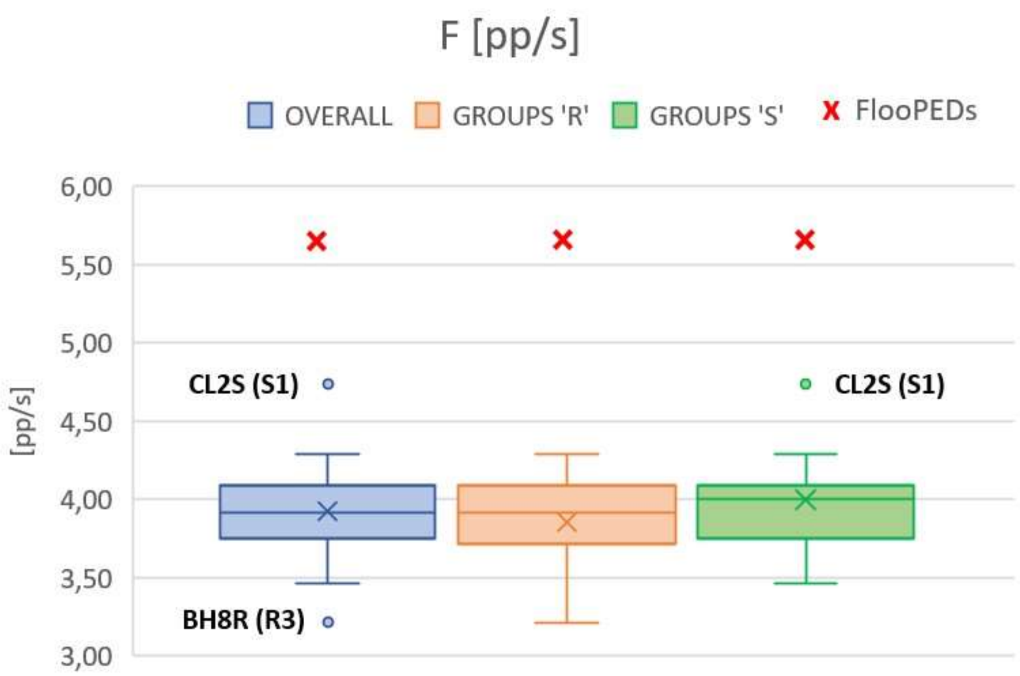

Figure 6: Comparison between the evacuation flow F values of the custom simulator (red cross) and of the generic simulator distinguishing overall (blue box) and groups data (orange and green boxes). Outlier setups are marked as follows: "Setup name (Group name)". Extended results for each setup are in Supplementary Materials S5.

Finally, Figure 6 shows how group phenomena seem to have a greater impact in the generic software than in the custom simulator, as the evacuation flows *F* are 30% smaller considering the mean values of the setup groups. Such phenomena could be linked to the aforementioned "forced" passage by the servers. On the other hand, no significant differences are due to the setup of the generic simulator (considering all the setups tested, the percentage differences are <5%, excluding the outliers).

3.4. Comparison with real-world data

The positioning of "attraction" objects (i.e., the *servers*) ensured the representation of attraction phenomena towards unmovable obstacles (i.e., the *floor* edges). According to Section 2.3, *homogeneous* or *by-literature* setups have been tested, thus representing different probabilities that a pedestrian can choose one of the "first servers".

	Dw≤1	*1<Dw≤2*	*Dw>2*	
Literature data	29	50	21	
Custom simulator	23 (L: -6)	66 (L: +16)	11 (L: -10)	
Generic simulator setup				
R1	37 (L: +8; C: +14)	29 (L: -21; C: -37)	34 (L: +13; C: +23)	Avg
	4	1	4	Dev. St.
R2	38 (L: +9; C: +15)	31 (L: -19; C: -35)	31 (L: +10; C: +20)	Avg
	4	2	5	Dev. St.
R3	37 (L: +8; C: +14)	33 (L: -17; C: -33)	30 (L: +9; C: +19)	Avg
	4	2	4	Dev. St.
S1	36 (L: +7; C: +13)	29 (L: -21; C: -37)	35 (L: +14: C: +24)	Avg
	4	1	4	Dev. St.
S2	36 (L: +7; C: +13)	32 (L: -18; C: -34)	32 (L: +11; C: +21)	Avg
	4	1	4	Dev. St.
S3	36 (L: +7; C: +13)	34 (L: -16; C: -32)	30 (L: +9; C: +19)	Avg
	5	2	4	Dev. St.
OVERALL	37 (L: +8; C: +14)	31 (L: -19; C: -35)	32 (L: +11; C: +21)	Avg
	4	2	5	Dev. St.

