VERIFICATION AND VALIDATION OF THE EVACUATION MODEL

MASTER's THESIS

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# Abstract

In our small project [1], we proposed an evacuation simulation model of a human crowd. This model is improved in this thesis with new algorithms of exit selection, smoke propagation, following indicators, dynamic walking speeds and deviation in the smoke, as well as supporting multi-layered environments. The model is verified by both existing benchmarks and a new set of tests developed by us. Additionally, the exit selection and the evacuation time are validated based on two existing experiments. Through the verification and validation, the model is proved to represent the evacuation process quantitatively and quantitatively.

# Acknowledgements

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# 1 Introduction

In the past two decades, considerable crowd simulation models have been developed and improved, such as the Social Force Model [2], the Cellular-Automata Model [3] and the Fluid Dynamics Model [4]. To simulate evacuation scenarios, the models were modified for supporting imperative features of evacuation, e.g. the multi-layered scenario [5], the special walking pattern during evacuation [6] and the occupant characteristics [7] [8].

Simulex [9], FDS+Evac [10], Legion [11], STEPS [12], PathFinder [13] and Exodus [14] are widely known commercial models [15] for simulating evacuation scenarios. They have their respective merits. For instance, Legion embeds artificial intelligence to simulate realistic behaviors of evacuees and FDS+Evac has its own fire model. However, none of them facilitates comprehensive features of evacuation involving smoke, lighting and response of evacuees to the environment. In addition, according to [16], a survey among 196 evacuation model users in 36 different countries indicates that validation/verification (V&V) is the most important factor when selecting an evacuation model. But some of these models do not offer their verification and validation results, which means the veracity and reliability of the models can not be proved.

In our small project [1], we proposed a comprehensive agent-based model, based on extensive existing knowledge associated with evacuation. The model consists of three levels. The bottom level (Path Planning level) is provided by the Utrecht University Crowd Simulation engine [17]. This level outputs a feasible path from a start point to a target point, dealing with dynamic collision avoidance and group coherence. In the second level (Action planning level), the action of the evacuee is decomposed into several path planning processes. Through iterative path planning, the walking trajectory of the evacuee can present special patterns in evacuation such as deviation in the smoke. The third level (Strategy level) is the global control. The exit selection, the pre-evacuation time, etc., are determined in this level.

In this thesis, our model is improved. This improved model supports multi-floored environments. Furthermore, the algorithms of exit selection, smoke propagation, following indicators, dynamic walking speeds and deviation in the smoke, etc., are enhanced. Moreover, new features such as dynamic exit availability and weighted regions are added into the model.

In addition, this thesis discusses validation and verification of the evacuation models and applies existing approaches and approaches developed by us to verify and validate our model.

In 2013, Ronchi et al. [18] suggested a complete set of benchmarks for verification. This set of benchmarks extends tests proposed by International Maritime Organization [19] and introduces important elements in evacuation simulation such as pre-evacuation time assignment into the evaluation standard. We mainly use this set of detailed benchmarks to verify our model, and we also consider suggestions from [20] [21] and [22]. Since Ronchi's standard is not concrete enough in some parts, we propose some new verification tests primarily associated with the exit selection and the pre-evacuation time. Besides, to validate the model, we compare the empirical data provided by two existing evacuation experiments with the data produced by simulation with two approaches. The first approach is logistic regression, and the second approach was established by Peacock [23], namely functional-analysis of evacuation time.

We will show that our model passed the majority of the verification tests. In addition, the validation result affirms the capability of the model to simulate exit selection and evacuation time accurately. However, we find two limits of our model. First, our model cannot solve the pedestrian flow properly in a high-density crowd. In the counter-flows test, a blockage was formed near the exit of the room, thus occupants in two rooms could not reach the opposite room. Second, the deviation algorithm and the weighted region cannot be used in the same time since they are based on different path planning algorithms.

This thesis is structured as follows. In Chapter 2, we discuss the previous evacuation model produced in our small project, as well as existing verification & validation approaches. In Chapter 3, the improved evacuation model is described in three aspects, i.e. the evacuation environment, the evacuee, and the evacuation simulation. Chapter 4 and Chapter 5 indicate the verification & validation processes and results of our model. In Chapter 6, we conclude that our model embeds necessary functions to simulate evacuation scenarios. The veracity and reliability of the functions are proved by a series of verification tests and validation tests. In addition, several limitations that we need to overcome in the future are also discussed in Chapter 6.

# 2 Related Work

## 2.1 Utrecht University Crowd Simulation Engine

The Utrecht University Crowd Simulation engine (UUCS) [17] offers an API that implements crowd simulation for agents, based on the Explicit Corridor Map (ECM) [24]. The ECM is a generalized Voronoi diagram. Its edges are annotated with event points together with their closest points to obstacles. With such a structure, a short and smooth path can be found in real-time, also taking the radius of the agent into account. Besides, the engine implements finding paths for coherent groups as well [25]. A backbone path of one agent is extended to a corridor by using the clearance along the path. Agents can move freely in the corridor. With simple API calls, we can define groups and generate collision-free paths for groups. Also, the engine supports weighted regions [26]. Each agent has preferences to defined regions, guiding them to walk along natural paths (such as street roads), rather than going through dense grass. This function is used in our evacuation model to distinguish indoor areas and outdoor areas. Last, in 2016, UUCS has been improved for supporting multi-layered environments [27] [28], which allows us to conduct evacuation simulation in multi-floored scenarios.

This engine is used as the bottom level in our model. Functions that we use are inputting obstacles, inputting walkable areas, finding a short path to the target, changing the speed of one agent, organizing groups, moving agents to follow the path and defining weighted regions. Due to these features, we generally observe realistic behaviors of evacuees, i.e. finding or waiting for group members, walking in the slowest speed within a group, slight deviation of the walking path (the evacuee does not walk in the shortest path in real life) and decrease of the speed in a congestion.

However, UUCS has some limitations. First, the agent-based path planning approach yields that the framework is unsuitable for simulating a crowd with an extremely high density. Second, there are bugs in the weighted region implementation, which could be fixed in the future.

## 2.2 Three-level comprehensive model for evacuation

The Three-level Comprehensive Model for Evacuation is an evacuation simulation model proposed in our small project [1]. The model consists of three levels. The bottom level

(Path Planning level) is provided by the Utrecht University Crowd Simulation engine. This level outputs a feasible path from a start point to a target point, dealing with dynamic collision avoidance and group coherence.

The second level is called Action planning level. In this level, the action of the agent is decomposed to several path planning processes. Through iterative path planning, the walking trajectory of the evacuee can present special patterns in evacuation. Three walking patterns are considered in this level, i.e. Destination Walk, Non-Destination Walk and Restricted Walk.

Destination Walk describes a walking procedure with one or more explicit target points. It is a sequence of movements. In each movement, the algorithm uses UUCS functions to find a short path from a start point to a target point. When the agent arrives at a target point, the target point becomes the new start point and the next target point becomes the new target point. The terminal condition is that the agent arrives at the last target point. Destination Walk is applied to simulate four types of behaviors in evacuation, i.e. walking to the selected exit, following indicators, checking specified zones (such as a nurse inspecting wards in order) and going outside of the building.

The Non-Destination Walk describes the walking behavior without an explicit target point. For a given time period, the algorithm generates target points in a specified zone continuously at random collision-free positions, leading the agent to reach each target point. Compared with Destination Walk, Non-Destination Walk is more like "strolling" or "wandering", instead of following an indicative path. Non-Destination Walk is applied to simulate behaviors of evacuees in their pre-evacuation periods.

Restricted Walk can be seen as walking behavior with a path-modifying process that makes one's route diverging from the original route, which describes the evacuee walking along the walls when his visibility is limited. Both the personality of the agent and the situation of the smoke are considered in the algorithm. In general, agents prefer to be close to the walls when the smoke is dense. The path planning method and the path following method in the bottom level are not modified in Restricted Walk; instead, the algorithm steers the agents by updating a proper target position constantly to maintain the agent walking along the walls meanwhile walking towards the exit.

The third level (Strategy level) is like a global control. The smoke propagation, the pre-evacuation time, etc. are determined in this level. Integrating existing research findings of evacuation from sociology, physics and psychology, the strategy level presents a conceptual structure of evacuation behaviors. One evacuee is seen as an agent, who can receive information from the environment and also can response to the environment. The agent has some initial parameters, including the exit selection, the walking speed, the visibility, etc. Triggers (such as smoke) from the environment toggle changes of the parameters according to specified probabilities. For instance, one evacuee might change his exit selection when all other evacuees are moving to another exit.

Besides, in the third level, an evacuation environment is structured with zones, smokes and lights. The zone is a rectangular area. Rooms, exits, safe zones and walls are all presented as zones, with their own special features. Since we keep the same definition of the rooms, exits and safe zones in the improved model, such environmental components will be explained concretely in Section 3.1. Walls are used in the Restricted Walk algorithm, representing where the agent can walk along. However, since the algorithm of deviation is changed, the wall is not used in the improved model any more(it will discuss it in Section 3.3). The smoke in the third level spreads towards all directions, ignoring obstacles. And the smoke grows itself in each time step. For each agent, we calculate the extinction coefficient of the smoke at the agent's position and we change the speed and the visibility of the agent according to the extinction coefficient. Last, the conventional and the EvaQ lighting systems (Nodazzle lighting system in the last years [29]) are considered in the model. Compared with a conventional lighting system, the EvaQ lighting system embeds red lightings to offer better visibility in the smoke [30], blinking green lightings to highlight the available exits [31], and indicators at 90 cm from the floor to show efficient evacuation routes [32]. With EvaQ lighting fixtures, the pre-evacuation times of agents are shorter [33] and the usage of the emergency exit is higher than with conventional lightings [29]. We consider the lighting effect globally except indicators, which means, when the user switches on the EvaQ lighting system mode, the programme will regard the whole evacuation environment under the EvaQ lightings, no matter how the user assigns the lighting fixtures. We still use this assumption in the improved model, due to two facts. First, as far as we know, it is unclear how the different lightings work together in the space. Second, in most cases, one building just adopts one lighting system. Hence, the global consideration of the lighting system is preferable in the present stage.

An agent in the third level has a state marking what he is doing, i.e. Idle, Pre-evacuate, Move, Help, Die and Wander. The agent can only be in one state in a time and the transition between states are based on some transition conditions (In the improved model, this structure is modified a little. We will discuss it in Section 3.2.5). In addition, five types of characters are proposed for convenient assignment, i.e. nurse, staff, elderly, visitor, disabled people. They have different familiarities of the building, different walking speeds and different pre-evacuation times, etc. In the improved model, the features of the agents are changed and the usage of the characters are more flexible.

There are two phases that are distinguished in an evacuation simulation. First, in the beginning of the simulation, agents select their target exits, pre-evacuation times and the speeds, etc., according to pre-defined distributions and the user's assignment. Second, during the simulation, the program has a stochastic process to dynamically change the parameters (target exit, the pre-evacuation time and the speed, etc.), based on triggers (such as noticing the smoke). In each time cycle, the algorithm checks whether the situation satisfies the trigger condition. If so, an event, such as shortening the pre-evacuation time would be executed in a specified probability. In the improved model, we propose a new exit selection algorithm, which is more flexible and could be used in both phases. Moreover, we redesign some functions in the second phase and add several new features such as dynamic time cycle (see Section 3.3).

The three-level evacuation model has been tested in a virtual single-layered scenario. The simulation result shows that the model has sufficient capability to represent different evacuation behaviors with and without smoke, under a conventional lighting system and under the EvaQ lighting system.

## 2.3 Verification and validation of the evacuation model

According to [16], a survey among 196 evacuation model users in 36 different countries indicates that validation/verification is the most important factor when selecting an evacuation model. While the concept of verification for an evacuation model is widely accepted as testing the model in a set of hypothetical scenario cases [19] and determining the correctness of the implemented functions, the concept of validation is still under discussion. According to [34], validation is defined as the "process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method". However, there is no any standard about how the users evaluate the accuracy of the tools, how many tests should be performed to assess the accuracy of the model predictions and who to perform these tests [35]. Whereas the verification could be conducted by a set of benchmarks, validation generally relies on the availability of experimental data and the subsequent uncertainties associated with them.

In 1999, Gwynne et al. [36] addressed the lack of data suitable for validation purposes. Until 2007, the international maritime organization released a guidance MSC/Circ.1238, including verification tests and expected results concisely. Although this document describes evacuation in a ship, it can be used in general evacuation scenarios. In 2013, NIST technical note 1822 [18] proposed numerous improvements and expansions based on MSC/Circ.1238, and addressed the need for a comprehensive methodology guidance. To date, several articles motivated by complementing verification tests and standardizing validation approaches have been published [20] [21] [22].

### 2.3.1 Behavioral uncertainty

Uncertainty is divided into different components in the context of fire safety engineering and modeling [18]: model input uncertainty, measurement uncertainty, and intrinsic uncertainty.

1. The model input uncertainty is associated with the parameters obtained from experimental measurements that are used as model input, i.e. the assumptions employed to derive model input from the experiments as part of the model configuration process.
2. The measurement uncertainty is associated with the experimental measurement itself, i.e., the data collection techniques employed.
3. The intrinsic uncertainty is the uncertainty associated with the physical and mathematical assumptions and methods that are intrinsic to the model formulation.

For the evacuation models containing stochastic processes, there is another type of uncertainty, namely behavioral uncertainty. The behavioral uncertainty is associated with the stochastic factors, such as an exit selection produced by a random process. However, the behavioral uncertainty can not be obtained within a single model run. For example, among totally 100 evacuees, 45 evacuees select exit A in the first model run, while 58 evacuees select exit A in the second model run. Through multi-times model runs of the same scenario, a trend or a expected value of the result is used to evaluate the stability of the model. The process of evaluating such a trend is called convergence measurement.

To address the stability of the model, convergence measurements are widely used to compare a few sets of data. In [37], a quantitative method using convergence criteria based on functional analysis is presented to address this issue. Five criteria, i.e. the total evacuation time (TET), the standard deviation of total evacuation times (SD), the Euclidean Relative Difference (ERD), the Euclidean Projection Coefficient (EPC) and the Secant Cosine (SC) should be measured in multi-times model's runs to evaluate the behavioral uncertainty. The evaluation procedure is as following:

1. Define the acceptance criteria.
2. Simulate $N$ runs of the same evacuation scenario.
3. Calculate the convergence measures.
4. Compare the convergence measures with the acceptance criteria. If five conditions are satisfied within $N$ runs, the curves generated by $N$ runs meet the acceptance criteria. If one or more of the conditions are not satisfied, we need to proceed with Step 5.
5. Simulate the same scenario extra $E$ times.

This stability evaluation procedure is also used as a part of a validation approach. Therefore, we will discuss its details in Section 2.3.3.

### 2.3.2 Verification approach

Gwynne et al. [38] identified five main elements that should be verified and validated (V&V) for an evacuation model, i.e. pre-evacuation time, movement and navigation, exit usage, route availability and selection, and flow condition/constraints. To assess the model capabilities, the presented behaviors in these five aspects of the model should be compared with ideal cases, which are understood as "scenario tests" in most of relevant researches. The tests are structured in five parts [18]: (1) *Geometry*: the configuration of the test; (2) *Scenario(s)*: the evacuation scenario that is going to be simulated; (3) *Expected result*: the result (qualitative or quantitative) that the evacuation model is supposed to produce; (4) *Test method*: the qualitative (e.g., visualization of the represented behavior) or quantitative (e.g., comparison of evacuation times, flows, etc.) method employed for the comparison between the expected result and the simulation results; (5) *User' actions*: the actions required of the tester while performing and presenting the tests.

After conducting verification tests, we compare the results produced by simulation and the expected results by hypothesis tests as follows:

- Anderson-Darling test [39]: Anderson-Darling test is a statistical hypothesis test of whether a given sample of data is drawn from a given probability distribution. In its basic form, the test assumes that there are no parameters to be estimated in the distribution being tested, in which case the test and its set of critical values is distribution-free.
- Chi-squared test: Chi-squared test is a statistical significance test used in the analysis of contingency tables. It is used to determine if there are nonrandom associations between two categorical variables. For the chi-square approximation to be valid, the expected frequency should be at least 5.
- Mann-Whitney U test [40]: In statistics, the Mann-Whitney U test is a nonparametric test of the null hypothesis that it is equally likely that a randomly selected value from one sample will be less than or greater than a randomly selected value from a second sample.
- two-sample Kolmogorov-Smirnov test [41]: The two-sample Kolmogorov-Smirnov test is one of the most useful and general nonparametric methods for comparing two samples, as it is sensitive to differences in both location and shape of the empirical cumulative distribution functions of the two samples.

### 2.3.3 Validation approach

#### Logistic regression and Wald test

For random variables valued 0 or 1, if the data only has one factor, we can apply Chi-squared test to compare the results. However, sometimes the experiment involves two or more factors. For instance, we want to compare the simulation result with the experimental result under two scenarios, where one factor is "simulation" or "experiment" and another factor is the scenario type. In this case, logistic regression is an available solution [42].

In logistic regression, one considers a categorical response variable $E(x,y)$ which depends on several independent variables. In our context, we consider two independent variables $x$ and $y$. The logistic regression model is given by

$$E(x,y) = \frac{1}{1 + e^{-(\alpha+\beta_1 x+\beta_2 y)}}. \tag{2.1}$$

Given a bunch of data $\{(x_1,y_1,E(x,y)_1),\ldots,(x_n,y_n,E(x,y)_n)\}$, we can think of the logistic regression as a curve-fitting process, i.e. it gives the estimates of the coefficients $\alpha,\beta_1$, and $\beta_2$. Unfortunately, there is no closed-form expression of the maximum likelihood estimations $\hat{\beta}_i$ for the coefficients $\beta_i$, but they can be computed numerically, together with their standard errors $\widehat{\text{se}}(\beta_i)$. In our work, such computations are done with Mathematica [43].

When we have obtained the logistic regression equation, several questions appear. One interesting question in our work is whether the dependent variable $E(x,y)$ really depends on a particular independent variable, say $y$. Such a question can be formulated in terms of the following hypothesis test on the coefficient $\beta_2$ of $y$

$$H_0 : \ \beta_2 = 0, \tag{2.2}$$

$$H_1 : \ \beta_2 \neq 0. \tag{2.3}$$

In the context of logistic regression, such a hypothesis test is called a *Wald Test*. The solution is to consider the $z$-statistics which is defined via

$$z = \frac{\hat{\beta}_2}{\widehat{\text{se}}(\beta_2)}. \tag{2.4}$$

It is called a $z$-statistic because it is asymptotically normal

$$z \sim N(0,1) \tag{2.5}$$

and the normal distribution $N(0,1)$ is dubbed the $z$-distribution.

According to the normal procedure of hypothesis tests and the cumulative distribution function of $N(0,1)$, we can roughly conclude that under the level of $\alpha = 0.05$, if $z < 1.96$, then the null conjecture $H_0 : \beta_2 = 0$ cannot be rejected, hence the dependent variable $E(x,y)$ does not depend on the predicator variable $y$. We will give explicit examples in Section 5.1, when we validate our model.

### Functional analysis validation

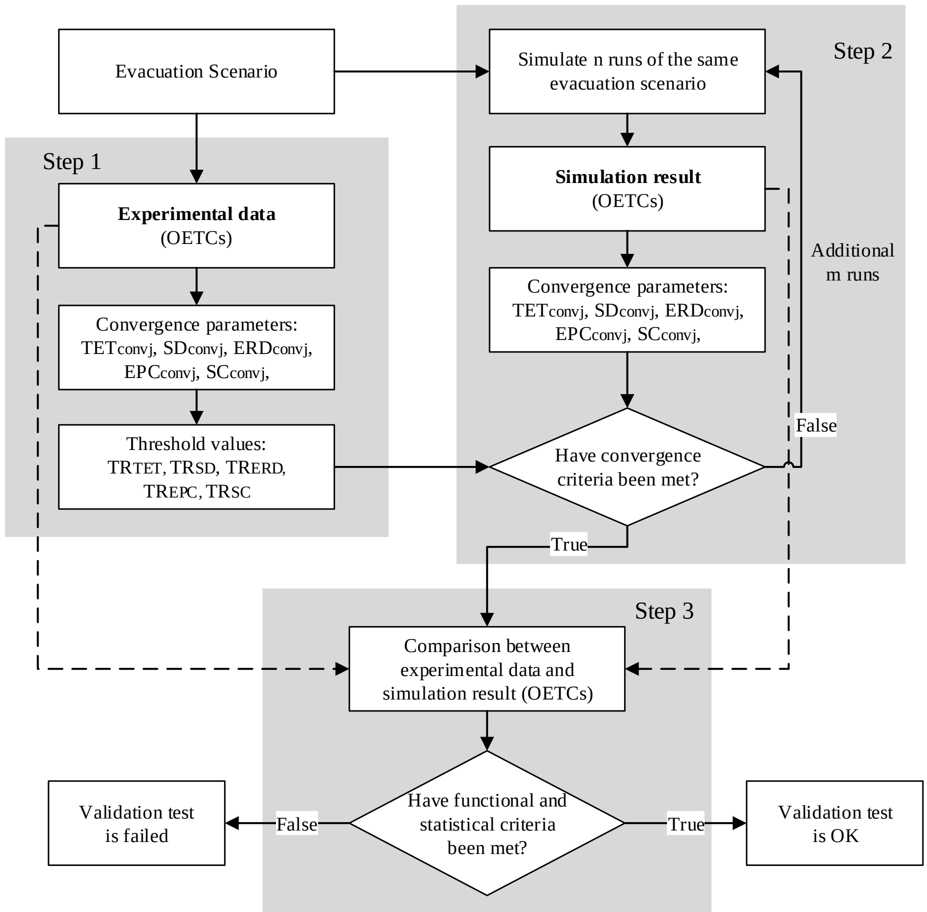



Figure 2.1: Conservation of mass [44]

The functional analysis approach for evacuation validation was established by Peacock [23] in 1999. Then in 2014, Lovreglio [44] gave a detailed validation procedure (see Figure 2.1), where $TET$ represents the average maximum evacuation time among several run times; $SD$ represents the standard deviation of maximum evacuation time among several run times; $ERD$, $EPC$ and $SC$ are three functional analysis operators, representing the differences between two time curves (time curve: evacuation times of evacuees in ascending order). From these, $TET_{convj}$, $SD_{convj}$, $ERD_{convj}$, $EPC_{convj}$ and $SC_{convj}$ represent the convergence levels of the parameters. $TR_{TET}$, $TR_{SD}$, $TR_{ERD}$, $TR_{EPC}$ and $TR_{SC}$ are the corresponding thresholds for the convergence levels.