Table 4: *Pedestrians frequency percentage distribution and variability for each distance class: comparison of the setup of the generic simulator, grouped according to the criteria shown in Figure 1, with experimental literature data (L)* (Bernardini et al., 2017b) *and the custom simulator data (C). Extended results for each setup are in Supplementary Materials S6.*

Table 4 compares the D_w percentage distribution of the distance between pedestrians and unmovable obstacles from the generic simulator with those obtained from the real-world observations (literature data are considered as a reference for the comparison (Bernardini et al., 2017b)), and the custom simulator. Results show non-significant differences between the setup groups, as the standard deviations range, in general, between 1-5%. On the other hand, the comparison with the custom simulator and the literature data shows more significant differences. In particular, concerning the class $1<D_w\leq 2$m, these differences are essentially due to the repulsive forces between pedestrians in the same, which induce lower frequency in this class of distance (negative differences). On the other hand, for $D_w>2$m, the distances are higher than the ones from real-world and custom simulator data (positive differences). Thus, from a hydrodynamic point of view, the generic simulator seems to overestimate the risk condition during the evacuation due to the possible proximity of pedestrians to walls. In fact, the streets seem to behave like open channels and the water speed at the edge decrease (Chow, 1959), thus possibly inducing pedestrians' speed increment.

3.5. Best setup discussion

Between all the setups tested, the BL8S (group S3) is the one that produced the closest results to the custom simulator, although differences in the modelling logics between them exist. In particular, they are both SFM-based, but the generic one ignores the attraction force toward unmovable obstacles as one of the simulated forces and is just considered as an "external" constraint for pedestrians' trajectories. BL8S setup is characterized by the following features that support the similarities with the custom simulator:

- The condition of the *squared entrance portals*, in which pedestrians are generated with a density of about 1pp/m^2, is similar to those of the custom simulator. The initial effect of the repulsive force between pedestrians seems to be mitigated because of their mutual distance, which is preserved along the pathway. Meanwhile, in the other configuration, the density is 3 times higher, so that pedestrians spread out at the very beginning of the pathway;
- *Two "first servers"* are positioned at 1/8 of the pathway length (i.e., about 10m from the start). This condition seems to allow increasing the attraction towards unmovable obstacles and the

interaction between the pedestrians. Considering the distance from the side of the pathway, the "first servers" are placed in the middle of each class of distance (i.e., *servers* at 0.5m and 1.5m from the wall), with a *by-literature* probability distribution for pedestrians to select one of them. This element of the setup seems to reduce the MassMotion trend in simulating higher pedestrian-unmovable obstacles distances. Anyway, having *servers* extremely close to the start of the pathway could represent a problem for what it concerns queue phenomena, especially with very large groups of pedestrians.

Figure 7 shows the evacuation curves and the D_w trends obtained from the proposed setup (red solid lines) and the custom simulator (black dashed lines). According to the results on KPIs introduced in Section 3.4, the evacuation curves are similar in shape and size (SC=0.78, EPC=1.01), close to each other (ERD=0.13), and without significant differences in underestimating/overestimating contingencies (DAUC=9%). Anyway, it is worthy of notice that the generic simulator seems to speed up the evacuation process for the first arrived pedestrians, which can be considered as free to move in the environment and to pass by the server with a reduction of group interactions. In this sense, the custom simulator better points out the group attraction phenomena, by reducing the time gap between the first and the last arrived pedestrians. However, in view of the above, considering such risk conditions in terms of the pedestrians' density and practicability conditions (i.e., pedestrians still manage to move in the floodwater without experiencing in instability problems), the two simulators produce comparable results concerning macroscopic aspects like the over-time progression of the evacuation process.