The validation procedure includes three steps:

1. Step 1 analyzes the experimental data.The main goal of this step is to investigate the behavioral uncertainty in experimental data and its variation around the average value with the increase in the number of trials.
2. Step 2 focuses on the analysis of evacuation simulation results. The number of repeated runs of a single scenario is defined in accordance with a set of acceptance criteria on the convergence of evacuation model predictions. This criterion is based on the comparison of the convergence measures used to investigate the experimental and simulated behavioral uncertainties.
3. Step 3 deals with the comparison between experimental data and simulation results.

To our knowledge, the only threshold standard is suggested by Galea et al. [45] in 2012.

## 2.4 Evacuation experiments

### 2.4.1 Alternative escape route indication

In 2010, M. Kobes, K. Groenewegen, and M. Ten Wolde conducted an evacuation experiment, associated with evacuation behaviors under different lightings [29]. In contrast to conventional lightings, the lighting company EvaQaid proposed the Nodazzle lighting system. Nodazzle is an alternative system for escape route designation. The system consists of three types of lighting fixtures. The first fixture embeds a green illuminated icon in an arrow shape, and shines light source pointing towards the ground. It is located at 90 cm above the ground. The second fixture has a red light source that indicates the escape route. The last fixture is placed at the emergency exit, providing green illumination. All these three types of lights have area illumination. The red lighting has an oblong distribution, which is suitable for illuminating a corridor. The experiment was aimed at validating the capability of the Nodazzle lighting system to shorten the movement time in the smoke, meanwhile to increase the usage of the emergency exit. In general, the experimental result meets the expectation, indicating positive effect of the Nodazzle lighting system on helping evacuees to find escaping routes.

To validate our model, we adopt the walking test in this article. The scenario of the walking test was one layer of a building (see Figure 2.2), i.e. KIWA building in Rijswijk, the Netherlands. A main exit was located at the right side of the corridor, connecting to a staircase, and a door to a room, i.e. K28, was assumed as an emergency exit in this scenario. Two smoke generation fixtures were assigned in the corridor, which filled the generated smoke in the corridor before the experiment begins. Two testing scenarios, embedding different lighting settings, were implemented in the experiment. In the conventional lighting scenario, there was a normal exit sign at position A (at height 2m), marking the location of the emergency exit. In the Nodazzle lighting scenario, four indicators pointing to the direction of the emergency exit were located at positions A, B, C and D, 90 cm above the ground. Besides, an exit sign with green illumination was assigned at a high position (at height 2m) at position A, and a fixture with red lighting was used in the middle of the corridor. In both scenarios, a lamp with normal white lighting was placed in room K31.

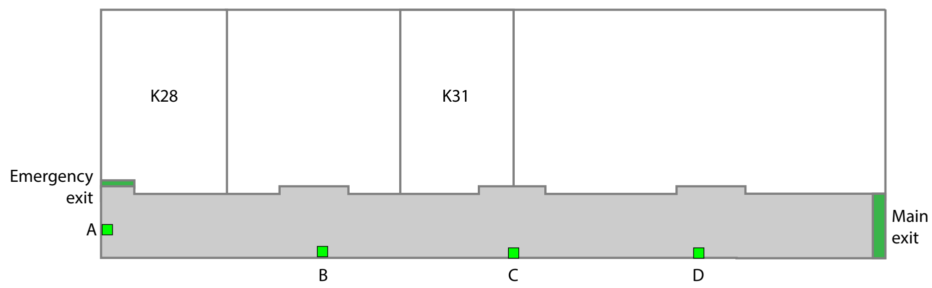



Figure 2.2: Walking test scenario

The participants were divided into two groups, corresponding to two scenarios. A test group entered the test corridor with the test coordinator, through the main exit in the scenario, which made the participants familiar with the route from K31 to the outside. At the moment that the participants walked towards K31, there was no smoke and the participants did not notice the emergency exit. The participants were asked in room K31 to wait. When the participants were waiting in room 31, smoke was blown into the corridor with two smoke generators. Then one test person from the group was taken to the starting position of the test, i.e. right outside the door to the hallway, where there was a hallway created so that the other participants had no direct view of the door. After that the test person was instructed to read an instruction paper while others did not know what the assignment was. On the note was the following message:

*"There is a fire. Leave the building via the emergency exit."*

The test coordinator recorded the begin time at this moment. After the participant egressed to one of two exits, the observer behind the door recorded the exit selection and the movement time of the participant.

There were in total 41 persons who participated the walking test. 20 among them took the experiment in the conventional lighting scenario and 21 among them took the experiment in the Nodazzle lighting scenario. The testing result and how we apply the experimental data to validate our model will be discussed in Section 5.1.

### 2.4.2 Evacuation in a classroom

An evacuation experiment associated with evacuation times and emergent phenomena was proposed by Zhang et al. [46] in 2008. The experiment was conducted in a classroom as schematically illustrated in Figure 2.3. There was only one exit in the classroom. The chairs folded automatically, which means, when the students stood up, the chairs would be folded and would not occupy the space for the students who wanted to move. Two video cameras were located at the platform and in front of the exit to record the evacuation process.

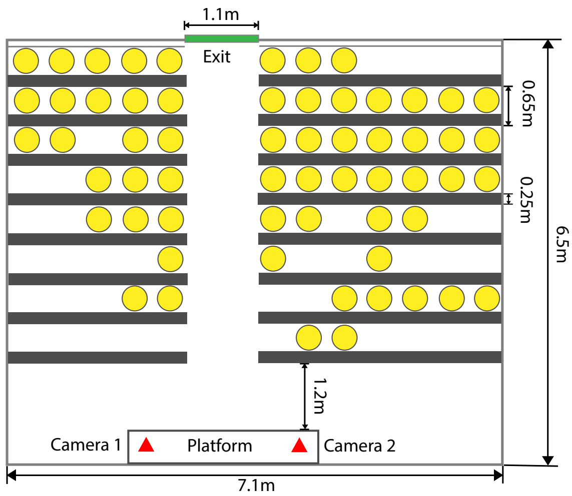



Figure 2.3: Classroom scenario

In total 60 students participated this experiment. At time $t = 0$, all students were sitting on their chairs while they heard the emergency alarm. Because of the restriction of desks, the students at the left (right) side of the aisle moved to right (left) to enter the aisle and then moved forward to the exit. Once the students arrived at the exit, they went through the exit and leaved the classroom. The whole evacuation process was recorded by the two cameras.

In this experiment, indicated by the camera recording, the authors obtained pre-evacuation times of students, which varied between 0.4 to 24.0 seconds. Except for the pre-evacuation times, several typical evacuation phenomena could also be observed, i.e. variable velocities, continuous pedestrian flows toward the exit and monopolizing exit.

In this experiment, the authors provide the evacuation time (pre-evacuation time + movement time) and the pre-evacuation time of each student in the experiment, shown in Table 2.1. The rows in the table correspond to the rows of the seats and the columns to the seat numbers in the classroom. By such detailed data, we can apply an functional analysis approach to validate our model, which will be discussed in Section 5.2.

Table 2.1: Individual evacuation times and pre-evacuation times

| Column | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row 1 | **27.5** | **25.5** | **22.5** | **17.0** | **2.7** | **5.7** | **10.7** | **14.0** | | | | |
| | 22.8 | 22.8 | 16.8 | 12.4 | 0.4 | 4.0 | 8.0 | 9.2 | | | | |
| Row 2 | **16.0** | **7.0** | **6.5** | **6.0** | **5.1** | **4.4** | **7.7** | **10.2** | **14.0** | **16.0** | **16.5** | **17.8** |
| | 9.6 | 2.8 | 2.4 | 2.4 | 3.2 | 2.8 | 4.8 | 3.6 | 4.4 | 6.0 | 8.4 | 8.4 |
| Row 3 | **30.7** | **30.5** | | **12.1** | **10.5** | **11.0** | **12.3** | **15.5** | **17.0** | **23.7** | **24.3** | **28.2** |
| | 24.0 | 22.8 | | 6.4 | 6.0 | 7.2 | 2.0 | 7.2 | 8.8 | 16.0 | 15.2 | 20.8 |
| Row 4 | | | **23.0** | **19.1** | **18.5** | **8.0** | **28.0** | **30.0** | **30.5** | **32.2** | **36.0** | **36.6** |
| | | | 16.0 | 11.2 | 11.2 | 5.2 | 16.0 | 14.0 | 16.8 | 20.4 | 21.2 | 18.4 |
| Row 5 | | | **34.8** | **33.6** | **28.5** | **14.5** | **18.0** | | **36.7** | **37.0** | | |
| | | | 18.8 | 21.2 | 19.6 | 6.4 | 8.4 | | 20.4 | 18.4 | | |
| Row 6 | | | | | **7.8** | **13.0** | | | **23.0** | | | |
| | | | | | 3.2 | 4.8 | | | 10.8 | | | |
| Row 7 | | | | **26.2** | **21.8** | | | **19.8** | **20.5** | **22.8** | **25.9** | **26.8** |
| | | | | 13.2 | 10.0 | | | 5.6 | 8.0 | 9.2 | 12.4 | 13.2 |
| Row 8 | | | | | | | **20.5** | **21** | | | | |
| | | | | | | | 7.6 | 8.0 | | | | |

The upper values in bold represent evacuation times and the lower values represent pre-evacuation times. The blank cells represent there was no student in that position.

# 3 Improved evacuation model

In this chapter, we describe the improved evacuation model in three aspects, i.e. evacuation environment, evacuee, and evacuation simulation. In section 3.1, we introduce how we construct an evacuation environment, involving obstacles, multi-floors, smokes and lightings. In section 3.2, we discuss how we model an intelligent agent to represent a realistic evacuee. In section 3.3, we describe how we conduct an evacuation simulation with two phases, i.e. initialization and modification. Last, in section 3.1.9, the implementation of the model will be explained.

## 3.1 Evacuation environment

Before we discuss the evacuation simulation, we introduce how we define an evacuation environment as follows:

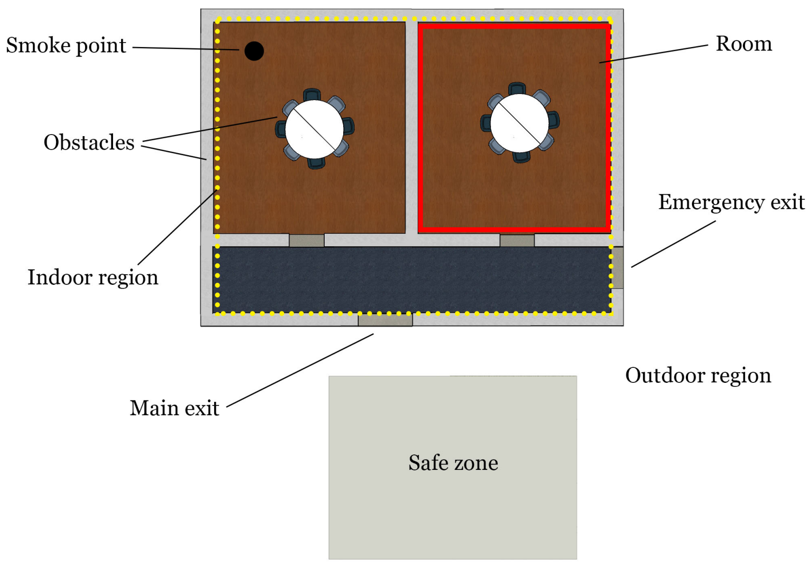



Figure 3.1: A single-layered environment

### 3.1.1 Walkable area and obstacle

A walkable area is defined as an area consisting of polygons, where agents can walk on. As shown in Figure 3.1, the whole space could be seen as a walkable area. For simulating walking in multi-layered environments, walkable areas can be specified in different layers. Even though the path planning on walkable areas are based on two dimensions, the walkable area itself can have any shape with fluctuations in the height, which allows the user to build elevated terrains in one layer. However, the overlapping walkable areas in the same layer can only be recognized as one.

An obstacle is an area where the agent cannot go through. Similar to walkable areas, obstacles in one layer are projected onto a plane, and the obstacles can be declared in multiple layers as well. As shown in Figure 3.1, walls and tables are obstacles. In addition, the user can add or remove removable obstacles during the evacuation simulation.

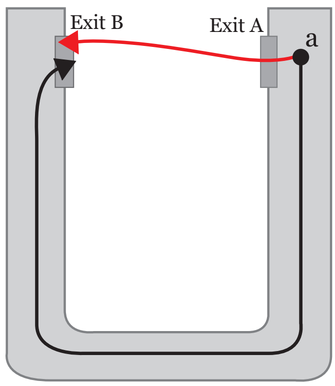



Figure 3.2: A U-shaped corridor

### 3.1.2 Region

In the previous model [1], when an agent selects a target exit, he always follows a short path. However, this is unrealistic in some scenarios. For example, in Figure 3.2, the agent $a$ is assigned to arrive at Exit B. The red line represents a possible trajectory produced by the previous model, in which $a$ firstly passes through Exit A before reaching Exit B.

To solve this problem, we assign different costs of different walking areas, which named "region". When an agent walks indoors, the cost of indoor region is set to 1 and the cost of outdoor region is set to a relatively high value. When the agent passes an exit and walks outdoors, the costs will be reversed. The path planning not only considers the walking distance, but also considers the cost of the path. The path with the minimum cost will be selected as a desired path. In Figure 3.2, the indoor region is marked in grey, as the other walkable areas are seen as outdoor regions. A correct trajectory is shown as a black line in Figure 3.2.

### 3.1.3 Room

The room is a rectangular area, defined with a minimum point and a maximum point. Agents can be generated in rooms and linger in rooms in their pre-evacuation times. In general, rooms are the places where agents stay in before they move to exits. In evacuation scenarios, a room can be used to represent an apartment or an office, etc. Actually, people always behave variously in different locations. It cannot be expected that people in a church, a cinema or a skating rink will react the same way in the event of a fire even though these buildings have different demographics. For instance, pre-evacuation times in an university, in a hospital, in a hotel and in stores are around 70.8 seconds [47], 14 seconds [48], 129.2 seconds [32] and 30 seconds [49], respectively. We concluded in our small project that in a private environment, people receive less stimuli such as others' actions compared with in a public environment. Therefore, we defined two types of rooms:

- Public room: The public room represents the area in which social communications happen between different agent groups. In a public room, we can observe herding behaviors of evacuees when they select target exits or determine times to move. In common cases, stores, waiting rooms in the hospital and churches can be classified as public rooms.
- Private room: The private room represents the area that has no social communication between different groups, which means evacuees do not consider the surrounding crowd. A private apartment is a typical example of a private room.

For a building, the user can assign different types of rooms for different parts. For example, in a high-rise residence block, the ground floor could be a public room and apartments should be set as private rooms.

### 3.1.4 Exit

The exit is a connection between an indoor region and an outdoor region. In Figure 3.1, the way out of the room is not an exit since both sides of the way out are indoor regions, while two way outs in the corridor are defined as exits. The exit is defined by a rectangular bounding as the room. When an agent moves to an exit, he actually moves to a randomly generated point in the rectangular area. The exit can be assigned in any layer as long as the user regards the outside of the exit is safe.

The exit can be opened or closed at any time. When the exit is open, agents can walk through it and when the exit is closed, agents can not pass through it any more. Two types of exits are considered in our model, i.e. the main exit and the emergency exit, which can both be used in evacuation. However, the emergency exit is usually ignored by evacuees, yielding congestions near the main exit [50]. How agents select their target exits will be discussed in Section 3.2.3.

### 3.1.5 Safe zone

After an agent passes through an exit, he does not stop his pace, instead, he continuously moves to a safe zone. Arriving at the safe zone means the agent is safe and he can stop walking. In real life, a safe zone usually represents a rallying point, such as the playground of an primary school. In our model, the safe zone is defined by a rectangular bounding box. One safe zone corresponds to at least one exit. How exits correspond to the safe zones is defined by the user. As the same as the exit, the user can set safe zones in any layer as long as he thinks the safe zone area is safe for the agents.

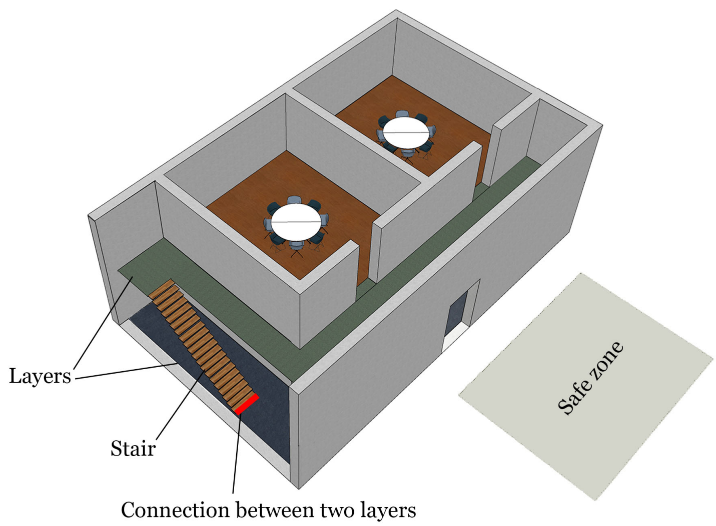



Figure 3.3: A multi-layered environment

### 3.1.6 Layer and stair

In real life, many evacuations happen in multi-layered environments such as high-rise residence buildings. To simulate such scenarios, we introduce the multi-layered environment. As shown in Figure 3.3, a stair (belonging to the upper layer) is built between two layers, with a connection on its bottom. The connection provides a means of moving between two layers [17].

- Layer: To construct a building, a floor could be defined as a layer. A layer includes information of walkable areas, obstacles, regions, rooms, exits, safe zones, stairs, smoke points and lightings.
- Connection: A connection is the way to connect two layers. It is defined with two endpoints, where the agent can walk through.
- Stair: In our model, a stair can be either a part of the upper layer or a part of the lower layer. It can also be an independent layer with connections with other layers. The stair has a pitch, which is normally lower than 45 degrees.

### 3.1.7 Smoke point

The smoke point represents the generation point of the smoke. A simple smoke function is embedded in our model, which can simulate smoke propagation in multi-layered two dimensions (2.5D) environments. Since the agent movement is considered in 2.5D in our model, a 3D fluid-dynamic smoke model might be too expensive and unnecessary to some extent. Even the 2.5D smoke model is not realistic as a 3D fluid-dynamic smoke model, it can still be seen as a real-time and feasible solution based in current stage.

In our smoke model, the smoke propagates indoors towards directions of eight neighborhoods. Compared with the smoke function in the previous model, the new smoke function considers the surrounding environment, involving the obstacles and layers. In addition, the new smoke function supports multiple smoke generation points.

To specify a smoke location and its parameters, the user need to declare at lease one smoke point in a layer, with the spreading speed $V$, the referred toxicity $TO$ and the trigger time $T$. Furthermore, we define the effect of the smoke by extinction coefficient $C_s$, which is the sum of the scattering coefficient and the absorption coefficient, representing the density of the smoke.

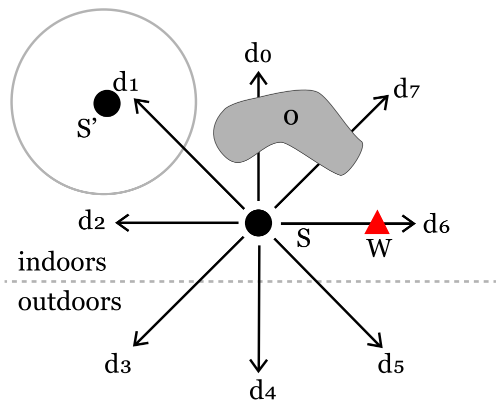



Figure 3.4: Smoke point

As shown in Figure 3.4, the propagation of the smoke is based on its eight neighborhoods in a two dimensional plane and the propagation ray's length. We denote the smoke point as $S$, another smoke point as $S'$, the obstacle as $O$, the walkable area as $W$, and the eight directions as $d_n$.