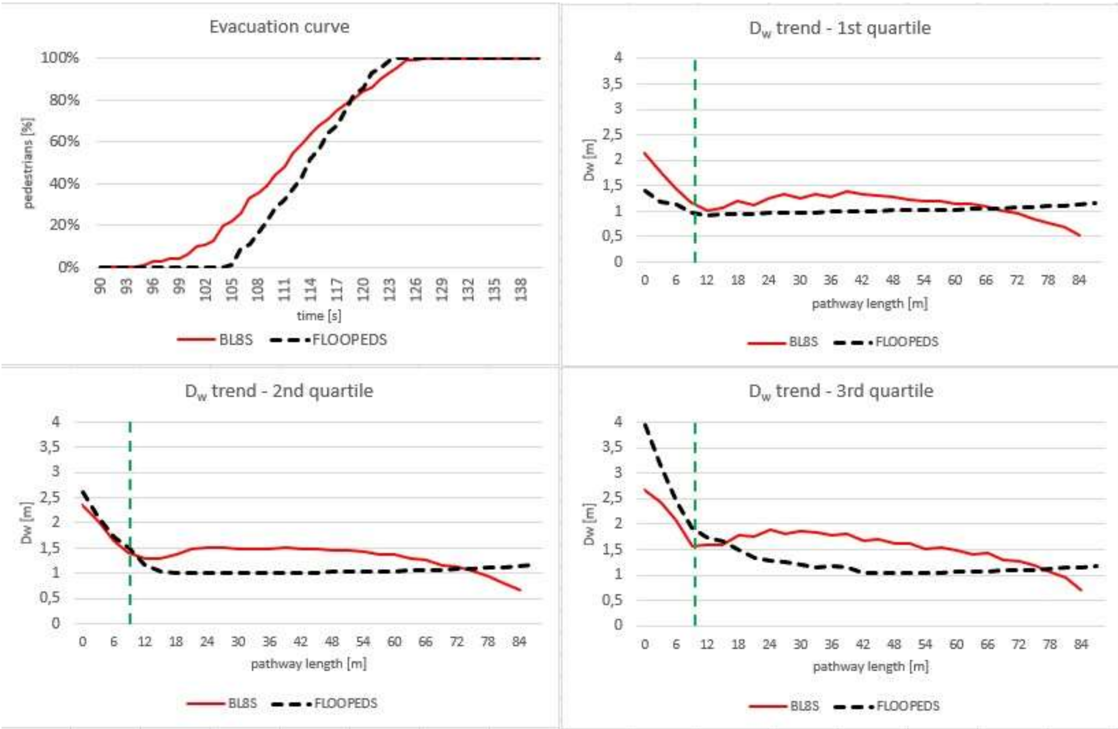

Figure 7: Comparison between the evacuation curves and the D_w trends obtained from the BL8S setup of the generic simulator (red solid lines) and the custom simulator (black dashed lines). The green dashed line indicates the "first servers" position along the pathway. The evacuation curves comparison considers the range between 90-140s, which from the arrival of the first pedestrian to the exit of the last one.

On the other hand, from a microscopic point of view, differences emerge in pedestrians' trajectories, as the D_w outcomes point out. In particular, the generic simulator BL8S setup seems to overestimate the pedestrians' risk if considering their trajectories, because the setup and the model force them to travel along larger trajectories towards the evacuation target. This implies higher exposition for pedestrians to the floodwaters (Chow, 1959), especially after the attraction points effect (i.e., the "first server") as shown in Figure 7. Table 5 summarizes the KPIs values concerning the D_w trends comparison, showing differences in the curves' shape and overall agreement. However, considering the probability distributions in class distances (Table 6), the generic simulator setup finds good agreement with the real-world data (differences <15%), meaning that the general trends can be considered as preliminary acceptable for simulation purposes (Robin et al., 2009; Schadschneider et al., 2009; Shiwakoti et al., 2008).

	SC	*ERD*	*EPC*	*DAUC*
1st quartile	0.53	0.36	1.10	10%
2nd quartile	0.71	0.33	1.09	14%
3rd quartile	0.65	0.35	0.99	11%

Table 5: KPIs measuring differences between curves tracing the Dw trend of the generic simulator best setup (BL8S) and the custom simulator (quartile analysis).

	Dw≤1	*1<Dw≤2*	*Dw>2*
Literature data	29	50	21
Custom simulator	*23 (L: -6)*	*66 (L: +16)*	*11 (L: -10)*
BL8S setup	*39 (L: +10; C: +16)*	*37 (L: -13; C: -29)*	*25 (L: +4; C: +14)*

Table 6: Pedestrians' frequency percentage distribution for each distance class: comparison of the generic simulator best setup (BL8S) with the literature distributions (Bernardini et al., 2017b) *and the custom simulator distributions. Percentage differences between literature (L) and custom software (C) data are pointed out into brackets.*

Finally, Table 7 shows the pedestrians' evacuation timing data concerning: (a) the maximum evacuation time t_{max}, which is almost identical between the two analyzed software, thus confirming non-particular underestimating/overestimating safety contingencies, (b) the waiting time percentage *W*, and (c) the evacuation flow *F,* whose values are by the way in line with the generic simulator overall trend.

	t_{max} [s]	***W*** [%]	***F*** [pp/s]
Custom simulator	125	-	5.63
Generic simulator (median)	126	8%	3.91

BL8S setup	***127 (C: 2%; G: 1%)***	***10% (C: -; G: 2%)***	***3.75 (C: -33%; G: -4%)***

Table 7: Comparison of the maximum evacuation time t_{max}, the waiting time percentage W, and the evacuation flow F of the generic simulator best setup (BL8S): percentage differences between the custom simulator (C) and the generic software median data (G) are pointed out into brackets.

4. Conclusions

The present work is a very first attempt to implement an outdoor flood evacuation model in a generic evacuation simulation software (MassMotion) to ease and speed-up the risk assessment analyses by using a quick no-code modification approach. Functions and features already included in the generic software are used to this end. Thus, different setups are tested to describe the pedestrians-floodwaters interactions during a flood evacuation in a simple typological scenario like a straight and flat street. As a benchmark, a previously developed and tested custom flood evacuation simulator was selected, that is FlooPEDs (Flooding Pedestrians' Evacuation Dynamics Simulator). Stationary flood conditions and compact groups of 10 pedestrians are considered in the comparison, which is consistent with basic outdoor BEs conditions for evacuation after the event's peak, but sufficiently detailed to represent a valid preliminary test. Simulation outputs have been organized to identify the best setup, which is the one that produces the closest outcomes to the ones of the custom simulator.

Considering the best setup, the comparison of the results shows slight differences between the two software in simulating a flood evacuation in stationary conditions, even with no modifications to the simulation code. Indeed, from a macroscopic point of view, the generic simulator manages to represent the main effects of the flood evacuation as proved by outcomes in terms of evacuation timing (i.e., evacuation curves, flow, and maximum evacuation time). On the other hand, considering microscopic aspects such as the pedestrian trajectories along the pathway (i.e., their distance from the buildings' walls), the best setup shows good agreement with the real-world data, while marked differences with respect to the custom simulator still exist. In particular, the generic simulator seems to overestimate the risk for pedestrians by computing higher distances from unmovable objects, which also implies lower evacuation speed and higher exposure to the water flow for pedestrians.

The proposed setup development and comparison methodology could be also extended to other existing generic simulation tools, especially those based on similar modelling logics, thus providing preliminary tests in simple outdoor BE conditions. From this point of view, although the current simple setup of the generic simulator seems to well represent the flood evacuation conditions, future works should provide modifications to the evacuation simulation code to include SFM-related interactions as proposed by the literature works. This action will ensure a more detailed description either of. (1) the outdoor evacuation behaviors in complex BEs (i.e., with the effective implementation of unmovable objects like trees, walls, fences, that can have an attractive effect on the pedestrians); and (2) the flood conditions, that is the variations in floodwaters levels to represent hydrodynamics conditions which can vary over time and space, thus affecting the pedestrians' motion and decision-making). The generic simulator software could also directly use data from external hydrodynamic simulators to represent the flood levels conditions variability over the simulation time, and so to directly test the effects on the pedestrians' motion. Additional tests on more refined scenarios are still encouraged to verify behavioral evacuation aspects (for instance, by investigating larger groups of pedestrians and/or with different physical and social features, or different environments such as more complex layouts or indoor scenarios), as well as to include them in the model to better represent real emergency scenarios and to evaluate human motion evacuation quantities.

Nevertheless, the performing results showed by this first work demonstrate how the setup-based simulator could be able to simulate human behavior during flood evacuations in outdoor BEs. Thus, such a steup-based generic simulation tool could be also used by low-trained technicians and Local Authorities to preliminary assess evacuation risks in BEs, to propose risk-mitigation strategies (i.e. architectural layout modifications, micro-scale re-thinking of built spaces, direct support to pedestrians by also using wayfinding and alert systems, management actions by rescuers, “invacuation” strategies) and finally to test their effectiveness by a user-centered and simulation-based approach. this kind of simulation tool could be hence used to increase the evacuees’ safety in both indoor and outdoor BEs, characterized by similar scenario conditions (e.g. wide spaces in public buildings or undergrounds), in both existing and new ones.

5. References

Ashley, S.T., Ashley, W.S., 2008. Flood Fatalities in the United States 805–818. https://doi.org/10.1175/2007JAMC1611.1

Bernardini, G., Camilli, S., Quagliarini, E., D’Orazio, M., 2017a. Flooding risk in existing urban environment: from human behavioral patterns to a microscopic simulation model. Energy Procedia 134, 131–140. https://doi.org/10.1016/j.egypro.2017.09.549

Bernardini, G., Postacchini, M., Quagliarini, E., Brocchini, M., Cianca, C., D’Orazio, M., 2017b. A preliminary combined simulation tool for the risk assessment of pedestrians’ flood-induced evacuation. Environ. Model. Softw. https://doi.org/10.1016/j.envsoft.2017.06.007

Bernardini, G., Quagliarini, E., D’Orazio, M., 2019. Investigating Exposure in Historical Scenarios: How People Behave in Fires, Earthquakes and Floods, in: RILEM Bookseries. https://doi.org/10.1007/978-3-319-99441-3_123

Bodoque, J.M., Amérigo, M., Díez-Herrero, A., García, J.A., Cortés, B., Ballesteros-Cánovas, J.A., Olcina, J., 2016. Improvement of resilience of urban areas by integrating social perception in flash-flood risk management. J. Hydrol. https://doi.org/10.1016/j.jhydrol.2016.02.005

Bosina, E., Weidmann, U., 2017. Estimating pedestrian speed using aggregated literature data. Phys. A Stat. Mech. its Appl. 468, 1–29. https://doi.org/10.1016/j.physa.2016.09.044

Chow, V.T., 1959. Open-Channel Hydraulics. Ven Te Chow. McGraw-Hill, New York, 1959. xviii + 680 pp. Illus. $17, Science.