**Algorithm 1** Smoke propagation algorithm

**Require:** $D \leftarrow$ eight directions
**Require:** $l_{max} \leftarrow$ the maximum length of the ray cast
**Require:** $d_f \leftarrow (0,0.1,0)$ ▷ the offset in height when generating a new smoke point

```
function SMOKE PROPAGATION()
    S ← center of the smoke
    l ← the length of the propagation ray
    for all d in D do
        hit ← RAYCAST(S, d, l_max)
        if hit = obstacle or hit = removable obstacle or hit = smoke then
            Continue
        else if hit = walkable area then
            GENERATE SMOKE(S + d ∗ l, Up)
        else if hit = empty then
            GENERATE SMOKE(S + d ∗ l, Down)
        end if
    end for
end function
function GENERATE SMOKE(p_e, d_e)
    hits[] ← RAYCASTALL(p_e, d_e, l_max)
    IfIndoor ← false
    d_m ← INFINITY
    nearHit ← and Hit
    for all hit in hits do
        if hit = indoor Region then
            IfIndoor ← true
        end if
        if hit = walkable area and hit.distance < d_m then
            nearHit ← hit
            d_m ← hit.distance
        end if
    end for
    if nearHit = walkable area and IfIndoor then
        p_s ← nearHit.position + d_f
        CLONE SMOKE(nearHit.layer, p_s)
    end if
end function
```

Firstly we calculate the period $f_s$ of the smoke propagation by:

$$f_s = \frac{l}{V}, \tag{3.1}$$

where $l$ represents the length of the ray casted from the smoke point (always 0.5 m to 1.5 m) and $V$ represents the user-defined smoke speed. A smoke point $s$ tries to diffuse to his eight neighborhoods at $f_s$ after its generation. It should be noted that we only consider the smoke propagation indoors to avoid unnecessary calculations.

When the propagation begins, for each direction $d$ corresponding to a neighborhood, a ray with length $l$ is casted from the smoke point $S$ towards $S + d$. It is implemented by the "RayCast" function with three parameters, i.e. a start point, a casting direction and a maximum length of the ray. If the ray collides with any obstacle or removable obstacle, the smoke cannot propagate to this direction. In addition, we also consider the collision between smoke points. The smoke has a box collider with width, height, and length which equals to $0.9 * l$. When the ray collides with the collider, the smoke cannot diffuse towards this direction as well. Besides, if the ray collides with a walkable area (the walkable area is a stair in most cases), such direction is regarded as available for propagation. In another case, the ray collides with nothing, then we also determine that we can try to generate a new smoke point towards this direction. In Figure 3.4, $d_2, d_3, d_4, d_5$ and $d_6$ are available directions.

After we have available propagation directions, we can check whether we can generate a new smoke at a expected point $p_e$ with a projection direction $d_e$, where $p_e$ and $d_e$ are offered by the "Smoke Propagation" function (shown in Algorithm 1). $p_e$ is calculated by

$$p_e = S + d * l. \tag{3.2}$$

$d_e$ is a up vector when the ray collides with a walkable area, or a down vector when the ray collides with nothing. In this step, we actually consider how we put the new smoke point in a proper position on the walkable area in a proper layer. A ray is casted from $p_e$ towards $d_e$ direction, with length $l_{max}$, and then we determine whether the first collided object is a walkable area and whether the walkable area is in a indoor region. If so, we can generate a new smoke point, with a small height offset on the surface of the walkable area. The new smoke is generated by the function "CloneSmoke", with two parameters, i.e. the generation point and the target layer. In Figure 3.4, even though $d_3, d_4$ and $d_5$ are available directions, we do not generate smoke points on these three directions because their corresponding positions are outdoor.

Except for propagation in the space, the smoke grows itself during the time. Unfortunately, we cannot find any existing research on simulating smoke growth in 2.5 dimensions. To our knowledge, all evacuation experiments applied a static smoke density rather than a variable smoke density. And all smoke research works in three-dimensions. Hence, to simply describe the growing smoke, we use a monotonic increasing function of extinction coefficient $C_s$, with a decreasing growth rate:

$$C_s = Log(t_s, 30), \tag{3.3}$$

where $t_s$ represents the time after the smoke generation. It should be noted that this function is designed without any academic knowledge, which should be improved in the future. The user can also use a statistic extinction coefficient or introduce other equations.

For an agent with position $p_c$ in a smoky environment, he has a overlap sphere which radius equals to $l/2$. We determine the smoke points in the range of the overlap sphere and select the highest extinction coefficient (the most dense smoke point), meanwhile the smoke points should be in the same layer with the agent.

In this smoke model, a small ray length will yield realistic performance of the smoke. In this case, the smoke point is more like a particle, and the propagation is like a 2.5D particle movement. While with a big ray length, the simulation can still keep correctness to some extent, since the contributing value, i.e. $C_s(p)$, is calculated based on the ray length. However, it should be noticed that a too big ray length may result in smoke that cannot diffuse to a narrow corridor. The suggested value of the ray length is between 0.5 m to 1.5 m.

### 3.1.8 Lighting

Two types of lighting system, i.e. the conventional lighting system and the EvaQ lighting system (developed by company EvaQaid [51]), are incorporated in our model.

In the conventional lighting system, lights in rooms and corridors are modelled as gray cylinders, with white and spherical illumination in emergency situations. And the conventional exit sign is modelled as a cuboid. It is arranged near the exit and activated in both the usual situation and the emergency situation, with self-illumination in white color. Under the emergency situation, other lights shut down, while these two types of lights offer the view for evacuees.

In the EvaQ lighting system, five types of lights are considered, i.e. the EvaQ AP recessed ceiling light, the EvaQ ER recessed ceiling light, the Luna light with AP module, the Salida Plus exit fixture, and the indicator light, shown in Figure 3.5.

- The EvaQ AP light and the EvaQ ER light have illuminations in the red color, which reflects danger and urges people to move early [52]. The difference between the EvaQ AP light and the EvaQ ER light is their illumination distributions. The former has a conventional spherical illumination distribution, while the latter has an oblong illumination distribution. Hence, the EvaQ AP light could be used in the room, and the EvaQ ER light is appropriate to be assigned in the corridor. Compared with the conventional light, the EvaQ ER lights can illuminate the whole corridor with just a few fixtures. To assign the EvaQ AP light and the EvaQ ER light, the user should determine the positions of the lights.

- The Salida Plus exit sign has not only a self-illuminated sign as the conventional exit sign, but also a green blinking (1 Hz) light in front of the fixture and a green blinking power LED with the beam aiming directly to the floor. In the emergency situation, a blinking green lighting is more attractive than normal static white lighting, concluded by Galea et al. [31] and Ronchi et al. [53], yielding higher usage of emergency exits. To assign the Salida Plus exit sign, the user should specify a position.
- The Luna light embeds two modules, i.e. the usual lighting module and the EvaQ AP module. It is suitable for family houses, offering both daily lighting and emergency lighting. To assign the Luna light, the user should determine the position of the light.
- On the indicator, the blinking (2 Hz) arrow represents an available direction of the evacuation route. To assign an indicator, the user need to declare a specified position and available directions of the indicator, i.e. left, right, both or neither.

(a) AP (b) ER (c) Luna (d) Exit Sign (e) Indicator

Figure 3.5: EvaQ lighting system

In 2004, Yamada et al. [30] indicate that the visibility is 20% - 40% better in the smoke with the red lighting, compared with the white lighting. Since the extinction coefficient is the only influenced factor to the visibility, we can determine the extinction under the red lighting as Equation (3.4) according to [54]:

$$C_{sr}(p) = \begin{cases} 0.939414C_{sw}(p)^{1.3}, & \mathit{for} \quad C_{sw}(p) < 1.23, \\ C_{sw}(p) & \mathit{for} \quad C_{sw}(p) \geq 1.23, \end{cases} \tag{3.4}$$

where $C_{sr}(p)$ represents the extinction coefficient at position $p$ under the red lighting and $C_{sw}(p)$ represents the extinction coefficient at position $p$ under the white lighting.

### 3.1.9 Implementation

The evacuation scenario is built in Unity3D, hence the user can easily import models of the buildings and the agents. To determine an evacuation scenario, the environmental elements mentioned in the above subsections should also be specified by the user.

The walkable area and the obstacle use the same definitions with the concepts in the bottom level of our model, i.e. the UUCS framework.

The region is implemented by the weighted region function in the UUCS framework. The weighted region API allows us to set region preferences of an agent to represent the region cost. The indoor region's preference of the agent is set to 1 when the agent walks indoors, meanwhile the outdoor region's preference is set to 1000. Once the agent passes through the exit and walks outdoors, the preferences of two regions will be reversed. The path planning algorithm calculates the cost for each path candidates and the selects the path with minimum cost as the indicative path. However, the weighted region function has some bugs, resulting in instability of the region feature.

For obtaining collision-free positions in rooms, exits and safe zones, we use a random sampling function in the UUCS framework. With a minimum point, a maximum point and a target layer, the function can outputs a collision-free position in the specified area.

We use the same definitions of the layer and the connection as in Van Toll et al. [17]. The endpoints of a connection need to be specified in a particular order: when standing on endpoint 1 and looking towards endpoint 2, layer 1 lies to the left of the connection, and layer 2 lies to the right. Since agents can only walk between two endpoints, endpoints should be set cautiously according to the width of the stair. The stair is implemented as a subtype of the walkable area, with a special parameter, i.e. pitch.

To implement the smoke model, we adopt the ray casting, the collision detection and the particle system functions in Unity3D. The lighting effects are implemented by default lightings in Unity3D and a open-source shader framework [55].

## 3.2 Evacuee

The agent in our model is not seen as a passive particle, but an active character, who makes decision himself. The agent has both constant features such as the body radius and variable features such as the speed. During the evacuation simulation, the agent receives information from the environment, and also gives feedback to the environment. To model an "intelligent" agent, the following features are considered.

### 3.2.1 Body radius, visibility, speed and accumulated toxicity

The agent is modelled as a disk with a static body radius in the bottom level, i.e. the path planning level. The body radius represents the minimum individual space, which cannot be crossed during the simulation. The user can set any value to the body radius or use the default, i.e. 0.239 m [56].

The visual acuity $V_A$ is used to describe the visibility of the agent in our model. $V_A$ is a constant for every agent in the scenario without smoke, i.e. 1.0, while it is variable in the smoke. According to the formula proposed by Jin et al. [54], the visual acuity at the position $p$ in the irritant smoke is presented as:

$$V_A(p) = \begin{cases} 1.0 & \textit{for} \quad C_s(p) < 0.25, \\ 0.133 - 1.47 \log C_s(p) & \textit{for} \quad 0.25 \leq C_s(p) < 1.2, \\ 0.01 & \textit{for} \quad C_s(p) \geq 1.2, \end{cases} \tag{3.5}$$

where $C_s(p)$ represents the extinction coefficient of the smoke at position $p$.

As an important sensor, the visibility influences the range of the view and the safety feeling of the agent. When the visibility is low, it will be difficult for an agent to find an exit or to notice an indicator. Furthermore, the agent feels restless and has to be close to the walls, which results in a longer movement time.

The walking speed $S$ is variable during the evacuation simulation. Except decreasing in the congestion, the speed varies on the stairs and in the smoke. When the agent is initialized, a preferred speed $S_p$ could be specified by the user or sampled from a walking speed distribution. There are three kinds of distributions. For the young adult, the distribution is a Weibull distribution with $\alpha = 10.14$ and $\beta = 1.41$ [48]; for the elderly people, the distribution is a uniform distribution from 0.71 to 1.85 [19]; for the disabled people, the distribution is a uniform distribution from 0.10 to 1.77 [57].

On the stairs, the speed declines according to the stair's gradient. We denote the gradient as $g$ (degree), then we can calculate the speed by the formula proposed by Fujiyama et al. [58]. The ascending walking speed of the young adult is presented as:

$$S = (-0.0136g + 0.8728)\, S_p \quad \textit{for} \quad 0^\circ < g \leq 64^\circ \tag{3.6}$$

The ascending walking speeds of the elderly people and the disabled people are presented as:

$$S = (-0.0152g + 0.9244)\, S_p \quad \textit{for} \quad 0^\circ < g \leq 60^\circ \tag{3.7}$$

The descending walking speed of the young adult is presented as:

$$S = (-0.0142g + 0.9644)\, S_p \quad \textit{for} \quad 0^\circ < g \leq 67^\circ \tag{3.8}$$

The descending walking speeds of the elderly people and the disabled people are presented as:

$$S = (-0.0165g + 1.0054)\, S_p \quad \textit{for} \quad 0^\circ < g \leq 60^\circ \tag{3.9}$$

In the smoke, the speed declines depending on the visibility. We calculate the speed in the smoke by the formula suggested by Yamada et al. [59]:

$$S = \begin{cases} S_p & \textit{for} \quad C_s < 0.1, \\ 0.97\,S_p & \textit{for} \quad 0.1 \leq C_s < 0.25, \\ 0.97\,V_A^{0.12}\,S_p & \textit{for} \quad C_s \geq 0.25, \end{cases} \tag{3.10}$$

When the agent walks on the stairs and simultaneously in the smoke, the product of two formulas' coefficients will be used as the new coefficient and so the walking speed is obtained by multiplying $S_p$ by the new coefficient.

The accumulated toxicity is a parameter used in the smoky environment. When the agent walks in the smoke, the accumulated toxicity in each time step is the maximum toxicity among the surrounding smoke points. If all of the children smoke points are derived by one parent smoke point, the accumulated toxicity in each time step only depends on whether the agent contacts with the smoke, which equals to the toxicity value of the parent smoke point. The toxicity $TO_p$ of a smoke point is calculated by:

$$TO_p = TO * C_s, \tag{3.11}$$

where $TO$ represents the referred toxicity of the smoke, provided by the user, and $C_s$ represents the extinction coefficient of the smoke point.

### 3.2.2 Pre-evacuation time

The pre-evacuation time is a period of time between the agent hearing the emergency alarm and moving to the exit. In the pre-evacuation time, people linger in their rooms or try to find their friends [60]. In our model, each agent has an initial pre-evacuation time. Even the pre-evacuation time could be shorten in considerable situations, a relatively long pre-evacuation time of each agent is generated in the initialization phase. Except for manually assignment, the initial pre-evacuation time can be sampled from the embedded distributions.

We consider that the pre-evacuation time distribution in a private room, without smoke, should be relatively maximum for an agent. Hence, the pre-evacuation data, i.e. the participants were relaxed in their private rooms, as was published by Kobes et al. [32], is adopted by fitting to a log-normal function $\mathrm{LogN}(\mu,\sigma^2)$ suggested by Shi et al. [61], with $\mu = 4.30008s$ and $\sigma = 0.628501s$. In which situation the pre-evacuation time could be shorten will be discussed in Section 3.3.2.

### 3.2.3 Exit selection

In the initialization, the agent selects a target exit, while the target exit could be changed during the evacuation simulation. In the previous model, the initial exit selection relies on the exit preferences inputted by the user, which is tedious for the user and cannot be re-used during the agent's movement (because the exit preference might be changed). According to existing evacuation research, the exit selection is based on the familiarity of the building and the distances from the agent to the exits [62] [32] [48]. Therefore, we propose a new automatic assignment algorithm in which the initial exit selection depends on these two factors. Two parameters are defined to represent the exit familiarity, i.e. the main exit preference $\rho_m$ and near exit preference $\rho_n$. These two values are both 1.0 when the agent has no preference to the exits. However, when the agent is unfamiliar with the environment, he has a higher probability to select a main exit, which yields $\rho_m$ higher than 1. And when the agent would like to select a near exit, $\rho_n$ is higher than 1.

The algorithm of the exit selection is shown in Algorithm 2. Firstly, we calculate the inverse of the distance between the exit and the agent for each exit, namely $P[e]$, representing the primary probability of the exit selection based on the distance. Secondly, we raise $P[e]$ to the power $\rho_n$. If the exit is a main exit, we give a weight $\rho_m$ to $P[e]$. Then we obtain the selection probability to each exit. Thirdly, we normalize each $P[e]$ to the range $(0,1)$. Lastly, we use a random sampling to select the target exit, according to the probabilities.

This algorithm can be used not only in the initialization phase, but also during the agent's evacuation time. How the agent changes his target exit during the evacuation will be discussed in Section 3.3.2.

### 3.2.4 Cooperate

Supported by the UUCS framework, the agents can be grouped in the evacuation simulation. Agents in one group select the target exit together, begin to move in the same time, and walk coherently with the slowest speed in the group [63]. A group leader is randomly chosen from the group, as a representative, to select the target exit and determine the pre-evacuation time. Besides, the group leader can also be selected by the user.

Except for the coherence within one group, cooperating between different groups are common in evacuations as well. In shopping malls, staff members inform customers about the emergency situation. And in hospitals, nurses help the disabled people to move. In fact, according to some research [64] [65], the notification from others is one of the mainly cue for the agent to egress. In our model, the agent has three boolean parameters, i.e. need help, help and inform, to describe the cooperate behaviors. The

**Algorithm 2** Exit selection algorithm

```
p_a ← position of the agent
E ← exits
ρ_m ← main exit preference of the agent
ρ_n ← near exit preference of the agent
P ← An array of the selection probabilities of the exits
for all  Available exit e in E do
    D ← DISTANCE(e, p_a)
    P[e] ← (1/D)^ρ_n
    if e is a main exit then
        P[e] ← P[e] ∗ ρ_m
    end if
end for
if P is empty then return Null
end if
 NORMALIZATION(P)
test ← Random(0,1)
p_a ← 0
for all P[e] in P do
    p_a ← p_a + P[e]
    if test < p_a then return e
    end if
end for
```

agent needing help, namely disabled agent, cannot move himself. The only way the disabled agent egresses safely is receiving help from others.

The agent who would like to inform other evacuees has a check list including at least one room (the room he stays in). When the agent's pre-evacuation time decreases to zero, the agent will begin checking rooms by the sequence of the check list. The checking behavior is implemented by sequently sampling goal positions from the rooms in the list, guiding the agent to move to each goal position. When the agent has checked every room in the check list, he moves to the exit. The check list is defined by the user, and the default check list only involves the room the agent stays in. The room where the agents have been informed is marked as an "informed room" and so agents in this room have probabilities to shorten their pre-evacuation times.

Furthermore, some agents not only inform others but also would like to help the disabled people to egress [47] [48]. If a helper finds an agent needing help when checking the rooms, he will group and move together to the exit with the disabled agent, even though he does not finish the check list. In such a group, the helper is assigned as the group leader for making a better route choice.

### 3.2.5 State

According to the evacuation timeline suggested by Lovreglio et al. [66], we divide the evacuation process into several phases from the view of the agent, namely states, as shown in Figure 3.6. The agent keeps precisely one state at every moment during the evacuation process, as the states' transition triggered by some rules.

The first state is "Idle". In this state, the agent stays at his initial position in a room. When the agent hears the alarm, his state transfers to "Pre-evacuate" or "Stay" depending on whether he needs help. Otherwise, strong stimuli such as chocking by the smoke will switch the state to "Move", skipping "Pre-evacuate". In the "Pre-evacuate" state, the agent randomly walks in his initial room in the pre-evacuation time. When the pre-evacuation time decreases to zero, the state of the evacuee will be changed to one of the two states, i.e. "Move" or "Check rooms", according to the agent's cooperating parameters. If the agent would like to inform others about the emergency situation, he will enter "Check rooms" state, or else he will move to the exit directly. Following finishing the check list or helping a disabled agent to move, the agent walks to the target exit. In states "Idle", "Pre-evacuate", "Stay", "Move" and "Check rooms", if the accumulated toxicity of the agent up to 1.0, the agent will enter "Die" state, which marks the evacuation of the agent is failed.

After passing through the target exit, the agent will move to the safe zone. This phase is called "Go outside". Arriving at a point in the safe zone represents the success of the evacuation, namely state "Safe". In "Safe" state, the agent stays at a point, without moving.

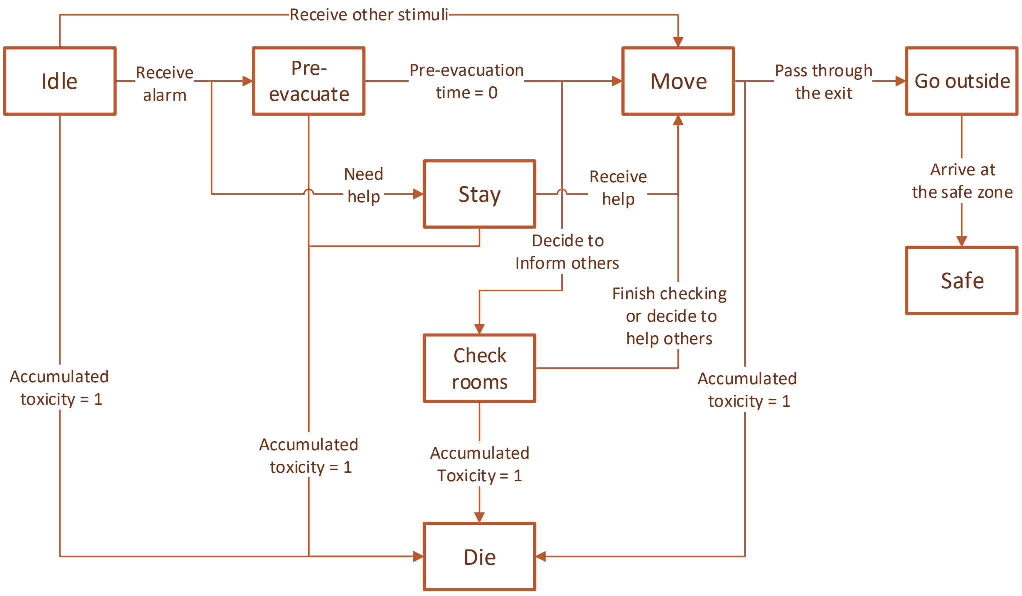



Figure 3.6: States of the evacuee

It is should be noticed that members in one group do not need to simultaneously keep the same state. They only share the same pre-evacuation time and the same exit selection. For example, in a congestion near the exit, one agent passes through the exit while his partner is still blocked by the crowd. In this case, one agent is in the state "Go outside" while another is in the state "Move". We suggest the user to assign the disabled agent and the helper independently (without group member), since different goal positions within a group might yield unexpected walking patterns of the agents. With such a state machine structure, we can easily obtain and analyze the evacuation results, such as the average pre-evacuation time, the average movement time and the surviving probability.