Cox, R.J., Shand, T.D.Blacka, M.J., 2010. Australian Rainfall & Runoff revision project 10: Appropriate safety criteria for people, Engineers Australia. https://doi.org/10.1038/103447b0

D'Orazio, M., Longhi, S., Olivetti, P., Bernardini, G., 2015. Design and experimental evaluation of an interactive system for pre-movement time reduction in case of fire. Autom. Constr. 52, 16–28. https://doi.org/10.1016/j.autcon.2015.02.015

Dai, Q., Zhu, X., Zhuo, L., Han, D., Liu, Z., Zhang, S., 2020. A hazard-human coupled model (HazardCM) to assess city dynamic exposure to rainfall-triggered natural hazards. Environ. Model. Softw. 127, 104684. https://doi.org/10.1016/j.envsoft.2020.104684

Dias, C., Rahman, N.A., Zaiter, A., 2021. Evacuation under flooded conditions: Experimental investigation of the influence of water depth on walking behaviors. Int. J. Disaster Risk Reduct. 58, 102192. https://doi.org/10.1016/j.ijdrr.2021.102192

European Commission, 2017. Overview of natural and man-made disaster risks in the European Union may face, Commission Staff Working Document. https://doi.org/doi:10.2795/861482

Fan, Q., Tian, Z., Wang, W., 2018. Study on Risk Assessment and Early Warning of Flood-Affected Areas when a Dam Break Occurs in a Mountain River. Water 10, 1369. https://doi.org/10.3390/w10101369

Fruin, J.J., 1971. Pedestrian planning and design, Metropolitan Association of Urban Designers and Environmental planners Inc. Metropolitan Association of Urban Designers and Environmental Planners, New York.

Gu, D., 2019. Exposure and vulnerability to natural disasters for world's cities. United Nations, Department of Economics and Social Affairs, Population Division, Technical Paper No. 4., Population Division, Technical Paper No. 4.

Helbing, D., Farkas, I., Vicsek, T., 2000. Simulating dynamical features of escape panic. Nature 407, 487–490. https://doi.org/10.1038/35035023

Ishigaki, T., Onishi, Y., Asai, Y., Toda, K., Shimada, H., 2008. Evacuation criteria during urban flooding in underground space.

Jamrussri, S., Toda, Y., 2018. Available Flood Evacuation Time for High-Risk Areas in the Middle Reach of Chao Phraya River Basin. Water 10, 1871. https://doi.org/10.3390/w10121871

Jebrane, A., Argoul, P., Hakim, A., El Rhabi, M., 2019. Estimating contact forces and pressure in a dense crowd: Microscopic and macroscopic models. Appl. Math. Model. 74, 409–421. https://doi.org/10.1016/j.apm.2019.04.062

Jia, X., Morel, G., Martell-Flore, H., Hissel, F., Batoz, J.-L., 2016. Fuzzy logic based decision support for mass evacuations of cities prone to coastal or river floods. Environ. Model. Softw. 85, 1–10. https://doi.org/10.1016/j.envsoft.2016.07.018

Kolen, B., van Gelder, P.H.A.J.M., 2018. Risk-Based Decision-Making for Evacuation in Case of Imminent Threat of Flooding. Water 10, 1429. https://doi.org/10.3390/w10101429

Lakoba, T.I., Kaup, D.J., Finkelstein, N.M., 2005. Modifications of the Helbing-Molnar-Farkas-Vicsek Social Force Model for Pedestrian Evolution. Simulation 81, 339–352. https://doi.org/10.1177/0037549705052772

Li, Y., Hu, B., Zhang, D., Gong, J., Song, Y., Sun, J., 2019. Flood evacuation simulations using cellular automata and multiagent systems -a human-environment relationship perspective. Int. J. Geogr. Inf. Sci. 33, 2241–2258. https://doi.org/10.1080/13658816.2019.1622015

MassMotion Guide, 2020. MassMotion Guide.

Matsuo, K., Natainia, L., Yamada, F., 2011. Flood and Evacuation Simulations for Urban Flooding. 5th Int. Conf. Flood Manag. 391–398.