### 3.2.6 Character

For the user without abundant knowledge about evacuation, it would be difficult for him to set parameters for each agent. Hence, we propose six types of typical agents, i.e. normal character, visitor, elderly, disabled agent, staff and nurse, for simply assigning agents to an evacuation scenario. The parameters of the characters are shown in Appendix A. Compared with the previous model, the user can both use these characters or assign values for the agents' features himself.

- Normal character: The normal character can be used as simulating a healthy young adult with medium familiarity with the environment, who does not need help from others neither helps others. It is usually the common character in most of evacuation scenarios.
- Visitor: The visitor is a similar character as the normal character. The only difference between these two characters is the visitor's unfamiliarity with the environment.
- Elderly: The elderly has a larger body radius compared with the normal character. Besides, the preferred speed of the elderly is slow and also decreases sharper on the stairs than the normal character. The elderly character could be used to simulate the agent with healthy limits.
- Disabled agent: The disabled agent has the largest body radius and slowest speed among the characters because of the wheelchair. The disabled agent cannot move himself and needs help from others.
- Staff: The staff member has a short pre-evacuation time and a higher near exit preference, since he is familiar with the environment. In addition, the staff member would like to inform others about the emergency situation. The staff character can be used to simulate not only a clerk but also an occupant at home, who knows its surrounding well.

- Nurse: The nurse character has the shortest pre-evacuation time and the highest near exit preference among the characters. Besides, the nurse would like to inform others and to help the disabled agent.

## 3.3 Evacuation simulation

The evacuation simulation is divided into two phases, i.e. initialization and modification. After setting up the environment and agents in the initialization phase, the environment and the agents are updated in each time step in the modification phase. For clarity, we present an example. An agent selects exit A in the initialization phase, however, in the modification phase, he finds that the exit A is blocked by obstacles and so he has to change his initial selection and moves to the exit B.

### 3.3.1 Initialization

In the initialization phase, the model firstly sets up the environment. Layers, walkable areas, obstacles, regions, rooms, exits, safe zones, stairs, connections, fire points and lightings are registered successively. After that, the agents are registered. The user can manually assign the agents to specified positions and tune the parameters. Additionally, automatically spawning characters in designated rooms is also available in our model. The features of the agents as we mentioned in Section 3.2 are given initial values in this phase. When the initialization finishes, the agent has values of the preferred speed, the visibility, the body radius, the exit selection, the pre-evacuation time and the cooperation parameters. The state of the agent is set to "Idle".

### 3.3.2 Modification

During the evacuation process, both the agent and the environment change dynamically. Supported by the UUCS framework, the user can add or remove a removable obstacle at any time. When a removable obstacle is added to the environment, the path planning algorithm of the agent will take the removable obstacle into account. In addition, the exit could also be opened or closed at any time specified by the user. The agent cannot pass through a closed exit, so the agent will re-select the target exit when he notices his target exit is closed. Additionally, as a variable element, the smoke is calculated in each time step.

In the initialization phase, we use the deterministic method to generate initial values of the parameters for each agent, such as the pre-evacuation time and the exit selection. However, equipped with sensors, some decision-making rules and actuators, the agent can interact with the environment and so changes his behaviors. A stochastic mechanism is presented to describe the agent's behaviors in the modification phase. With such a mechanism, the model can simulate randomness related to the evacuees' behaviors and shows a global trend among the evacuees correlating to empirical results as well. The stochastic algorithm is shown in Algorithm 3.

**Algorithm 3** Stochastic algorithm

```
c ← trigger condition
e ← event
T ← time cycle of testing the condition
p ← the probability of executing the event in each time cycle
timer = timer + ΔTime
if timer > T And c is true then
    timer = 0
    test = Random(0,1)
    if test < p then
        Execute (e)
    end if
end if
```

The stochastic algorithm is executed in each time frame for an agent. The variable $c$ represents a trigger condition, which is always the information obtained from the environment, e.g., a special red lighting. $T$ is the testing time cycle, meaning the period of the conditional test, and $p$ is the probability of executing the event in each time cycle. If we regard $c$ as a stimulus, $T$ could be understood as the stimulating period and $p$ could be seen as the intensity of the stimulus. In each time cycle, the algorithm judges the trigger condition. If the condition is true, a random number between 0 and 1 will be generated to compare with the event probability, and the event $p$ will be executed after the successful random testing. A boolean parameter, i.e. sensitive, is used in this phase, to describe whether the agent is alert to the environment. An alert agent has a higher probability to execute the event. In the initialization phase, the sensitive parameter is assigned to false. As in the modification phase, it might be switched to true in several cases such as noticing the smoke.

### Update the basic features

In each time frame, the model updates the position of the agent by fetching data from the UUCS framework and interpolating between two points. Since the path planning is based on two dimensions, the height (y axis in our model) of the agent is set according to the height of the layer at the same horizontal position, based on the assumption that the agent adheres to the floor all the time. The visibility, the speed and the accumulated toxicity of the agent are updated one time per second with their calculation functions.

**Shorten the pre-evacuation time**

Except the alarm, there are more kinds of stimuli to motivate the agent to move. Receiving stimuli from the environment might shorten the agent's pre-evacuation time or directly changes the state of the agent to "Move" without the alarm.

First, when the agent stays in a public room, he always has a relatively short pre-evacuation time as we discussed in Section 3.1.3. Our model regards the public room as a trigger condition, with the time cycle set to 0.5 seconds. In each cycle, we calculate the executive probability according to the equation:

$$p = 0.5 * \frac{N_m}{N_{sum}}, \tag{3.12}$$

where $p$ represents the executive probability, $N_m$ represents the number of agents in "Move" state in this room and $N_{sum}$ represents the total number of agents in this room. If the agent passes random testing, his pre-evacuation time will be set to zero and he will move to the exit immediately. The parameters are tuned based on an evacuation experiment in a university [47] (can be seen as a big public room), where the average pre-evacuation time is 70.8 seconds.

Second, the notification from an "informant" agent is possible to shorten the pre-evacuation time of the agent. Since the notification is a discontinuous stimulus, the time cycle of the notification is 0.8 seconds initially and then increases 0.15 seconds in each time cycle, representing the stimulus receding, while another notification will reset this value to 0.8 seconds. In each time cycle, the executive probability is 0.05. The successful random testing will shorten the pre-evacuation time of the agent to zero. The parameters are tuned based on an evacuation experiment in a store [49] (can be seen as a big public room with staff members), where the average pre-evacuation time is 30 seconds.

Third, according to the reference [65], the smoke is a strong stimulus for the agent to begin movement, so that in our model, the trigger condition of the smoke effect is the agent standing in the smoke (the overlap sphere of the agent collides with at least one smoke's collider), and the time cycle is set to 0.35 seconds. If the random test number is smaller than 0.08, the agent will move immediately. Besides, the sensitive parameter of the agent will be assigned to true. The parameters are tuned based on assumption that the smoke is the strongest stimulus. The further validation should be conducted in the future.

Last, the red lighting also motivates people to move earlier (we discussed it in Section 3.1.8). The time cycle of the red lighting effect is 0.5 seconds and the executive probability is 0.02. The successful random testing will shorten the pre-evacuation time of the agent to zero. As same as the smoke, the red lighting is a special stimulus for the agent, therefore the agent's sensitive parameter is set to true. The parameters are tuned based on assumption that the red lighting is a medium stimulus. The further validation should be conducted in the future.

**Re-select the target exit**

When the agent is in the "Move" state, he probably changes his mind of exit selection under four situations. First, the agent notices that the target exit is unavailable. In each time frame, the agent casts a ray from its eyes to the target exit. If the ray collides with the exit and the exit is closed, the agent will re-select the exit based on his current position by the exit selection algorithm. The length of the ray is limited to $50 * V_A$. In a non-smoky scenario, the agent can see the exit within 50 meters range, while in a smoky environment, the eyesight range is declined with the density of the smoke.

Second, the herding effect would influence the exit selection of the agent. The herding behavior occurs whenever people behave as a group by putting aside their ability to act as individuals. In the exit selection context, the herding behavior means that the agent chooses the most congested exit only because that is the most popular choice, rather than an exit with less people which may ensure a lower evacuation time [67]. The trigger condition of this case is at least one visible exit for the agent. As a medium stimulus, the time cycle of following others is 0.5 seconds and the executing probability is 0.3 in each time cycle. For each visible exit, we calculate the number of the agents moving towards this exit in the range of 5 meters. And then the most "popular" (most agents moving towards) exit is selected as the new target, while updating the new target exit for the whole group.

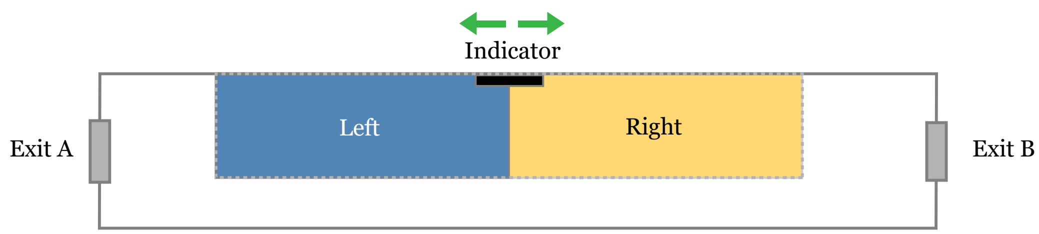



Figure 3.7: Select a goal position near the indicator

Third, when the agent notices a near exit, he might change his exit selection. This rule is commonly used in numerous evacuation models, which says that the path planning is based on the visibility. In our model, noticing the exit is seen as a trigger condition, in which the length of the ray cast is limited to $5 * V_A$ to ensure the candidates of the new target exit are near enough to the agent. As a medium stimulus, the time cycle of following people is 0.5 seconds. Besides, the executing probability is set to 0.2 and 0.45 respectively when the agent is insensitive and sensitive to the environment. With the

Salida Plus exit signs, such a probability will be doubled. The nearest visible exit will be selected as the new target for each member in the group if the random testing is passed. The parameters are validated together with the forth situation in Section 5.1.

Forth, some agents would like to follow the indicators. Concluded by paper [68], people use a shorter time to find a way out with exit indicators, than without indicators. Additionally, Kobes et al. [32] consider that a proper design of the indicators increases the usage of the emergency exits. In our model, the agent casts rays with maximum length $10 * V_A$ to each indicator and tries to find a visible indicator in each time cycle, i.e. 0.8 seconds. The executing probability is set to 0.3 and 0.7, respectively, when the agent is insensitive and sensitive to the environment. If the nearest visible indicator is selected, the agent will attempt to recognize the possible directions pointed by the indicator. According to the research [69], 97% of the evacuees understands correctly the meaning of the indicators and finally reaches the exit, hence, we do not consider the misunderstanding of the indicator. The indicator has three types, i.e., pointing left, pointing right and pointing both directions. To describe the "influencing area" of the indicator, we build a rectangular zone with 18 meters width along the parallel direction and 4 meters length along the perpendicular direction of the indictor, as shown in Figure 3.7. The influencing area is divided into two parts, i.e., the left part corresponding to the left pointing direction and the right part corresponding to the right pointing direction. When the agent decides to follow the instruction of the indicator, the members in his group will together select a random position in the available direction's influencing zone as their new goal positions (The position is at the indoor region, and out of the obstacles). Furthermore, the sensitive parameter is switched to true in this case. Since the sensitive status yields higher executive probabilities of noticing a near exit or an indicator, after the agent arrives at the new goal position, he will pay attention to the exits near him as well as the indicators. An expected result is that the agent follows instructions of a series of indicators and finally egresses from the building. However, when the indicators are in a bad design, such as indicating to a dead end, the agent cannot find an exit in the pointing direction. The parameters are validated together with the third situation in Section 5.1.

We consider that sometimes an agent stops moving. For example, the user introduces some dynamic obstacles during the evacuation and the agent cannot find a path to his goal position. A heavy congestion is built near the exit and so the exit is blocked for a long time. Or the agent decides to follow the instruction of an indicator but he does not receive any other information from the environment to find a way out, therefore he loses his goal position and idles at one point. To solve this problem, we propose a passive blockage solving approach. We calculate how long time the agent stays at one position (except the disabled agent). If the time is longer than 2 seconds, the agent will select a new goal position. In the "Move" state, the agent will re-select the target exit according to his current position. It not only solves the agent's blockage, but also represents some realistic evacuation behaviors, such as avoiding an extremely crowded exit.

### Deviation in the smoke

In the previous model, we proposed a path modification algorithm to represent an agent's deviation in the smoke. However, under a multi-layered environment, the previous algorithm sometimes yields the agent being blocked behind a wall. It is because the old algorithm selects a near wall according to the distance between the wall and the target exit, but in a multi-layered environment, the indicative path is not always towards the exit and the "near" wall is not near any more. To deal with this problem, we use a new method to represent the deviation.

The concept "Safe area" $A_{safe}$ in the previous algorithm is adopted in the new method. It is used to describe one's psychological reliability to the surrounding environment, representing not only the visibility, but also the touching range of a person. Literally, it is the area that an evacuee feels safe. For example, in non-smoky scenario, $A_{safe}$ is large, while in smoky scenario, $A_{safe}$ is becoming smaller as the density of smoke becoming higher. The safe area is modelled as a disk with radius $R_{safe}$, calculated by:

$$R_{safe}(p) = \frac{0.7}{C_s(p)}, \tag{3.13}$$

where $C_s(p)$ represents the extinction coefficient of the smoke at position $p$.

We use the side preference function in the UUCS framework to represent how the agent would like to be close to the obstacle. After the Explicit Corridor Map (ECM) is generated, the agent has a side preference $p_s$ to move in the ECM. If the agent has no preference, then $p_s = 0$; If the agent prefers the left side of the ECM, then $-1 \leq p_s < 0$; If the agent prefers the right side, then $0 < p_s \leq 1$. In our model, each agent has a basic side preference $p_0$, i.e. -1 or 1. And when the safe radius changes, the side preference $p_s$ of the agent is calculated as Equation (3.14):

$$p_s = \begin{cases} p_0/R_{safe} & \text{for} \quad R_{safe} > 1, \\ 1 & \text{for} \quad R_{safe} \leq 1. \end{cases} \tag{3.14}$$

With this new method, the user does not need to manually define walls as before. Not only walls, but also other obstacles including removable obstacles, are taken into account when we construct an environment with API of the UUCS framework. The deviation behavior is actually considered in the bottom level, i.e. the path planning level. However, since this method is based on the ECM structure and the weighted region is based on the weighted grids structure, the deviation function and the weighted region function can not be used in the same time.

# 4 Verification

In this chapter, we discuss the verification process of the evacuation models. The existing benchmarks and tests developed by us are used to verify our model. The verification tests are divided into two categories. The first category is called analytical verification (AN_VERIF) and it refers to testing where the expected results can be derived by simple mathematical formula or evidence. The second category is the verification of emergent behaviors (EB_VERIF), which refers to the verification of the ability of evacuation models to qualitatively produce results which reflect the current knowledge on evacuation. The gender of the agent is not explicitly mentioned in tests. Appendix B presents the list of suggested tests in relation to the core components under consideration.

## 4.1 Pre-evacuation time

Five tests are discussed in this section to verify the model's capability to simulate pre-evacuation times of agents in different environments. The verification test **Verif.1.1** is suggested to verify the model's ability to assign distributions of pre-evacuation times to agents. As we observed in numerous data collections, the following three situations always shorten average pre-evacuation times: the evacuation happens in a public building; a staff member informs others to evacuate; the evacuee notices the smoke. **Verif.1.2**, **Verif.1.3** and **Verif.1.4** are designed to verify the abilities of the evacuation model to simulate these three phenomena, respectively. In addition, a newly developed evacuation lighting system, namely EvaQ lighting system, is being proved to shorten the agent's pre-evacuation time with red lighting. Based on the assumption that the red lighting has positive effect on shortening the pre-evacuation time, **Verif.1.5** is designed to verify the capability of the model to represent such a phenomenon.

All five test scenarios were built in Unity3D. The room had a size of 8 m long, 5 m wide and 3.3 m high. A 1 m exit was located on a wall with 8 m length. 10 evacuees were randomly generated at collision-free positions in this room. The alarm rang at the 2nd second, which was heard by every agent.

**Verif.1.1 Pre-evacuation time distributions** This test is proposed by Ronchi et al. [18], verifying the representation of pre-evacuation times within the evacuation model. The proposed test is a modified version of IMO Test 5 from MSC/Circ.1238 [19].

**Geometry** A room of size 8 m by 5 m with a 1 m exit.

**Scenario** Ten persons are randomly located in the room. Check the types of distributions (e.g. uniform, normal, log-normal, etc.) used by the evacuation model to represent pre-evacuation times. Repeat the test for each distribution of pre-evacuation time embedded in the model.

**Expected result** Verify that each agent starts moving at an appropriate time and that the responses of the population fall within the specified range.

**Test method** The test method is a quantitative verification of the model assignment expressed in terms of pre-evacuation time. In relation to the type of distribution under consideration, the model tester needs to identify a suitable quantitative method to evaluate the differences among the simulated and assigned distributions.

**User's actions** It should be noted that this test should be repeated several times (i.e. multiple runs of the same scenario should be done) in order to verify the simulation of the expected pre-evacuation time distributions over multiple runs.

A log-normal distribution $\mathsf{LogN}(\mu,\sigma^2)$ with $\mu = 4.30008s, \sigma = 0.628501s$ [32] is embedded in our model. For each agent, we assigned an initial pre-evacuation time $t_i$ by sampling from the distribution and then turned off all functions related to modifying the pre-evacuation time. Both the initial pre-evacuation time $t_i$ and the observed pre-evacuation time $t_o$ are recorded, where $t_o$ was measured when the evacuee began moving towards the exit. A comparison between initial pre-evacuation times $t_i$ and observed pre-evacuation times $t_o$ is shown in Table 4.1. Indicated by the table, the error, i.e. $0.01 \leq t_o - t_i \leq 0.1$, may be caused by the algorithm execution time and the measurement approach. We ran our model 10 times, until the average pre-evacuation time fluctuates no more than 1%. We calculate the mean, the standard deviation, the maximum and the minimum values among total 100 pre-evacuation times, presented in Table 4.2. Since the pre-evacuation times of agents are independent from each others, the above quantities could be regarded as general results of the pre-evacuation time assignment.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $t_i(s)$ | 62.20 | 91.36 | 65.49 | 48.40 | 104.26 | 37.46 | 47.15 | 70.00 | 65.43 | 44.88 |
| $t_o(s)$ | 62.21 | 91.41 | 65.51 | 48.50 | 104.30 | 37.51 | 47.21 | 70.01 | 65.51 | 44.89 |

Table 4.1: Comparison between $t_i$ and $t_o$

| | Mean (s) | SD (s) | Maximum (s) | Minimum (s) |
|---|---|---|---|---|
| Verif.1.1 | 84.62 | 58.06 | 357.81 | 15.3 |

Table 4.2: Statistical result of Verification test 1.1

A smooth histogram of $t_o$ was generated by Mathematica to compare with the imposed distribution as shown in Figure 4.1. We use the Anderson-Darling test to verify that $t_o$ is drawn from LogN$(\mu,\sigma^2)$, with the null hypothesis $H_0$ that data is drawn from the distribution. For a test for goodness of fit, a cutoff $\alpha = 0.05$ is chosen such that $H_0$ is rejected only if $p < \alpha$. Since we have $p = 0.402899 > \alpha$, we conclude that the observed pre-evacuation time $t_o$ is drawn from LogN$(\mu,\sigma^2)$.

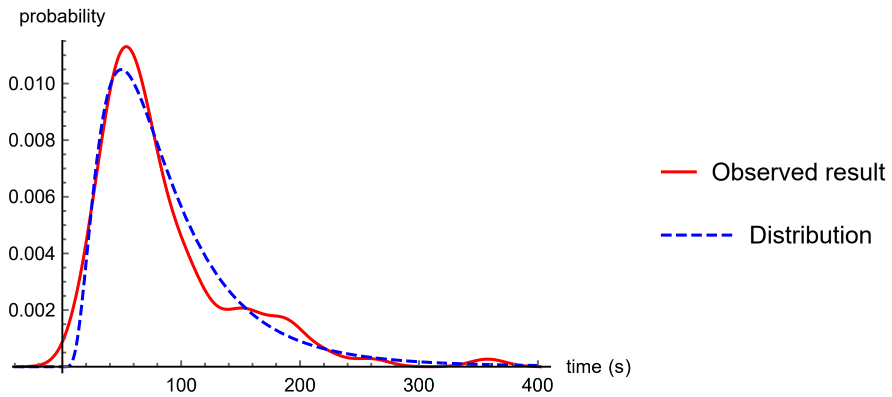



Figure 4.1: Comparison between the distribution of $t_o$ and LogN$(\mu,\sigma^2)$.

**Verif.1.2 Pre-evacuation time in a pubic room** This test is proposed to verify the ability of the model to simulate shorter pre-evacuation time in a public room (such as a store) compared with in a private room (such as an individual residence). The geometry of this test is the same as Verif.1.1.

**Scenario** Scenario 1: Ten persons are randomly located in the room, who are considered as completely independent. Impose a pre-defined distribution of the pre-evacuation time in the initialization process (before running the simulation). Record the pre-evacuation times of these ten agents.

Scenario 2: Ten persons are randomly located in the room. The agents are allowed to communicate as they are in a public room. The distribution of the pre-evacuation time is equal to scenario 1 in the initialization process. Record the pre-evacuation times of these ten agents.

**Expected result** The pre-evacuation time in scenario 2 is shorter than in scenario 1.

**Test method** This test is a qualitative evaluation of the model's capability to present different pre-evacuation times according to the locations.

**User's actions** It is should be noticed that this test should be repeated several times until the tester gets stable pre-evacuation times. If the model does not allow location types, the tester is recommended to discuss this limitation in the documentation associated with the V&V of the model.

To conduct a simulation in this scenario, we used the same assignment with Verif.1.1, except that the type of the room was changed to public. We ran this test 10 times and recorded total 100 pre-evacuation times, where the average pre-evacuation time fluctuates no more than 1%. The result is presented in Figure 4.2.

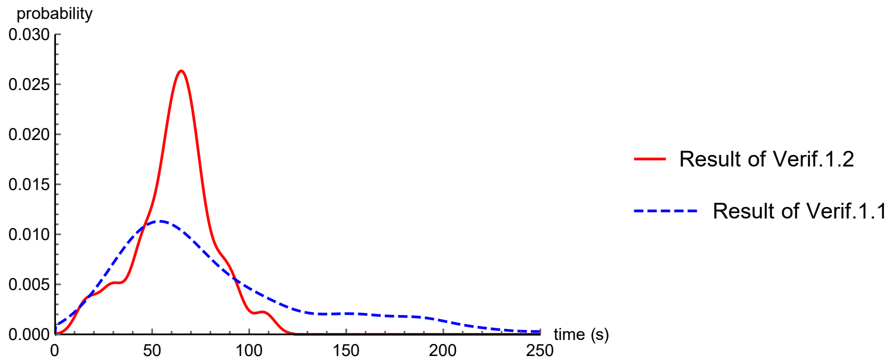



Figure 4.2: Pre-evacuation times of Verif.1.1 and Verif.1.2

The result of this test is compared with the result of Verif.1.1 by running the Mann-Whitney U test and two-sample Kolmogorov-Smirnov test. Firstly, we confirm the effectiveness of the location type in our model by two-sample Kolmogorov-Smirnov test, which is suitable for comparing the entire shapes of two samples. The null hypothesis $H_0$ is that the pre-evacuation time in Verif.1.1 is from the same distribution with the pre-evacuation time in Verif.1.2. For the test for goodness of fit, a cutoff $\alpha = 0.05$ is chosen such that $H_0$ is rejected only if $p < \alpha$. Since we have $p = 0.00126559$ as comparing $t_o$ from Verif.1.1 and $t_o$ from Verif.1.2, and that $p < \alpha$, we confirm the effectiveness of the location type in our model. Second, we apply the Mann-Whitney test to verify the difference between two distributions behind two samples. The null hypothesis $H_0$ is set as the $t_o$ from Verif.1.1 is not greater than $t_o$ from Verif.1.2. For the test for goodness of fit, a cutoff $\alpha = 0.05$ is chosen such that $H_0$ is rejected only if $p < \alpha$. Since we have $p = 0.0467329 < \alpha$, we can conclude that the pre-evacuation time in a private location is generally longer than in a public location in our model.

**Verif.1.3 Pre-evacuation time in a building with staff** This test is proposed to verify the ability of the model to simulate shorter pre-evacuation times in an environment with staff compared with an environment without staff. The geometry, the expected result and the user's action of this test are the same as Verif.1.2.

**Scenario** Scenario 1: Same as Scenario 1 of Verif.1.2.

Scenario 2: Add one staff character to the scenario. Record the pre-evacuation times of ten normal agents.

**Test method** This test is a qualitative evaluation of the model's capability to present different pre-evacuation times with and without staff.

To conduct a simulation in this scenario, we used the same assignment with Verif.1.1, except for an extra staff member. We ran this test 10 times and recorded total 100 pre-evacuation times, where the average pre-evacuation time fluctuates no more than 1%. The result is presented in Figure 4.3. It should be noted that the pre-evacuation time of the staff member is not included in the result, because the initial pre-evacuation time of the staff member is sampled from a different distribution from normal agents.

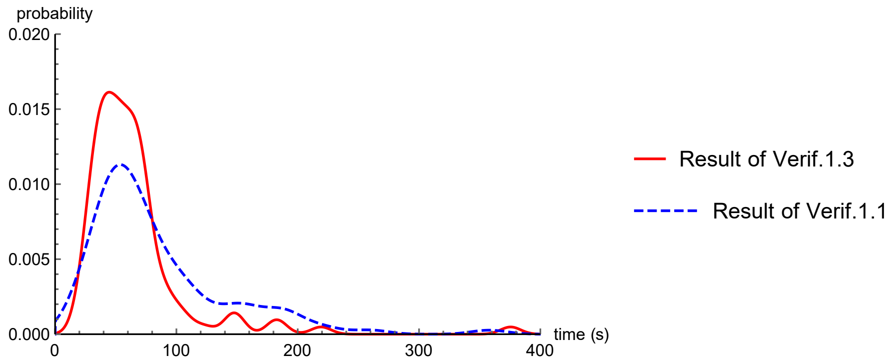



Figure 4.3: Pre-evacuation times of Verif.1.1 and Verif.1.3

To compare the results between Verif.1.1 and Verif.1.3, we use the same approach as Verif.1.2. The two-sample Kolmogorov-Smirnov test and the Mann-Whitney U test are conducted sequentially. As the $p$ value of two-sample Kolmogorov-Smirnov test is 0.00987 and the $p$ value of the Mann-Whitney U test is 0.0038, which are both less than 0.05, we can confirm the effectiveness of the notification from staff on shortening the pre-evacuation time in our model.

**Verif.1.4 Pre-evacuation time in the smoke** This test is proposed to verify the ability of the model to simulate shorter pre-evacuation time in a smoky environment compared with a non-smoky environment. The geometry, the expected result and the user's action of this test are the same as Verif.1.2.

**Scenario** Scenario 1: Same with Scenario 1 of Verif.1.2.

Scenario 2: The smoke is generated in the center of the room. We assume in this test that the smoke does not influence the walking speed, the walking trajectory, the visibility, group behaviors, etc. In another words, only the smoke's effect on the pre-evacuation time is considered. The extinction coefficient of the smoke is assigned as static, i.e. 0.5, and the propagation speed of the smoke is set to 1.0 m/s.

**Test method** This test is a qualitative evaluation of the model's capability to present different pre-evacuation times with and without the smoke.

To conduct a simulation in this scenario, we used the same assignment with Verif.1.1, except for the smoke in Scenario 2. We ran this test 10 times and recorded total 100 pre-evacuation times, where the average pre-evacuation time fluctuates no more than 1%. The result is presented in Figure 4.4.

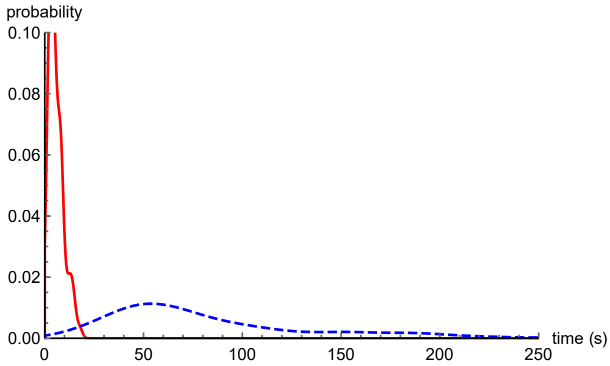



Figure 4.4: Pre-evacuation times of Verif.1.1 and Verif.1.4

To compare to result between Verif.1.1 and Verif.1.4, we use the same approach as Verif.1.2. The two-sample Kolmogorov-Smirnov test and the Mann-Whitney U test are conducted sequentially. As the $p$ value of two-sample Kolmogorov-Smirnov test is $4.41752 * 10^{-57}$ and the $p$ value of the Mann-Whitney U test is $1.35322 * 10^{-34}$, which are both less than 0.05. In this test, we observe the pre-evacuation times of agents are much shorter than Verif.1.1, because the smoke is a strong stimulus and it is assigned to propagate fast. Hence, while the smoke fills the room in a short time, the agents response quickly and egress from the room immediately. According to this analysis, we can confirm the effectiveness of the smoke on shortening the pre-evacuation time in our model.

**Verif.1.5 Pre-evacuation time with red lighting** This test is proposed to verify the ability of the model to simulate shorter pre-evacuation time in an environment with red lighting compared with an environment without red lighting. The geometry, the expected result and the user's action of this test are the same as Verif.1.2.

**Scenario** Scenario 1: Same with Scenario 1 of Verif.1.2.

Scenario 2: A red light is assigned in the ceiling of the room, instead of a conventional white light.

**Test method** This test is a qualitative evaluation of the model's capability to present different pre-evacuation times with red lighting and with white lighting.

To conduct a simulation in this scenario, we used the same assignment with Verif.1.1, except for a red light in Scenario 2. We ran this test 10 times and recorded total 100 pre-evacuation times, where the average pre-evacuation time fluctuates no more than 1%. The result is presented in Figure 4.3.

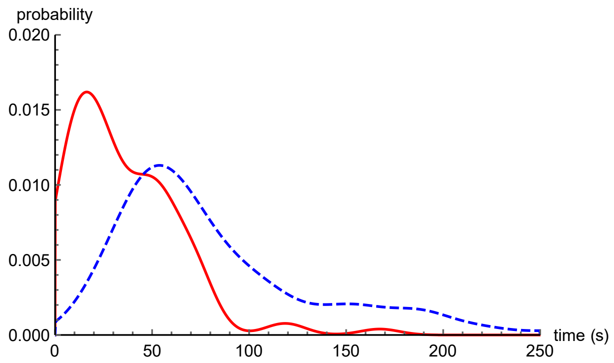



Figure 4.5: Pre-evacuation times of Verif.1.1 and Verif.1.5

To compare to result between Verif.1.1 and Verif.1.5, we use the same approach as Verif.1.2. The two-sample Kolmogorov-Smirnov test and the Mann-Whitney U test are conducted sequentially. As the $p$ value of two-sample Kolmogorov-Smirnov test is $8.44837 * 10^{-11}$ and the $p$ value of the Mann-Whitney U test is $7.46293 * 10^{-15}$, which are both less than 0.05, we can confirm the effectiveness of red lighting on shortening the pre-evacuation time in our model.

## 4.2 Movement and Navigation

This subsection presents eleven verification tests of a core element, i.e., movement and navigation (navigation is more about the path planning and the path following, while the movement represents the other actions). Seven tests are aimed at analytical verification of the models (AN_VERIF), and four tests verify the representation of emergent behaviors (EB_VERIF).

**Verif.2.1. Speed in a corridor** This test is proposed by Ronchi et al. [18]. It is proposed to verify the simulation of an evacuee maintaining an assigned walking speed over time. The test is based on IMO Test 1 from the IMO Guidelines [19].

**Geometry** A corridor of 2 m wide and 40 m long.

**Scenario** One evacuee with an assigned walking speed of 1 m/s walking along the corridor.

**Expected result** The evacuee should cover the distance of the corridor in 40 s.

**Test method** The test method is a quantitative verification of model results, i.e., the test checks the difference between the expected result and the simulation results.

**User's actions** The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use coarse and fine grids, results may be dependent on the configuration of the grid adopted. In the case of models using a fine grid to represent the walkable spaces, results may be affected by the rotation of the corridor in relation to the grid in use. The test should, therefore, be performed by using at least two different rotations of the geometry (e.g., 0 degree and 45 degrees). Considerations should also be made on the necessity to perform this test with different grid configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size.

**Improvements** To improve this test, Isenhour et al. [21] recommend testing this scenario with an input flux of 1 pedestrian/s, assigning each pedestrian a walking speed of 1 m/s. The expected result would be a line of pedestrians spaced approximately 1 meter apart walking along the entire length of the corridor with an average velocity of 1 m/s. This improvement can assess both the speed assignment and the flow control. Porzycki et al. [22] propose that the test should be conducted for more detailed spectrum of angles, rather than 0 degree and 45 degrees, since evacuation models use different methods to deal with possible systematic errors caused by grid size and orientation. As mentioned in paper [20], considering about some models which do not allow an exact speed (1 m/s) or an exact length, the authors propose to check whether results are in a given range rather than exact results. With a slight modification, i.e., uniformly distributed pedestrians with high density up to $7 pedestrian/m^2$ moving in the same direction, this test could be used to observe density waves.

The corridor was built with two walls. Agents were generated with a flux of 1 person/s and a maximum of 10 agents in one run, at random positions in a small specified area of one end of the corridor. The speeds of the agents were set to 1 m/s and the goals of the agents were set to the other end of the corridor. Denoting the time when the agent began to move by $T_{begin}$ and the time when the agent arrived at his goal position by $T_{end}$, we calculated the movement time $T_{move} = T_{end} - T_{begin}$. This test was repeated 5 times until the average evacuation time fluctuates no more than 1%. Since the path planning algorithm embedded in our model is not based on grids, we did not test our model in corridors with different angles.

The result shows that the average movement time of the evacuee is 40.6167 s, which is close to but not accurately 40.0 s, for which there are two causes. First, the generated position and the goal position of the evacuee are both randomly sampled in areas, not at specified points, which would yield the distance between the start point and the end point is not accurately 40 m. Second, according to the feature of the path planning algorithm, mostly, the path of a character is not a straight line, neither the shortest path between the start point and the end point. In addition, according to our observation, no agent collided with each other, keeping a distance, i.e. around 1.0 m, all the time. In general, we conclude that our model passes this test.

**Verif.2.2. Speed on Stairs** This test is proposed by Ronchi et al. [18], based on IMO Guidelines [19]. It is relative to the agent's speed up or down a staircase.

**Geometry** A stair of 2 m wide and 100 m long measured along the incline.

**Scenario** One evacuee with a walking speed of 1 m/s (upwards or downwards) is walking along the stair.

**Expected result** The evacuee is expected to cover the distance in 100 s (upwards or downwards).

**Test method** The test method is a quantitative verification of model results, i.e., the difference between the expected result and the simulation results.

**User's actions** IMO Test 2 and IMO Test 3 examine the same component. Evacuation models may use the same input to modify people movement on stairs (either upward or downward movement). For example, the user defines a speed factor (either directly assigned or determined by specifying a stair's tread and width). It could be possible to perform only one of those two tests if the models are using the same basic function to simulate the movement upwards and downwards (i.e. two tests may become unnecessary if the input employed by the model is the same). The requirement to test unconventional stair designs can be added in order to extend the applicability of building evacuation models to those scenarios (e.g. spiral stairs, curved stairs, etc.). It should also be noted that current models do not generally permit a direct representation of the impact of fatigue on walking speeds on stairs. Once this feature is implemented in the models, a corresponding verification test should be developed. Also in this test, the tester has to show, in the case of network models (coarse or fine network), the sensitivity of model results to the network employed and assess if the rotation of the geometry has any impact on results.

**Improvements** The same improvements as **Verif.2.1** are suggested in paper [20] and [22], i.e. more testing angles and the feasible error range. Isenhour et al. [21] give a proof, that if we set up the stairs with 30° gradient (by using a step height of 0.154 meters and a tread length of 0.267 meters), that the step size for a person traveling up a flight of stairs is approximately 0.5 meters and the corrected step size for a person descending a flight of stairs is approximately

0.66 meters. The velocities of ascending the stairs and descending the stairs are 0.463 m/s and 0.502 m/s respectively.

To conduct this test, we built two planes connected with a 100 m long stair. We tested the walking speed of the agent in scenarios with three different degrees of the stair, both ascending and descending directions. The agent began movement at a specified point at the end of the stair, and the goal of the agent was a random point in the range of the exit. Denoting the time when the agent began to move by $T_{begin}$ and the time when the agent arrived at his goal position by $T_{end}$, we calculated the movement time $T_{move} = T_{end} - T_{begin}$. In this test, each scenario has been repeated for five times, until the movement time fluctuates no more than 1%.

| | | 15° | 20° | 25° |
|---|---|---|---|---|
| Ascending | Theoretical (s) | 149.522 | 166.445 | 187.688 |
| | Observed (s) | 149.12 | 165.912 | 186.936 |
| Descending | Theoretical (s) | 133.085 | 146.972 | 164.096 |
| | Observed (s) | 133.232 | 147.016 | 163.996 |

Table 4.3: Walking speeds on stairs

As shown in Table 4.3, the table records the theoretical and observed walking speeds in six scenarios, where the theoretical speeds are calculated by the equations in Section 3.2.1. Here we can only say the observed result is close to the theoretical result. The criteria of the acceptable deviation is still lacking. Generally, the model can accurately represent the expected walking speeds. The small deviation might be caused by two factors as we explained in Verif.2.1, i.e., due to unspecified goal positions and not straight walking paths.

**Verif.2.3. Movement around a corner** This test is proposed by Ronchi et al. [18]. It is used to verify whether the model is able to correctly simulate the boundaries of a scenario. IMO Test 6 [19] is the benchmark for this test, i.e., a test to verify that evacuees successfully navigate around a corner.

**Geometry** A corner is represented in accordance with Figure 4.6.

**Scenario** Twenty persons are uniformly distributed in one end of the hallway (in a space measured 2 m by 4 m). They have immediate pre-evacuation times and a walking speed of 1 m/s.

**Expected result** The evacuees are expected to successfully navigate around the corner without penetrating the boundaries.

**Test method** The test method is a qualitative verification of the evacuee movement. The qualitative analysis is performed by observing the walking path

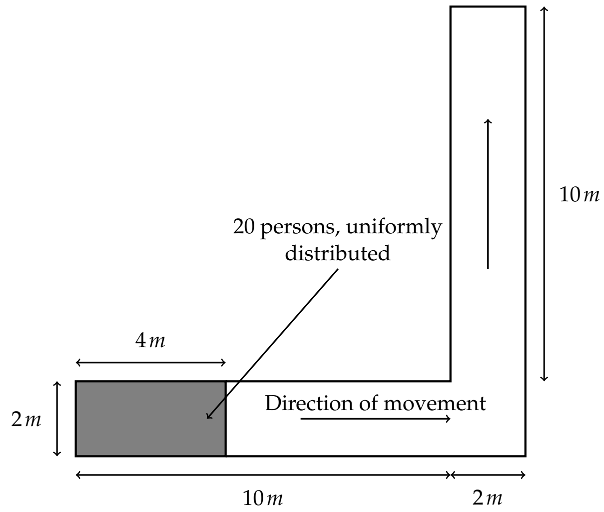



Figure 4.6: Geometric layout of Verif.2.3 Test [19]

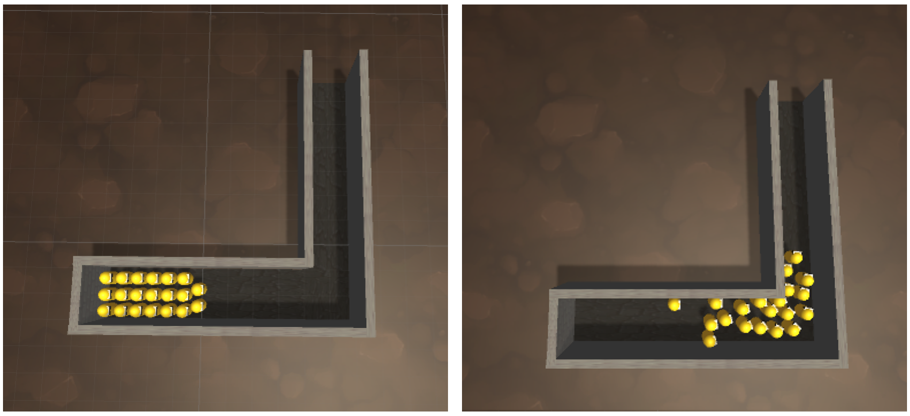
of the evacuees. If possible, this evaluation can be performed by using the visualization tool of the model or tracking the coordinates of the agents' paths.

**User's actions** It should be noted that the current test of movement around a corner is intended only as a verification of the boundaries available in the scenario, i.e. no evaluation of the expected pattern in the corner is made (i.e. the current test is not a verification of emergent behaviors). When the literature on human behavior in fire is able to provide a detailed understanding of the expected movement patterns of people, model testers will need to include this in the test.

**Improvements** Authors of references [20] and [22] suggested this test could be extended to verify space usage of the pedestrians, as, for example, it can vary vastly for preference of fastest rather than shortest path. Isenhour et al. [21] propose that the testers can also initialize the evacuees in specified locations rather than randomly distributed locations. It would be interesting to manually assign extreme input and verify the navigation capability of the model.

We assigned agents at specified positions (see Figure 4.7(a)) rather than random positions in this test. The speeds of the agents were set to 1 m/s and goals of the agents were set to the opening of the corridor. We tested two types of path planning approaches, i.e. short path and fast path, which were embedded in UUCS [70]. Each path planning approach has been tested 5 times. We recorded the movement time by the same method as Verif.2.1.