Mignot, E., Li, X., Dewals, B., 2019. Experimental modelling of urban flooding: A review. J. Hydrol. 568, 334–342. https://doi.org/10.1016/j.jhydrol.2018.11.001

Milanesi, L., Pilotti, M., Ranzi, R., 2015. A conceptual model of people's vulnerability to floods. Water Resour. Res., 51, 182–197, doi10.1002/ 2014WR016172 5375–5377. https://doi.org/10.1002/2013WR014979.Reply

Najafi, M.R., Zhang, Y., Martyn, N., 2021. A flood risk assessment framework for interdependent infrastructure systems in coastal environments. Sustain. Cities Soc. 64.

https://doi.org/10.1016/j.scs.2020.102516

Opper, S., Cinque, P., Davies, B., 2010. Timeline modelling of flood evacuation operations 3, 175–187. https://doi.org/10.1016/j.proeng.2010.07.017

Paquier, A., Mignot, E., Bazin, P.-H., 2015. From Hydraulic Modelling to Urban Flood Risk. Procedia Eng. 115, 37–44. https://doi.org/10.1016/j.proeng.2015.07.352

Piyumi, M.M.M., Abenayake, C., Jayasinghe, A., Wijegunarathna, E., 2021. Urban Flood Modeling Application: Assess the Effectiveness of Building Regulation in Coping with Urban Flooding Under Precipitation Uncertainty. Sustain. Cities Soc. 75. https://doi.org/10.1016/j.scs.2021.103294

Robin, T., Antonini, G., Bierlaire, M., Cruz, J., 2009. Specification, estimation and validation of a pedestrian walking behavior model. Transp. Res. Part B Methodol. https://doi.org/10.1016/j.trb.2008.06.010

Ronchi, E., 2020. Developing and validating evacuation models for fire safety engineering. Fire Saf. J. 103020. https://doi.org/10.1016/j.firesaf.2020.103020

Ronchi, E., Kuligowski, E.D., Reneke, P.A., Peacock, R.D., Nilsson, D., 2013a. The Process of Verification and Validation of Building Fire Evacuation Models. NIST Tech. Note 1822.

Ronchi, E., Nilsson, D., Nilsson, D., 2013b. The Process of Verification and Validation of Building Fire Evacuation Models NIST Technical Note 1822 The Process of Verification and Validation of Building Fire Evacuation Models.

Samany, N.N., Sheybani, M., Zlatanova, S., 2021. Detection of safe areas in flood as emergency evacuation stations using modified particle swarm optimization with local search. Appl. Soft Comput. 111, 107681. https://doi.org/10.1016/j.asoc.2021.107681

Schadschneider, A., Klingsch, W., Klüpfel, H., Kretz, T., Rogsch, C., Seyfried, A., 2009. Evacuation Dynamics: Empirical Results, Modeling and Applications. Encycl. Complex. Syst. Sci. https://doi.org/10.1007/978-0-387-30440-3_187

Shi, L., Xie, Q., Cheng, X., Chen, L., Zhou, Y., Zhang, R., 2009. Developing a database for emergency evacuation model. Build. Environ. 44, 1724–1729. https://doi.org/10.1016/j.buildenv.2008.11.008

Shirvani, M., Kesserwani, G., Richmond, P., 2020. Agent-based modelling of pedestrian responses during flood emergency: mobility behavioural rules and implications for flood risk analysis. J. Hydroinformatics 22, 1078–1092. https://doi.org/10.2166/hydro.2020.031

Shiwakoti, N., Sarvi, M., Rose, G., 2008. Modelling pedestrian behaviour under emergency conditions – State-of-the-art and future directions 457–473.

Takagi, H., Li, S., de Leon, M., Esteban, M., Mikami, T., Matsumaru, R., Shibayama, T., Nakamura, R., 2016. Storm surge and evacuation in urban areas during the peak of a storm. Coast. Eng. 108, 1–9. https://doi.org/10.1016/j.coastaleng.2015.11.002

Xia, J., Falconer, R.A., Lin, B., Tan, G., 2011. Numerical assessment of flood hazard risk to people and vehicles in flash floods. Environ. Model. Softw. 26, 987–998. https://doi.org/10.1016/j.envsoft.2011.02.017

Young, A.F., Jorge Papini, J.A., 2020. How can scenarios on flood disaster risk support urban response? A case study in Campinas Metropolitan Area (São Paulo, Brazil). Sustain. Cities Soc. 61, 102253. https://doi.org/10.1016/j.scs.2020.102253

6. Appendix A

Figure 8 shows some main views of the *floor* configuration simulating the linear pathway for the verification tests. In particular, *portals* and *servers* (MassMotion Guide, 2020) are introduced to reproduce the attraction of the *agents* (i.e. pedestrians) towards unmovable obstacles (i.e. buildings). We offered the specific software configuration terms, underlining MassMotion option in italics, and in square brackets, where needed.

Entrance only and *destination portals* (respectively, where *agents* enter and exit the simulation *floor*) are placed close to the later *floor* limit, to reproduce the ideal maximum distance among pedestrians and buildings according to the considered experimental-based model (Bernardini et al., 2017b). An *entrance only portal* (whose dimensions depend on the setup tested) and a *destination portal* are placed at each *floor* side. Figure 8-B shows two views of the *entrance portal* position.

The *servers* are introduced to increase the attraction behavior towards unmovable obstacles, that are the pathways sides. The start points of the *servers* (whose number depends on the setup tested) are placed at each *floor* lateral side, as shown by Figure 8-A. In respect to the pathway length, the *servers* were tested in three different positions: halfway, a quarter, and an eighth of the *floor*. Thus, the first part of the pathways is intended to replicate the pedestrians' organization alongside the pathway side, being the *agents* attracted by the *servers* start points (Bernardini et al., 2017b). Concerning these start points' distances from the *floor* lateral edge, multiple setups were also tested in order to represent the classes of distance by literature (Bernardini et al., 2017b). Moreover, *servers* are connected through a single internal connection, the *dispatch*, to a single end point (placed near to the pathways end, at the *destination portal*). By this way, the configuration tries to force the *agents* to move near the *floor* edge by reproducing the maximum attraction phenomena for building-pedestrians distances of about 2m (Bernardini et al., 2017b).

The *agents'* motion has been configurated so as to link them towards the *servers* placed on the same generation *floor* side, and then towards the final *destination portal*. In particular, the *agents* are divided between the elements of the *server* according to two distributions: homogeneous, where agents have the same of probability in choosing the related *server*, and by-literature, according to the real-world data about the frequency for each class of distance from unmovable obstacles. The *dispatches* also increase the possibility of motion interaction between *agents* moving from the two start points to the unique end point. The *servers'* configuration also includes the following features:

1. *agents* are initially generated at the *entrance only portal*, and then directly move towards the exits [*approach: standard walk to target; Target: server exit*]. Each *server* influences the *agents'* motion as a waypoint for the evacuation motion, only because of its position (the *server* length is not relevant);

2. no limitations in the exit flows are considered [*Processors: unlimited; Capacity: infinite; Contact time: disabled*]. The impact of queueing phenomena on the *server* motion steps and at the exit can be reduced by combining this setup strategies to previous point 1.
3. the correct evacuation direction is identified in a unique manner to avoid coming-and-going behaviors and street-crossing behaviors along the *floor*, which are not noticed in flood evacuation conditions [*Dispatch objects* are configurated to directly connected the *servers* along the evacuation motion direction.

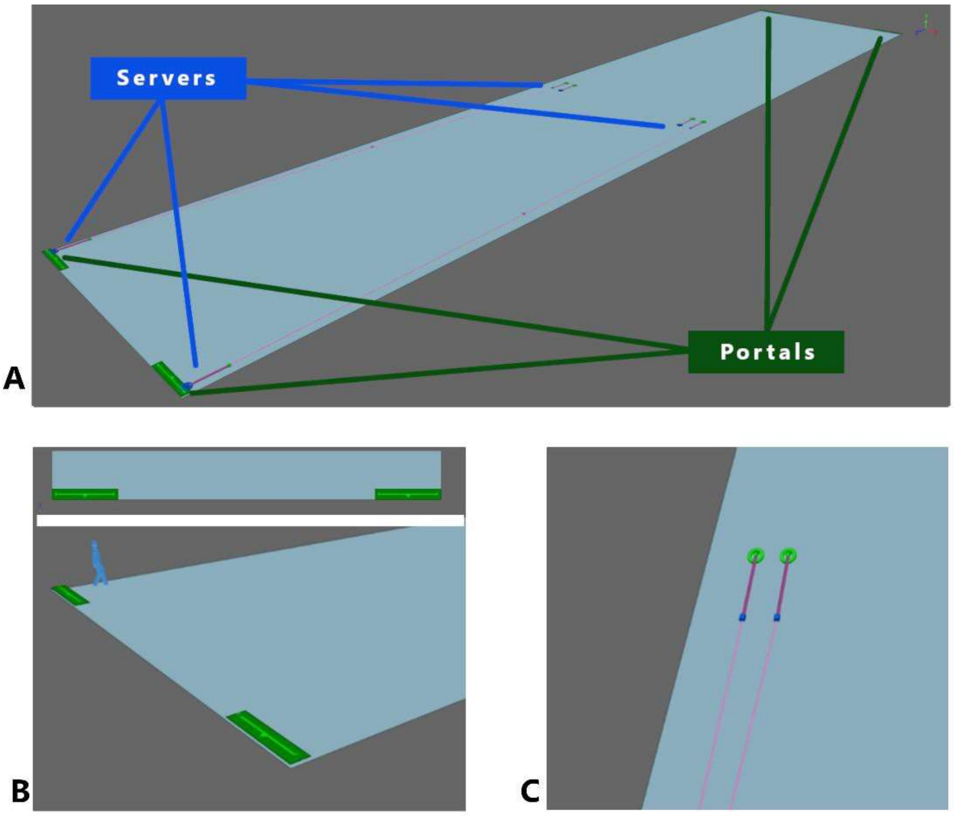

Figure 8: overall floor configuration view (A), by including the portals at the end/beginning of the floor in plan and 3D view (B) and some of the servers included along the floor by including the access point (green circles), the target exit (blue point) and the dispatches (pink lines) towards the next server (C).