When the agent passed through the corner, he had to avoid collision with other agents. Hence, sometimes the agent stopped and waited (see Figure 4.7(b)), yielding discontinuous walking of the agent. With the short path planning approach,



(a) (b)

Figure 4.7: test scenario of Verif.2.3

the average movement time of agents was 17.8008 s, while the fast path planning approach resulted in an average movement time of 17.6993 s. We did not observe any agent penetrating the boundaries during the test. Hence, we conclude that our model passes this test.

**Verif.2.4. Assigned occupant demographics** Proposed by Ronchi et al. [18], this test is aimed at verifying the ability of the model to assign population demographic parameters. This test is a modified version of the IMO Test 7 [19].

**Geometry** A square room of size 100 m by 100 m.

**Scenario** Choose a sub-population consisting of a population selected in accordance with the expected characteristics of the building(s). For example, Lord et al. [71] present possible occupant demographics. Assign the walking speeds over a population of 100 occupants who are evenly distributed in the room.

**Expected result** Show that the assigned walking speeds are consistent with the distribution specified in the scenario.

**Test method** The test method is a quantitative verification of model assignments, i.e. the analysis of the walking speeds simulated by the evacuation model. In relation to the type of distribution under consideration, the model tester needs to identify a suitable quantitative method to evaluate the differences among the simulated and assigned distributions.

**User's actions** It should be noted that values to be used for the characterization of occupant demographics are dependent on several factors, such as building usage, nationality, etc. Also in this case, model testers should demonstrate that the simulation of occupant demographic distributions is verified over multiple runs, i.e., the test should be repeated several times.

We set up the scenario as an office, with a demographic of 15% elderly and 85% adults [71]. Agents were assigned at specified positions in this test. To calculate real speeds $V_{real}$ of the agents, we recorded the path length $L_{real}$ in $t_{real}$ seconds for each agent. Then, we computed the speed as $L_{real}/t_{real}$. The test has been repeated 5 times until the average movement time fluctuates no more than 1%.

An Anderson-Darling test is used to verify that $V_{real}$ was drawn from the specified distribution, with the null hypothesis $H_0$ that data was drawn form the distribution. For a test for goodness of fit, a cutoff $\alpha = 0.05$ is chosen such that $H_0$ is rejected only if $p < \alpha$. The result of this test shows $p = 0.81507$ for the adult data and $p = 0.223539$ for the elderly data. Hence, we conclude that the speeds of the adults and the elderly were drawn from their speed distributions.

**Verif.2.5. Reduced visibility vs walking speed** Proposed by Ronchi et al. [18], this test is aimed at quantitatively verifying the ability of evacuation models to reproduce the physical impact of smoke upon evacuee's walking speeds.

**Geometry** A corridor of 2 m wide and 100 m long. One exit (1 m wide) is placed at the end of the corridor.

**Scenario** Smoke reduces the walking speed due to the reduced visibility. The unimpeded walking speed of an evacuee in a smoke-free environment is set to a constant value of $1.25m/s$. A constant extinction coefficient of $1.0m^{-1}$ is implemented in the corridor prior to running the simulation. No external sources of lights are present in this test, i.e, the environment is assumed to be constituted only by objects which do not emit light. The evacuee has to reach the exit at the end of the corridor.

**Expected result** The expected result is that the time needed by the evacuee to cover the distance of the corridor is the same as the time manually calculated employing the correlation used by the model (i.e. in line with the speed reduction factor used by the model).

**Test method** A quantitative evaluation of model results in terms of time differences is performed. In relation to the type of correlation employed by the model, the tester needs to identify a suitable quantitative method to evaluate the differences among the simulated and expected time.

**User's actions** The test should be repeated in order to verify different values in the correlation, i.e. different combinations of unimpeded walking speeds for a smoke-free environment and constant extinction coefficients need to be tested. Examples of such values may be $1.0m/s$, $0.75m/s$, $0.5m/s$, and $0.25m/s$ for the unimpeded walking speeds and $10m^{-1}$, $7.5m^{-1}$, $3.0m^{-1}$, and $0.5m^{-1}$ for the extinction coefficient. These values are suggested in order to cover the range of walking speeds and extinction coefficients included in the two main data-sets available in the literature [72]; It should be noted that the tester needs to know the correlation employed by the model and then compare the test results with hand calculations performed beforehand, i.e. the tester calculates in advance the assumed reduction of speed due to the smoke. Models may also consider the impact of smoke irritancy on people performance. This test does not consider the effects of irritant smoke and toxic gases on evacuee's speed (i.e. crawling behaviors, etc.), i.e., only the impact of reduced visibility on walking speed is taken into account.

**Improvements** The literature [72] suggests two data-sets related to smoke. However, the two data-sets, i.e. Jin's data collection [73] and Frantzich's data collection [74] differ from each other significantly. So we refer to other two articles [75] [76], and finally decide to adopt Jin's data, since the extinction coefficients $7.5m^{-1}$, $10m^{-1}$ etc., proposed by Frantzich et al., are extremely larger than other data collections. The suggested testing extinction coefficient should be between 0 and 2.

| $V_{normal}$ $(m/s)$ | 1.25 | 1 | 0.75 |
|---|---|---|---|
| Manually calculated $V_{smoke}$ $(m/s)$ | 0.9518 | 0.7614 | 0.5710 |
| Observed $V_{smoke}$ $(m/s)$ | 0.9515 | 0.7613 | 0.5711 |
| Manually calculated $T_{move}$ $(s)$ | 105.06 | 131.34 | 175.13 |
| Observed $T_{move}$ $(s)$ | 105.19 | 131.49 | 174.69 |

Table 4.4: Speed and movement time in smoke, when $C_s = 1.0$

| $V_{normal}$ $(m/s)$ | 1.25 | 1 | 0.75 |
|---|---|---|---|
| Manually calculated $V_{smoke}$ $(m/s)$ | 1.1347 | 0.9078 | 0.6808 |
| Observed $V_{smoke}$ $(m/s)$ | 1.1343 | 0.9064 | 0.6806 |
| Manually calculated $T_{move}$ $(s)$ | 88.13 | 110.15 | 146.89 |
| Observed $T_{move}$ $(s)$ | 88.49 | 110.60 | 146.81 |

Table 4.5: Speed and movement time in smoke, when $C_s = 0.5$

| $V_{normal}$ $(m/s)$ | 1.25 | 1 | 0.75 |
|---|---|---|---|
| Manually calculated $V_{smoke}$ $(m/s)$ | 1.2125 | 0.97 | 0.7275 |
| Observed $V_{smoke}$ $(m/s)$ | 1.2127 | 0.9713 | 0.7281 |
| Manually calculated $T_{move}$ $(s)$ | 82.47 | 103.09 | 137.46 |
| Observed $T_{move}$ $(s)$ | 83.00 | 103.49 | 137.52 |

Table 4.6: Speed and movement time in smoke, when $C_s = 0.1$

As same as Verif.2.1, the agent in this test was generated in a small area at the end of the corridor, and his goal position was a random point at the exit. We tested three extinction coefficients, i.e. $1.0m^{-1}$, $0.5m^{-1}$, $0.1m^{-1}$, in combination with three walking speeds in smoke-free environment, i.e. $1.25m^{-1}$, $1.0m^{-1}$, $0.75m^{-1}$, and recorded the speed and the movement time.

$V_{normal}$ represents the normal speed in smoke-free environment, where $V_{smoke}$ represents the speed in the smoke, and $C_s$ is the extinction coefficient. The results are shown in Table 4.4, 4.5 and Table 4.6. Upon inspections on the tables, we can conclude that the model has ability to represent the walking speed in a smoky environment correctly. The small differences of movement times are caused by the same reasons as Verif.2.1, i.e. unspecified goal positions and not straight walking paths.

**Verif.2.6. Evacuee's incapacitation** This test is proposed by Ronchi et al. [18] to qualitatively and quantitatively verify the ability of evacuation models to simulate evacuee's incapacitation due to the toxic and physical effects of smoke. The incapacitation of an evacuee is represented with Fractional Effective Dose (FED) concept [77].

**Geometry** A room with no fire source (10 m x 10 m x 3m).

**Scenario** The implementation of the FED concept is tested. Step 1: place an evacuee in the center of the room (see Figure 4.8). The evacuee is held in a fixed initial position by setting a high pre-evacuation time (>10000000 s). Hazardous conditions are implemented in the model in relation to the incapacitation sub-model in use. Examples of such conditions are the exposure to toxic, irritant and physical hazards such as HCN, CO, CO2, HCl, HBr, HF, SO2, NO2, elevated temperature, thermal radiation, etc. Step 2: Construct the same room and perform a FED-measurement in the same location of the evacuee, either by using hand calculations or an independent validated fire model using the same FED calculations implemented in the evacuation model.

**Expected result** The expected result is that the time to reach evacuee incapacitation (FED=1) in Step 1 is the same as the time to reach FED=1 in the measurement point in Step 2. This test should be repeated for each hazardous condition available in the incapacitation sub-model (e.g. CO or HCN concentrations, elevated temperature, etc.)

**Test method** The test method employed is a quantitative verification of model assignment. The evaluation of the differences in the times to reach FED=1 during the two steps of the test is performed.

**User's actions** It should be noted that the tester needs to know the toxicity and hazard sub-model(s) embedded in the evacuation model to perform the test. The present test is a static test. Model testers may consider expanding the verification of FED calculations by considering an evacuee moving in the space. If the model under consideration does not embed toxicity and hazard sub-models, it is recommended that the tester discusses this limitation in the documentation associated with the V&V of the model.

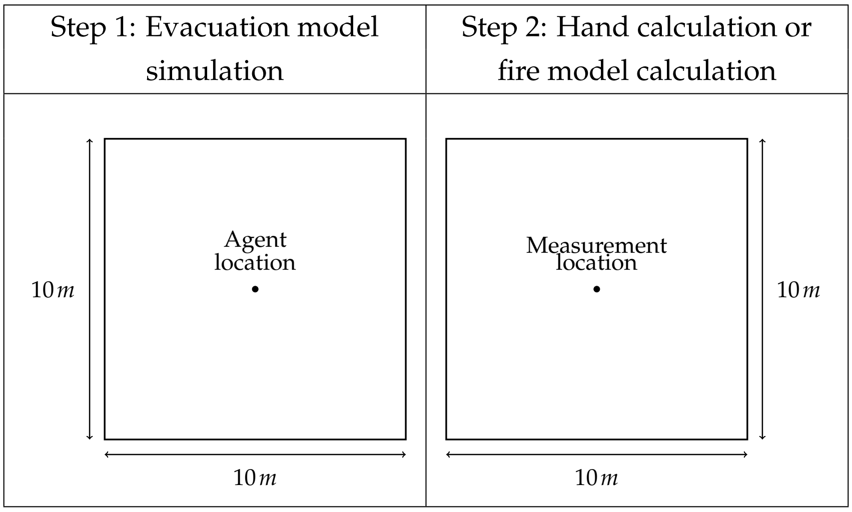



Figure 4.8: Geometric layout of Verif.2.6 [18]

In this test, we set a smoke point in the center of room, with three referred toxicities, i.e. 0.035, 0.05, 0.08 and a static extinction coefficient $1.0m^{-1}$. Each referred toxicity has been tested 10 times until the average death time fluctuates no more than 1%. In the beginning, the agent idled in the center of the room and then began to move around at a specified speed $1.0m/s$.

We recorded the average death time of the agent in each scenario as shown in Table 4.7. Theoretically, the death times under the three referred toxicities should be 28.57 seconds, 20 seconds and 12.5 seconds, respectively. In practice, the accumulated toxicity of an agent is updated per second in our model. Hence, the expected death times could be rounded up to 29 seconds, 20 seconds and 13 seconds, respectively. Compared with the manually calculated death times, the observed death times are higher. It might be caused by the statistical error. In general, we conclude that our model passes this test.

| Referred toxicity | 0.035 | 0.05 | 0.08 |
|---|---|---|---|
| manually calculated death time (s) | 28.57 (29) | 20 | 12.5 (13) |
| observed death time (s) | 29.27 | 20.18 | 13.098 |

Table 4.7: Testing result of Verif.2.6

**Verif.2.7. Elevator Usage** This test is proposed by Ronchi et al. [18], aimed at verifying the capability of the model to simulate elevator's usage during the evacuation.

However, our model does not include any elevator function, so this test is not been conducted.

**Verif.2.8. Horizontal counter-flows (rooms)** This test is proposed by Ronchi et al. [18], suggested to verify the ability of models to simulate counter-flows. It is a modified test of the IMO Test 8 [19].

**Geometry** Two rooms of 10 m wide and 10 m long are connected via a corridor of 10 m long and 2 m wide (see Figure 4.9).

**Scenario** Choose a sub-population consisting of a population of 100 persons with pre-evacuation time of 0 s and distribute the walking speeds in accordance with the population of the building (Lord et al. [71] present possible occupant demographics). Step 1: One hundred persons move from room 1 to room 2, where the initial distribution is such that the space of room 1 is filled from the left with maximum possible density. The time the last person enters room 2 is recorded. Step 2: Step one is repeated with an additional ten, fifty, and one hundred persons in room 2. These persons should have identical characteristics to those in room 1. Both sub-populations move simultaneously to the opposite room and the time for the last persons from room 1 to enter room 2 is recorded.

**Expected result** The expected result is that the recorded time increases as the number of persons in counter-flow increases.

**Test method** The test method is a qualitative evaluation of the capabilities of the model of reproducing horizontal counter-flows (counter-flows in rooms). The model results need to be compared and the differences (expressed in terms of evacuation times) between the steps of the test are presented.

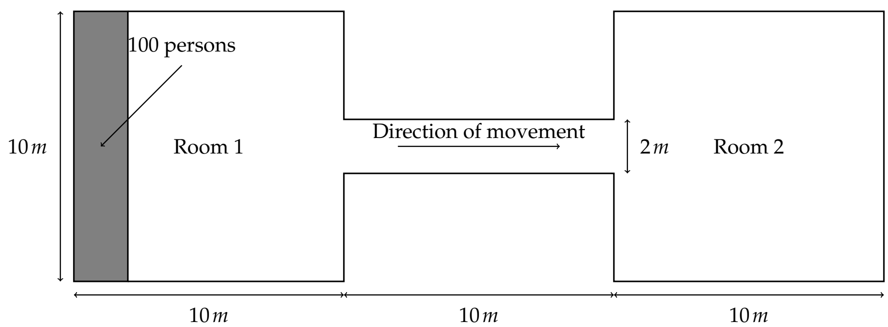



Figure 4.9: Geometric layout of Verif.2.8. Test based on the IMO Test 8 [19]

**User's actions** The model tester should qualitatively discuss the extent of the recorded time increases due to counter-flows.

**Improvements** Lubaś et al. [22] [20] propose extra expected results, i.e., observation of line formation phenomenon, detailed passage times and oscillations.

With slight modifications, this test may be used to observe freezing-by-heating effect when there are 100 pedestrians in each room moving to the opposite room.

This test was assumed in an office, with 85 adults (yellow characters) and 15 elderly (blue characters) in room 1. Walking speeds of the agents were selected according to the speed distribution embedded in the model. In scenario 1, agents could successfully move to another room. However, in scenario 2, with 10 extra adult agents in room 2, the counter flows completely blocked the corridor. All of the agents in room 1 and room 2 wanted to move to their opposite rooms and nobody conceded, yielding that they squeezed in the middle of the corridor and could not cross each other. As shown in Figure 4.10, agents moved successfully in scenario 1, while in Figure 4.11, agents were failed to move to opposite rooms. The complete blockage is not the expected result of the test. We have to conclude that it is a limitation of our model.

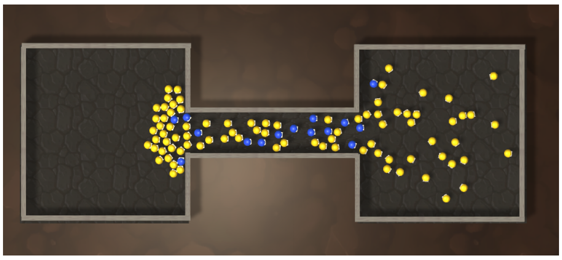


Figure 4.10: Testing scene of Verif.2.8: successful movement

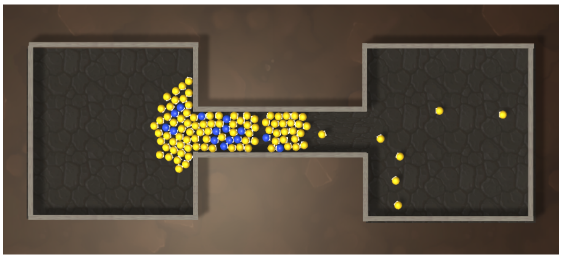


Figure 4.11: Testing scene of Verif.2.8: failed movement

**Verif.2.9. Group Behaviors** Proposed by Ronchi et al. [18], this test is designed to perform a qualitative verification of the emergent behaviors of groups. The test identifies whether a group sub-model is available and if it is able to reproduce group behaviors not only as a set of individuals with the same characteristics, but as a group of evacuees remaining together even in the case of different evacuee characteristics (e.g., different evacuee walking speeds).

**Geometry** A room of size 15 m by 20 m with a 1 m exit.

**Scenario** Five evacuees are assigned to the same group, namely Group 1, in the top of the room (see zone 1 in Figure 4.12) with pre-evacuation time of 0

s. Four evacuees in Group 1 have a constant unimpeded walking speed of 1.25 m/s. The fifth evacuee of Group 1 has a constant unimpeded walking speed of 0.5 m/s. In the central part of the room, 10 slower evacuees, namely Group 2, with a constant unimpeded walking speed of 0.2 m/s are uniformly distributed in Zone 2 as it is shown in Figure 4.12. The evacuees in Zone 1 have to reach the exit of the room.

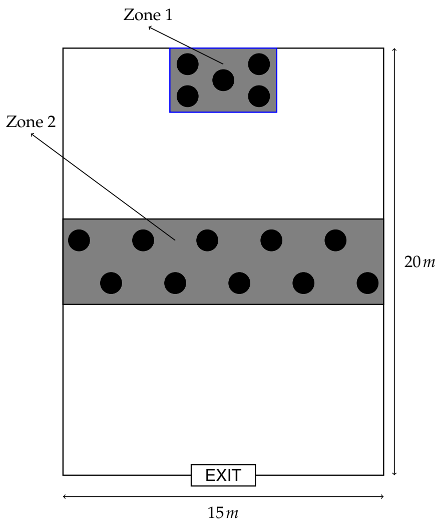



Figure 4.12: Schematic geometric layout of Verif.2.9 Test.

**Expected result** The test should demonstrate that the evacuees of Group 1 will reach the exit together (i.e., the times for evacuees of Group 1 to reach the exit should not differ of more than 10 s). If possible, this evaluation can be performed by using the visualization tool of the model. The choice of 10 s is arbitrary driven by the need to set a number to make a quantitative comparison. Preliminary tests were performed with an evacuation model which uses assumptions very similar to most of the models representing group behaviors in order to assess the approximate time needed to reach the exit and evaluate the expected differences.

**Test method** The test method is an evaluation of emergent behaviors which uses quantitative criteria. The analysis is performed by comparing the time needed by the evacuees of Group 1 to reach the exit.

**User's actions** If the model under consideration does not permit the simulation of group behaviors, the tester is recommended to discuss this limitation in the documentation associated with the V&V of the model.

We assigned four normal characters with speed 1.25 m/s and one visitor with speed 0.5 m/s in Group 1. In Group 2, we assigned 10 elderly with speed 0.2 m/s. In this test, there is no other differences between different character types except for their speeds and body radius (0.239 m for normal characters and the visitor;

0.241 m for the elderly). This assignment was just aimed at distinguishing different agents by their colors, as shown in Figure 4.13.

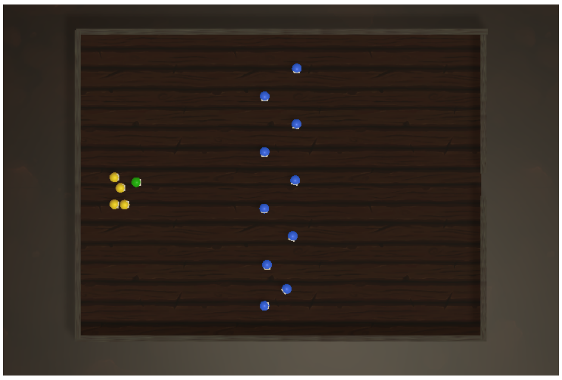


Figure 4.13: Testing scene of Verif.2.9

We recorded the time the agent passing through the exit by the last time that the agent was in the exit area. The result is presented in Table 4.8. The times for agents in Group 1 to pass the exit varies from 50.0 s to 55.0 s, where the difference is not more than 10 seconds. Besides, we recorded the speeds of the agents as well, see Table 4.9. It is should be noticed that the speed was dynamic during the movement and the shown result is just a sample in 5 seconds. Different sampling times may yield different results. In our test, all five evacuees in Group 1 walked under the speed 0.5 m/s, because they had to keep together within a distance threshold. Waiting each others and coherence lead to low speeds. In general, we conclude that our model passes this test.

| | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ |
|---|---|---|---|---|---|
| Time(s) | 53.2 | 50.0 | 55.0 | 51.8 | 54.1 |

Table 4.8: Passing exit time of evacuees in Group 1

| | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ |
|---|---|---|---|---|---|
| Defined Speed (m/s) | 1.25 | 1.25 | 1.25 | 1.25 | 0.5 |
| Observed Speed (m/s) | 0.37 | 0.32 | 0.45 | 0.35 | 0.33 |

Table 4.9: Speeds of evacuees in Group 1

**Verif.2.10 People with movement disabilities** This test is proposed by Ronchi et al. [18], designed for the verification of behaviors of people with disabilities. It is aimed at testing the possibility of simulating an evacuee with reduced mobility (e.g. decreased walking speeds and increased space occupied by the evacuee) as well as representing the interactions between impaired individuals and the rest of the population and the environment.