Each simulated *agent* moving on *floor* is characterized by a unique profile according to the *Agent Behaviour Tab* setup interface. Compact groups are simulated by considering no pre-movement time delay [*Population*: *arrival* -> *instant*]. The default speed-density relation has been adopted since no current advances by literature on these aspects have been provided for the flood evacuation case. The *agents'* queue spacing has been similarly set up according to the default normal distribution (minimum=0m, maximum=1m, mode=0.25m, standard deviation 0.125m) for the same reason. The selected *direction bias* is "*none*" to avoid influencing the overtaking of other *agents*. Beside the configuration of *portals* and *servers*, the minimization of *floor* crossing probability is also assigned to each *agent* [*assigned goal -> grouped: lowest cost*] by hence representing an improved attraction behavior towards the *floor* limits where they are generated.

7. Appendix B

Setup symbol and property				
	A-B-C-D	H-L	2-4-8	R-S
Setup	Servers' distance from the wall: "first servers" * // second server [m]	Probability a pedestrian can choose one of the "first servers" * [%]	First servers' distance from the start of the pathway [m]	Entrance portals configuration: width; length; distance from the wall [m]
AH2R	1; 2 // 1	50; 50	43.5	3; 1; 0
AL2R	1; 2 // 1	29; 71	43.5	3; 1; 0

BH2R	0.5; 1.5 // 0.5	50; 50	43.5	3; 1; 0
BL2R	0.5; 1.5 // 0.5	29; 71	43.5	3; 1; 0
CL2R	0.5; 1.5; 2.5 // 0.5	29; 50; 21	43.5	3; 1; 0
DH2R	1; 2 // 0.5	50; 50	43.5	3; 1; 0
AH4R	1; 2 // 1	50; 50	21.75	3; 1; 0
AL4R	1; 2 // 1	29; 71	21.75	3; 1; 0
BH4R	0.5; 1.5 // 0.5	50; 50	21.75	3; 1; 0
BL4R	0.5; 1.5 // 0.5	29; 71	21.75	3; 1; 0
CL4R	0.5; 1.5; 2.5 // 0.5	29; 50; 21	21.75	3; 1; 0
DH4R	1; 2 // 0.5	50; 50	21.75	3; 1; 0
AH8R	1; 2 // 1	50; 50	10.87	3; 1; 0
AL8R	1; 2 // 1	29; 71	10.87	3; 1; 0
BH8R	0.5; 1.5 // 0.5	50; 50	10.87	3; 1; 0
BL8R	0.5; 1.5 // 0.5	29; 71	10.87	3; 1; 0
CL8R	0.5; 1.5; 2.5 // 0.5	29; 50; 21	10.87	3; 1; 0
DH8R	1; 2 // 0.5	50; 50	10.87	3; 1; 0
AH2S	1; 2 // 1	50; 50	43.5	3; 3; 1
AL2S	1; 2 // 1	29; 71	43.5	3; 3; 1
BH2S	0.5; 1.5 // 0.5	50; 50	43.5	3; 3; 1
BL2S	0.5; 1.5 // 0.5	29; 71	43.5	3; 3; 1
CL2S	0.5; 1.5; 2.5 // 0.5	29; 50; 21	43.5	3; 3; 1
DH2S	1; 2 // 0.5	50; 50	43.5	3; 3; 1
AH4S	1; 2 // 1	50; 50	21.75	3; 3; 1
AL4S	1; 2 // 1	29; 71	21.75	3; 3; 1
BH4S	0.5; 1.5 // 0.5	50; 50	21.75	3; 3; 1

BL4S	0.5; 1.5 // 0.5	29; 71	21.75	3; 3; 1
CL4S	0.5; 1.5; 2.5 // 0.5	29; 50; 21	21.75	3; 3; 1
DH4S	1; 2 // 0.5	50; 50	21.75	3; 3; 1
AH8S	1; 2 // 1	50; 50	10.87	3; 3; 1
AL8S	1; 2 // 1	29; 71	10.87	3; 3; 1
BH8S	0.5; 1.5 // 0.5	50; 50	10.87	3; 3; 1
BL8S	*0.5; 1.5 // 0.5*	*29; 71*	*10.87*	*3; 3; 1*
CL8S	0.5; 1.5; 2.5 // 0.5	29; 50; 21	10.87	3; 3; 1
DH8S	1; 2 // 0.5	50; 50	10.87	3; 3; 1

Table 8: Each setup (first column) is based on four properties coded by four symbols, and the properties characterization is discussed in each of the column, as also shown by to Table 1 criteria. Best setup in italics. Notes: * Each "first servers" group can be composed of two or three servers according to Section 3.3 criteria, so the semicolon separates the value for each of them.