**Geometry** Construct two rooms at different heights, namely room 1 (1 m above the ground) and room 2 (at the ground), connected by a ramp (or a corridor/stair if the model does not support a ramp). Insert one exit (1 m wide) at the end of room 2 (see Figure 4.14 for the schematic representation of the rooms).

**Scenario** Scenario 1: Room 1 is populated with a sub-population consisting of 24 evacuees in zone 1 (with an unimpeded walking speed of 1.25 m/s and the default body size assumed by the model) and 1 disabled evacuee in zone 2 (the evacuee is assumed to have an unimpeded walking speed of 0.8 m/s on horizontal surfaces and 0.4 on the ramp (see Figure 4.14). The disabled evacuee is also assumed to occupy an area bigger than half the width of the ramp (>0.75 m) (e.g., a wheelchair user). All evacuees have to reach the exit in room 2. Scenario 2: Re-run the test and populate zone 2 with an evacuee having the same characteristics of the other 24 evacuees in zone 1 (i.e. no disabled evacuees are simulated). All evacuees have to reach the exit in room 2.

**Expected result** The expected result is that evacuees in zone 1 in Scenario 1 reach the exit in a time slower than evacuees in zone 1 in Scenario 2. If possible, this evaluation can be performed by using the visualization tool of the model.

**Test method** The test is a qualitative verification of emergent behaviors. The tester should qualitatively evaluate whether the model is able to simulate disabled populations and their possible impact on the evacuation times.

**User's actions** If the model under consideration does not permit the simulation of people with movement disabilities or it does not permit the simulation of agents of different dimensions, the tester is recommended to discuss this limitation in the documentation associated with the V&V of the model.

**Improvements** Isenhour et al. [21] suggest to modify the length of the ramp to 12 meters (rather than 2 meters), since the ramp should not exceed a 8.33% grade.

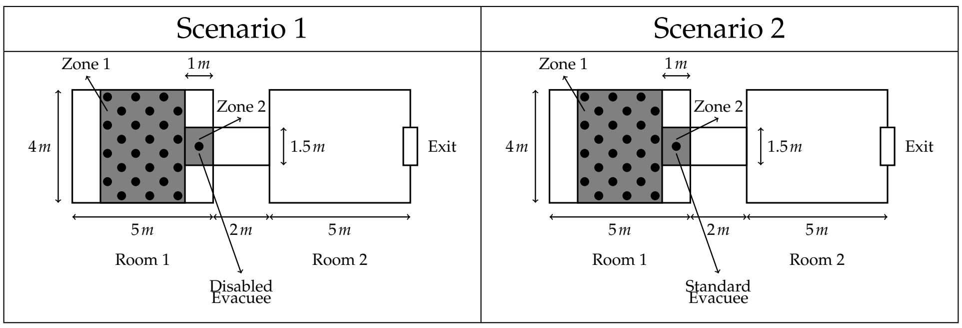
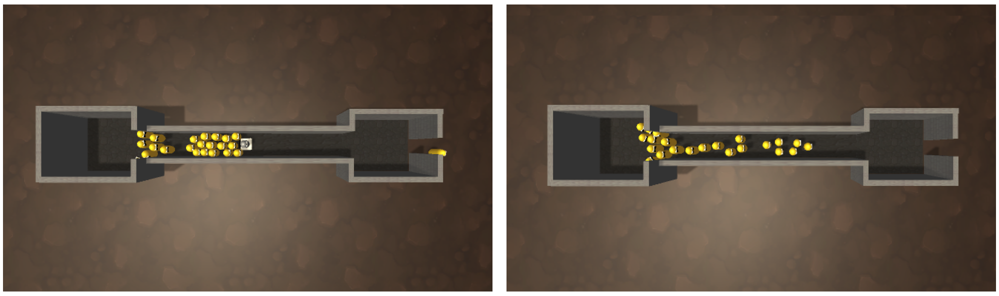



Figure 4.14: Schematic geometric layout of Verif.2.10 Test. [18]



(a) Scenario 1 (b) Scenario 2

Figure 4.15: test scenario of Verif.2.10

In our model, the evacuee with disability is modeled with a wheelchair. The radius of the disabled person is 0.375 m, neither 0.239 m (normal character) or 0.241 m (elderly). To build a realistic stair, we set the length of the stair to 12 m instead of 2 m, with a slope of 4.76 degrees. We tested both scenario 1 and scenario 2 5 times until the average movement times fluctuate no more than 1%. As we observed in the tests, the disabled agent obviously blocked the pedestrian flow in scenario 1, while the pedestrian flow was continuous in scenario 2 (see Figure 4.15).

We compare the movement times in two scenarios (see Table 4.10). In all five tests, the average movement times and the maximum movement times among 24 agents are shorter in scenario 2 than in scenario 1. In addition, a Mann-Whitney U test is conducted to verify the differences between average movement times in two scenarios. The null hypothesis $H_0$ is set as the average movement time from Scenario 1 is not greater than the average movement time from Scenario 2. For the test for goodness of fit, a cut off $\alpha = 0.05$ is chosen such that $H_0$ is rejected only if $p < \alpha$ . Since we have $p = 0.01078 < \alpha$, we can conclude that the average movement time in Scenario 1 is longer than in Scenario 2, and our model passes this test.

| | | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ |
|---|---|---|---|---|---|---|
| Average movement time (s) | scenario 1 | 29.25 | 24.70 | 31.38 | 46.69 | 26.05 |
| | scenario 2 | 22.47 | 24.05 | 25.32 | 24.46 | 21.16 |
| Maximum movement time (s) | scenario 1 | 45.21 | 39.49 | 45.30 | 62.31 | 38.00 |
| | scenario 2 | 31.89 | 35.89 | 36.00 | 37.00 | 29.38 |

Table 4.10: Movement times of evacuees

**Verif.2.11. Deviation in the smoke** Instead of walking directly to the exit, the evacuee always moves along the wall when his visibility is limited [78]. This test is used to qualitatively verify the ability of evacuation models to simulate the evacuee's deviation in the smoke due to the limited visibility.

**Geometry** A room with 30 m × 30 m size. One exit (1 m wide) is placed at the middle of a wall.

**Scenario** Scenario 1: One evacuee is located at 3 m away from the bottom wall of the room, with constant walking speed 1.25 m/s. A constant extinction coefficient equals to $1.0m^{-1}$ is implemented prior to running the simulation. The deviation behavior is considered in this scenario. Record the time needed by the evacuee to reach the exit.

Scenario 2: The scenario's setting is same as Scenario 1, expect that there is no smoke in Scenario 2 and the deviation behavior is not considered. Record the time needed by the evacuee to reach the exit.

**Expected result** Because the speeds in scenario 1 and scenario 2 are equal, longer evacuation time indicates longer walking path. The expected result is that the evacuation time in scenario 1 is longer than in scenario 2.

**Test method** The test method employed is a qualitative verification of model results in terms of walking deviation. A visible trajectory comparison is strongly suggested.

**User's Action** Except for the path trajectory, other features of the evacuee should not be changed during the simulation, such as the speed.

Before the simulation, we set the smoke propagation speed as 2.0 m/s, and the pre-evacuation time of the agent was assigned to 0. Functions related to the dynamic speed, changing pre-evacuation time, were all turned off. This test has been conducted 10 times for each scenario until the average movement time fluctuates no more than 1%.

We calculate the average movement times of Scenario 1 and Scenario 2. The average movement time of Scenario 1 is 31.11 seconds, longer than in Scenario 2, i.e. 22.08 seconds. Besides, we use a Mann-Whitney U test to verify the difference between movement times in two scenarios. The null hypothesis $H_0$ is set as the movement time from Scenario 1 is not greater than the movement time from Scenario 2. For the test for goodness of fit, a cut off $\alpha = 0.05$ is chosen such that $H_0$ is rejected only if $p < \alpha$ . Since we have $p = 0.000101578 < \alpha$, the movement time in Scenario 1 is longer than in Scenario 2. The smoke results in the deviation and a longer movement time of the evacuee. In general, we can conclude that our model passes this test.

## 4.3 Exit choice/usage

In this section, tests are provided to verify either the ability of the model to specify exit usage or the ability of the model to allocate exit usage given certain parameters. The exit choice in evacuation may rely on simple criteria (shortest distance, user-defined), allowing for a deterministic rather than predictive result. An exit route allocation test based on IMO Test 10 [19] is suggested. Besides, two verification tests aimed at evaluating the capabilities of evacuation models in simulating social influence (**Verif.3.2**) and affiliation/familiarity with the exit (**Verif.3.3**) are also presented. Moreover, **Verif.3.4** is presented to verify the group coherence in the model. Last, **Verif.3.5** and **Verif.3.6** are designed to evaluate whether the evacuees can re-select their exit routes according to the surrounding environment.

**Verif.3.1. Exit Route Allocation** This test is proposed by Ronchi et al. [18], based on IMO Test 10 [19]. A set of exit route allocations is suggested in order to verify the deterministic assignment of exit usage.

**Geometry** Construct a corridor with rooms in accordance with Figure 4.16.

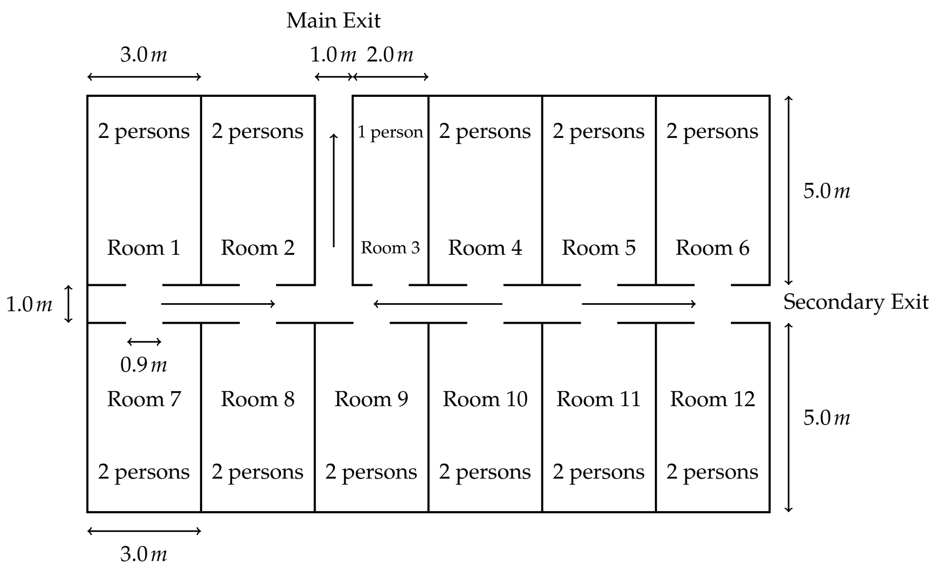



Figure 4.16: Geometric layout of Verif.3.1. Test based on IMO test 10 [19].

**Scenario** Populate the rooms with evacuees having walking speeds and characteristics in accordance with the expected demographics of the population of the building(s) (see Lord et al. [71] for possible evacuee demographics). Distribute the walking speeds and pre-evacuation times of 0 s over a population of 23 persons. The persons in room 1, 2, 3, 4, 7, 8, 9, and 10 are allocated to the main exit. All the remaining passengers are allocated the secondary exit.

**Expected result** The allocated evacuees move to the appropriate exits. If possible, this evaluation can be performed using the visualization tool of the model.

**Test method** The test method is a qualitative verification of model assignment, i.e. the ability of the model to represent exit route allocation.

**User's actions** The tester needs to mention if the exit choice sub-model is based on deterministic assumptions or it is predictive in the documentation associated with the test where the results of the model are presented.

The scenario was assumed as a layer of a residence building, with 13 elderly, 5 young adults and 5 disabled people [71]. Agents were assigned as in Figure 4.17, where the blue character represented the elderly, the yellow character represented the young adult and the gray character with a wheelchair represented the disabled evacuee. It is should be noticed, although some agents were assigned in the same room, that were not in one group, i.e. they would not express any group behavior. The walking speeds of evacuees were assigned by the walking speed distribution embedded in our model. In this test, functions related to re-selecting the exit were disabled.

Our model supports both user-defined exit selection and automatic exit selection. In this test, the former approach was applied. In the initialization process, agents in room 1, 2, 3, 4, 7, 8, 9 and 10 were arranged to select the main exit, and agents in room 5, 6, 11 and 12 were arranged to select the secondary exit. The observed result was consistent with the pre-defined exit selection.

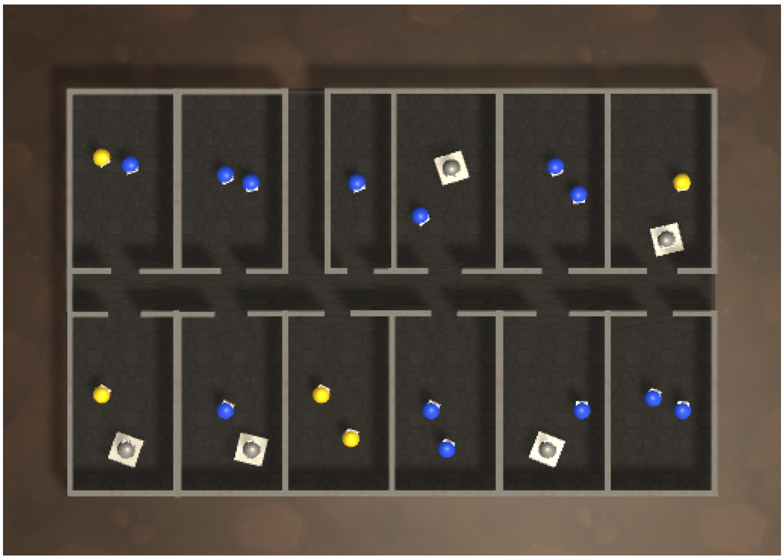


Figure 4.17: Testing scene of Verif.3.1

**Verif.3.2. Social influence** One of the main factors that may impact route usage/exit choice is social influence. Social influence is defined as changes in attitudes, beliefs, opinions or behaviors as a result of the fact that one has encountered others. A test is suggested by Ronchi et al. [18] for the analysis of emergent behaviors regarding social influence in evacuation models. This test is aimed at qualitatively verifying model's capability to simulate the impact of social influence on the exit choice.

Previous studies demonstrated the importance of social influence as a key aspect that needs to be addressed to perform exit usage predictions [79]. This test requires an exit choice sub-model which allows simulating the social interaction and its impact on the exit usage.

**Geometry** Construct a room of size 10 m by 15 m. Two exits (1 m wide) are available on the 15 m walls of the room and they are equally distant from the 10 m long wall at the end of the room (see Figure 9, where the center of the doors is 12 m from the 10 m long wall).

**Scenario** Scenario 1: Insert one evacuee (evacuee 1) in the room with a pre-evacuation time of 0 s and a constant walking speed of 1 m/s as shown in Figure 4.18 (the black dot represents the evacuee which is 1 m away from the bottom wall that is 10 m long). The evacuee does not have a preferred exit (i.e. they are not familiar with any of the exit). The evacuee should be placed always in the same position among different runs and his/her position should be equidistant to both exits. Run the test several times until you get a stable percentage of exit usage for both exits i.e., exit usage does not vary more than 1% with an additional run. Annotate the exit usage for the two exits.

Scenario 2: Insert an additional evacuee (evacuee 2) in the room with pre-evacuation time of 0 s and a constant walking speed of 1 m/s as shown in Figure 4.18 (two evacuees in total). The additional evacuee is placed 2 m away from the bottom wall that is 10 m long. This evacuee is deterministically assigned to Exit 2. Run the test several times until you get a stable percentage of exit usage for the two exits for both evacuees i.e., the exit usage does not vary more than 1% with an additional run. Annotate the exit usage for both evacuees.

**Expected result** The expected result is that the usage of Exit 2 is increased in Scenario 2 for evacuee 1.

**Test method** The evaluation method of this test is a quantitative evaluation of model results in terms of exit usage.

**User's actions** It should be noted that the exit choice sub-models of evacuation models may rely on simpler criteria (shortest distance, user defined), i.e. they may be based on a deterministic choice of the user rather than a prediction of the exit usage. For this type of model it is expected that the evacuees will always choose the closest exit in all scenarios if the exit choice is not driven by the user input. The tester needs to document this limitation.

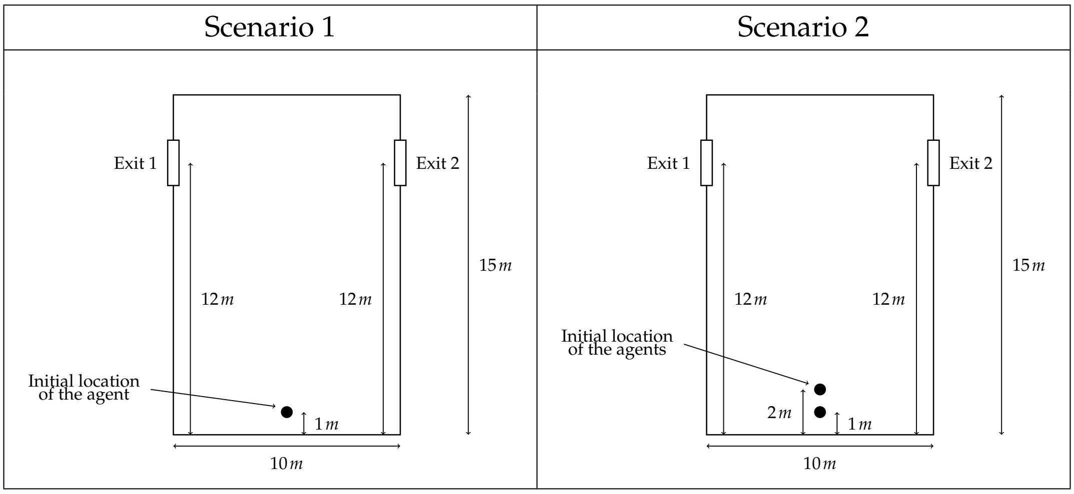



Figure 4.18: Schematic top view of the geometric layout for Verif.3.2 test. [18]

In the first Scenario, the speed of the agent $e_1$ was set to 1.25 m/s. However, it was difficult to define a completely equal distance from the agent to both exits. We tried to put the agent at several positions, i.e. 1 m away from the bottom, and recorded the probabilities of both exit selections. Finally, the position is specified as the probabilities of selecting Exit 1 and Exit 2 are 49.94% and 50.06% respectively, based on the same familiarity of both exits. We ran the first Scenario for 100 times. The agents selected the Exit 1 for 58 times while he selected the Exit 2 for 42 times. Denoted the usage of Exit 2 as $u$. We Assumed the null hypothesis $H_0$ that $u = 0.5$ and alternative hypothesis $H_1$ that $u \neq 0.5$. The cumulative distribution function of the use times of Exit 2 at $x = 42$ was $p = 0.0666$. If the significance level $\alpha = 0.05$, we could not reject $H_0$ when $x = 42$ since $p > \alpha$. Hence, we can conclude that with high probability, the usage of Exit 2 produced by the test was consistent with what we expected.

In Scenario 2, the agent $e_1$ was allocated at the same position with in Scenario 1. Another agent $e_2$ was allocated at 1 m in front of $e_1$, with walking speed equaling to 1.25 m/s. We assigned $e_2$ moving towards Exit 2. It could be expected that, even though $e_1$ had almost equal probabilities to select Exit 1 and Exit 2 in the initialization process, he would be influenced by $e_2$ and selected Exit 2 for more times compared with selecting Exit 1. In this test, only one exit re-selection function related to the social influence was enabled, while other exit re-selection functions were disabled. Running the test for 100 times, the agent $e_1$ selected Exit 2 for 71 times and selected Exit 1 for 29 times. We compared results of Scenario 1 and Scenario 2 by the Chi-Square test. The null hypothesis $H_0$ was set so that the usages of Exit 2 were equal between Scenario 1 and Scenario 2. The value of the Chi-square test statistic was $\chi^2 = 17.1091$. Under the significance level $\alpha = 0.05$, $\chi^2_{0.05}(1) = 3.84 < 17.1091$, $H_0$ was rejected. Hence, we can conclude that the usage of Exit 2 in Scenario 2 was higher than in Scenario 1, significantly, so that our model can represent the social influence on exit choice.

**Verif.3.3. Affiliation** This test is proposed by Ronchi et al. [18]. It is aimed at qualitatively verifying the capabilities of evacuation models to simulate the effect of an individual's familiarity with an exit on exit usage. Affiliation is a concept, which relates to the likelihood of a person preferring to use a familiar exit over an unfamiliar one during the evacuation process. This test requires an exit choice sub-model which includes a variable that can directly simulate the affiliation of the evacuees with the exits.

**Geometry** Construct a room of size 10 m by 15 m. Two exits (1 m wide) are available on the 15 m walls of the room and they are equally distant from the 10 m long wall at the end of the room.

**Scenario** Scenario 1: Insert an evacuee in the room with a pre-evacuation time of 0 s and a constant walking speed of 1 m/s, allocated at 1 m away from the 10 m long wall on the bottom of the room. The evacuee should always be placed in the same position among different runs and his position should be equidistant to both exits. The evacuee is assumed to be unfamiliar with the exits. Run the test several times until you get a stable percentage of exit usage for both exits i.e., exit usage does not vary more than 1% with an additional run. Annotate the exit usage for the two exits.

Scenario 2: The evacuee is assigned as in Scenario 1, except that he is not affiliated with Exit 1 (e.g. Exit 2 is the favored exit chosen by the evacuee if all the other conditions affecting choice are the same for all exits). Run the test several times until you get a stable percentage of exit usage for both exits i.e., exit usage does not vary more than 1% with an additional run. Annotate the exit usage for both exits.

**Expected result** The expected result is that the usage of Exit 2 in scenario 2 is higher than the Exit 2 usage in scenario 1.

**Test method** The evaluation method of this test is a quantitative evaluation of model results in terms of exit usage.

**User's actions** The model tester should document if the model includes a dedicated algorithm for the simulation of affiliation and if the exit choice sub-model is based on deterministic assumptions (i.e. user defined percentage of exit usage) or if it includes a predictive sub-algorithm.

Scenario 1 in Verif.3.2 and this test were completely the same, hence we only tested Scenario 2 to verify the capability of our model to simulate the effect of an individual's familiarity with an exit. In this test, we defined Exit 1 as an emergency exit and Exit 2 as a main exit since Exit 2 is assumed as a favored exit. And then we assigned an agent at 1 m away from the bottom of the room with walking speed 1.25 m/s. The exit preferences of the agent is 1.3 bias to the main exit and 1.0 bias to the emergency exit.

The result indicates that the agent selected Exit 2 for 59 times among total 100 times run. We compare results of Scenario 1 and Scenario 2 by the Chi-Square test. The null hypothesis $H_0$ was set so that the usages of Exit 2 were equal between Scenario 1 and Scenario 2. The value of the Chi-square test statistic was $\chi^2 = 5.7806$. Under the significance level $\alpha = 0.05$, $\chi^2_{0.05}(1) = 3.84 < 5.7806$, $H_0$ was rejected. Hence, we can conclude that the usage of Exit 2 in Scenario 2 was higher than in Scenario 1 significantly, so that our model has the ability to represent the affiliation affecting the exit choice.

**Verif.3.4. Group coherence** This test is designed by Lubaś et al. [20], in order to verify the model's ability to maintain group coherence. In situation of more than one available solution, pedestrians in one group usually choose the same path.

**Geometry** Details of test geometry are presented in Figure 4.19.

**Scenario** A group of 12 evacuees are located in the beginning of the corridor, they should move to the exit. The speeds and pre-evacuation times of evacuees should be assigned using the embedded distribution. evacuees do not have any affiliation to a specific path.

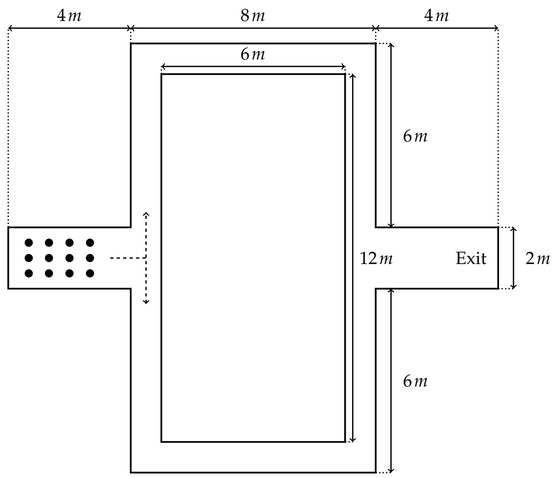



Figure 4.19: Schematic top view of the geometry layout of Verif.3.4. test.

**Expected result** All members in the group are expected to choose one path to an exit. Moreover, similarly to Verif.2.9, they should reach the exit together in a given range of time between the first and last pedestrian, i.e. 10 seconds.

We assigned 12 agents at specified positions in the left room of the scenario. The pre-evacuation times of the agents were all arranged to 0, and the walking speeds of the agents were sampled from the distribution of young adults walking speeds embedded in our model.

Figure 4.20: test scenario of Verif.3.4

| Agent | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_{move}(s)$ | 61.4 | 61.9 | 62.1 | 63.1 | 63.3 | 63.4 | 64.5 | 64.7 | 66.5 | 67.0 | 67.0 | 68.0 |

Table 4.11: The time of the agents reaching the exit

As is shown in Figure 4.20, when the agents began to move, they followed the same route moving towards the exit and a queue emergent. However, when the agents were close to the exit, since the corridor was wide, they did not queue. We recorded the time that one agent passed through the exit by the last time he stayed in the exit area. The resulting numbers of times agents passing through the exit is presented in Table 4.11. The arrival time between the first agent and the last agent is 6.6 seconds, which is not cross the threshold of 10 seconds. Hence, we can conclude that our model can represent the group coherence.

**Verif.3.5. Environment perception** This test is suggested to qualitatively evaluate whether the model can simulate an evacuee's perception of the environment and re-select the exit route. For instance, when an evacuee notices an exit that is close to him, he may choose this exit, rather than to walk to a further exit. This test can also be used to verify the dynamic availability of exits and how evacuees response to an unavailable exit.

**Geometry** Construct two connected corridors both with width 2 m. The lengths of two corridors are both 8 m. Exit 1 is available on the left 8 m wall. Exit 2 is on one the 2 m wall (see Figure 4.21).

**Scenario** 12 evacuees are located in the bottom area (see Figure 4.21) of the room with uniform distribution. Each evacuee has a pre-evacuation time of 0 s and a constant walking speed of 1 m/s. All of the evacuees are assigned to Exit 2 initially (before running the simulation). Run the simulation and record the final exit usage for the two exits. If the test associated with exit allocation such as Verif.3.1 has not been conducted, an extra scenario should be tested, i.e. turning off the exit re-selection functions, all evacuees are expected to move to Exit 2.

**Expected result** The expected result is although all of the evacuees are allocated to Exit 2 initially, that some of them finally select Exit 1.

**Test method** The evaluation method of this test is a qualitative evaluation of model results in terms of exit usage. If possible, the evaluation can be performed using the visualization tool for the model.

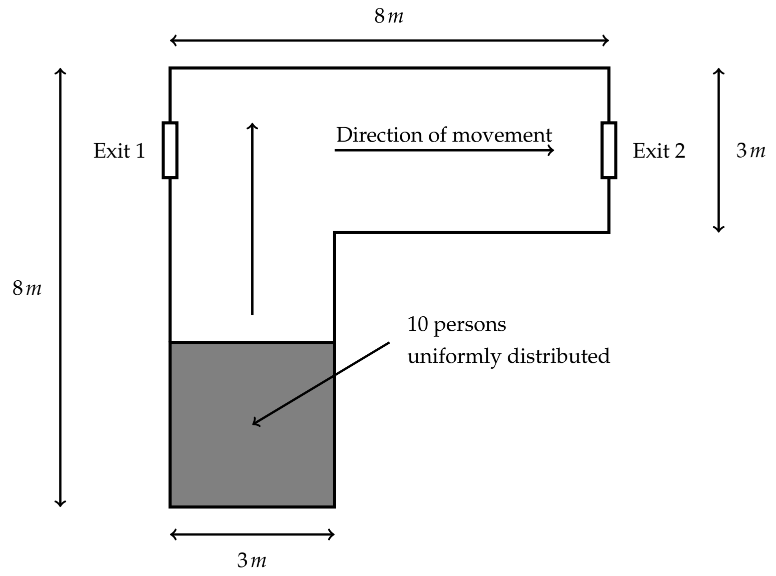



Figure 4.21: Schematic top view of the geometry layout of Verif.3.5 test.

Our model simulates the exit re-selection with a stochastic method. For environment perception, in each time interval $T$, an agent has a probability $p$ to check whether he is close to a visible exit. If so, he will change his initial exit selection and move to the new target exit. In this test, only an exit re-selection function related to the environment perception was enabled, other exit re-selection functions were disabled.

As shown in Figure 4.22, one agent noticed Exit 1 and then selected Exit 1 rather than Exit 2. In ten times runs, 43 agents selected Exit 1 among total 120 agents. The result is shown in Table 4.12, revealing the model has capability to simulate the environment perception of the agent.

| Run Times | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Number of agents selected Exit 1 | 6 | 3 | 5 | 4 | 6 | 2 | 4 | 3 | 5 | 5 |

Table 4.12: The number of agents selected Exit 1, Verif.3.5

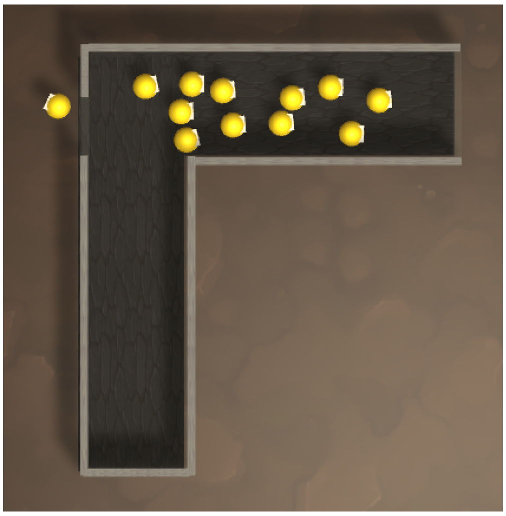


Figure 4.22: Testing scene of Verif.3.5

**Verif.3.6. Following the indicator** In the evacuation systems, the indicator (exit signal) has a strong effect for evacuees to select exit routes. This test is suggested to qualitatively evaluate the capability of the model to simulate the behavior of following indicators.

**Geometry** Construct two crossed corridors both with width 2 m. One corridor measures 12 m in length and another corridor measures 5m in length. Exit 1 and Exit 2 are located at the ends of one corridor. The indicator is located in the middle of the 12 m wall, pointing to Exit 1 (see Figure 4.23).

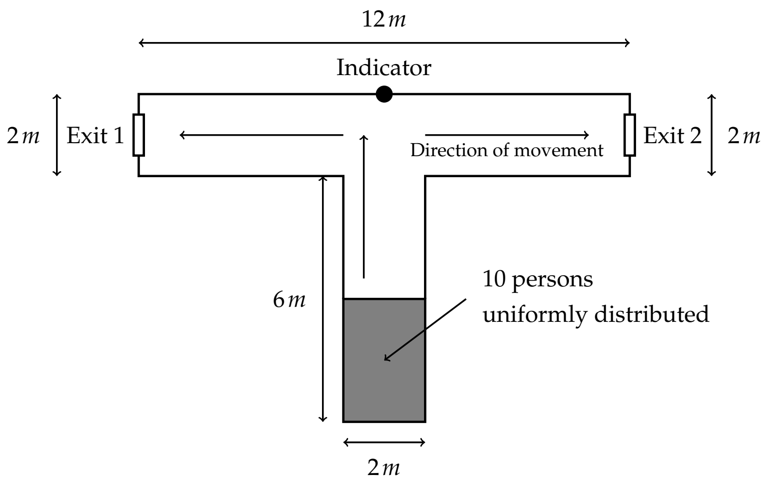



Figure 4.23: Schematic top view of the geometry layout of Verif.3.6 test.

**Scenario** 12 evacuees are located in the bottom area (see Figure 4.23) of the room with uniform distribution. Each evacuee has a pre-evacuation time of 0 s and a constant walking speed of 1 m/s. All of the evacuees are allocated to Exit 2 initially (before running the simulation). Record the final exit usage for the two exits. If the test associated with exit allocation such as Verif.3.1 has not been conducted, an extra scenario should be tested, i.e. turning off the exit re-selection functions, all of the evacuees are expected to move to Exit 2.

**Expected result** The expected result is, that although all of the evacuees are allocated to Exit 2 upon initialization, some of them select Exit 1 finally.

**Test method** The evaluation method of this test is a qualitative evaluation of model results in terms of exit usage. If possible, the evaluation can be performed by using the visualization tool for the model.

In this test, exit re-selection functions related to the environment perception and following indicators were enabled (these two functions work together to imply the expected effect), other exit re-selection functions were disabled.

As shown in Figure 4.24, some agents noticed the indicator and moved towards the pointing direction of the indicator. In ten runs, 66 agents selected Exit 1 among total 120 agents. The result is shown in Table 4.13, indicating the model has the capability to simulate agents following indicators.

| Run Times | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Number of agents selected Exit 1 | 6 | 6 | 9 | 5 | 5 | 6 | 7 | 8 | 6 | 8 |

Table 4.13: The number of agents selected Exit 1, Verif.3.6

Figure 4.24: Testing scene of Verif.3.6

## 4.4 Route Availability

A verification test (Verif.4.1.) is suggested in this section in order to determine the ability of the model to simulate exit availability dynamically. For instance, an exit could be unavailable during the evacuation because of smoke, heat, etc.

**Verif.4.1. Dynamic availability of exits** This test is proposed by Ronchi et al. [18], aimed at qualitatively evaluating the capabilities of the model to represent the dynamic availability of exits.

**Geometry** Construct a room of size 10 m by 15 m. Two exits (1 m wide) are available on the 15 m walls of the room and they are equally distant from the 10 m long wall at the end of the room (see Figure 4.25).

**Scenario** Insert an evacuee in the room with a pre-evacuation time of 0 s and a constant walking speed of 1 m/s as shown in Figure 11. Exit 1 becomes unavailable after 1 s of simulation time. Check the exit usage for both Exit 1 and Exit 2.

**Expected result** The expected result is that Exit 1 is not used by the evacuee.

**Test method** The model capabilities are analyzed in this test using a quantitative evaluation of the results in terms of exit usage. If possible, this evaluation can be performed using the visualization tool of the model.

**User's actions** If the model does not include the possibility to simulate dynamic exit usage, the model tester should document this limitation.

**Improvements** Lubaś et al. present in the paper [22] that, it is also worth to consider a rigorous test. Should pedestrians know immediately about the facts of closed doors, even a few rooms away?

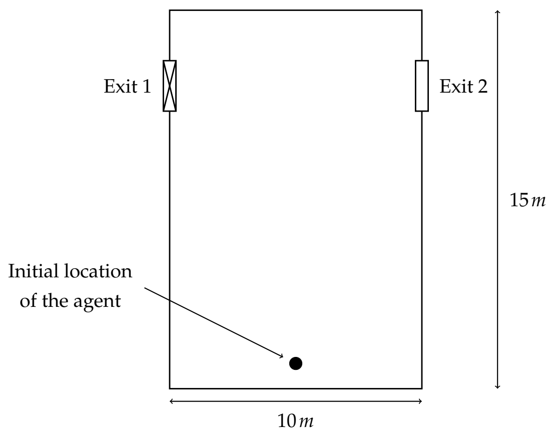



Figure 4.25: Schematic top view of the geometric layout for Verif.4.1 test. [18]

In this test, we disabled all exit re-selection functions, except for one associated with the exit availability. The agent was allocated to exit 1 initially. According to the suggestion presented in [20], we built the scenario as shown in Figure 4.26(a). Two walls were placed to prevent the agent from seeing Exit 1 directly, so that the agent could not know the availability of Exit 1 until he saw the exit. When the agent walked to the position shown in Figure 4.26(b), he noticed the unavailability of Exit 1, then he turned back and passed through Exit 2. We ran this test 10 times.

The agent selected Exit 2 in all 10 times. Hence, we conclude that our model has the capability to represent the dynamic availability of exits. Moreover, the agent in our model does not have global knowledge about the environment, instead, he perceives the environment with his visibility and tactile sense, as in real life.

(a) (b) (c)

Figure 4.26: test scenario of Verif.4.1

## 4.5 Flow Constraints

This core behavioral element deals with the representation of the relationship between evacuees' speeds, flows, densities, the population size and other egress components under consideration. A verification test (Verif.5.1) is suggested to verify the capabilities to reproduce congestion within evacuation models. A test on maximum flow rates is also presented (Verif.5.2). The evacuees' pre-evacuation times and the alarm times were assigned to zero and the functions related to shortening pre-evacuation times were disabled.

**Verif.5.1. Congestion** This test is proposed by Ronchi et al. [18] and suggested for verifying how the model simulates congestions. A modified version of IMO Test 11 [19] is proposed, aimed at verifying the flow constraints in a staircase.

**Geometry** Construct a room connected to a stair via a corridor (see Figure 12 for room, stair, and corridor dimensions).

**Scenario** Populate the room with a sub-population consisting of 100 evacuees, corresponding to a density of 2.5 people/$m^2$, having the characteristics in accordance with the population of the building(s) (see Lord et al. [71] for possible evacuee demographics). evacuees have pre-evacuation times of 0 s and walking speeds are varied over a population of 100 persons.

**Expected result** The expected result is that congestion appears at the exit connecting the room and the corridor, which produces a steady flow in the corridor with the formation of congestion at the base (i.e. the bottom) of the stairs given the different flow characteristics of the corridor and the stair. If possible, this evaluation can be performed by using the visualization tool of the model.

**Test method** The test method is a qualitative verification of model results in terms of simulated congestions.

**User's actions** It should be noted that since building evacuations generally occur moving downward, the geometry of the IMO Test 11 [19] has been modified, i.e., the stairs lead to a lower level rather than an upper level.

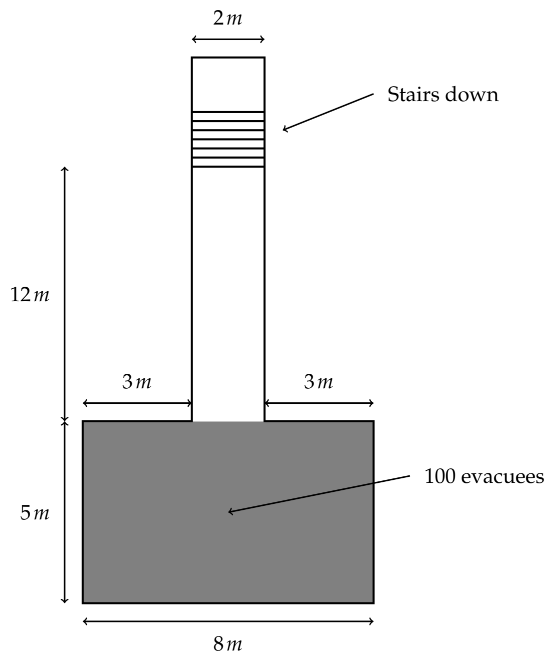
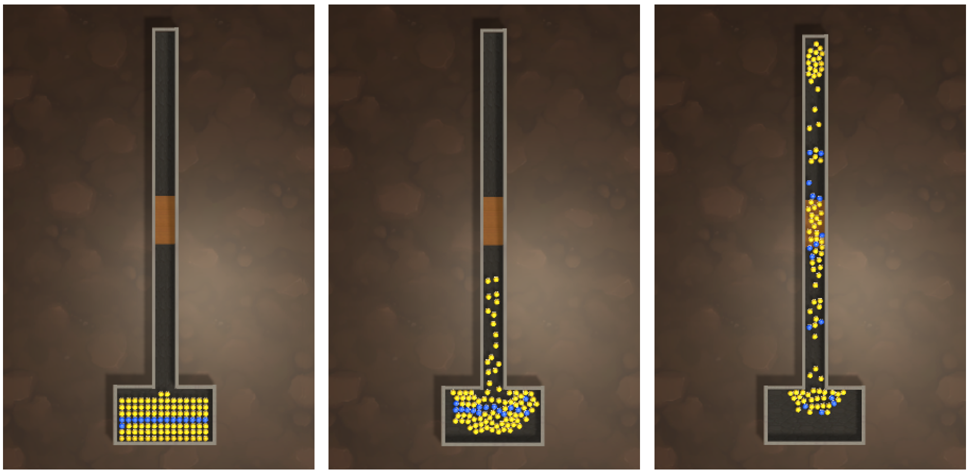



Figure 4.27: Top view of the geometric layout for Verif.5.1. test IMO test 11 [19].

We constructed the staircase of 4.5 m length and with a slope of 30 degrees slope. When an agent walked down along the stair with 30 degrees, his walking speed would decrease 46.16% compared with normal speed. Two corridors, with 12 m and 13.5 m length, respectively, are connected with the stair. The geometry of the scenario is shown in Figure 4.28(a), in which the orange colored part represents the stair. Assuming the scenario is an office, we allocated 85 young adults and 15 elderly in the scenario. The speeds of the agents were sampled from the walking speed distributions embedded in our model.

As we observed in the test, the congestion was built at both the exit of the room and the stair (see Figure 4.28(b) and Figure 4.28(c)). A steady flow was produced in the corridor. Since there was no exit in the scenario, some evacuees squeezed at bottom of the corridor. In general, we conclude that our model can represent realistic crowd flows in a corridor and on stairs.



(a) (b) (c)

Figure 4.28: test scenario of Verif.5.1

**Verif.5.2. Maximum flow rates** Proposed by Ronchi et al. [18], this test is suggested to set a conservative requirement of maximum admitted flow rates. This test is designed based on IMO Test 4 [19].

**Geometry** Construct a room of size 8 m by 5 m with a 1 m exit located centrally on the 5 m wall.

**Scenario** Place 100 evacuees in the room and assign them to the exit.

**Expected result** The flow rate at the exit over the entire period should not exceed a pre-defined maximum threshold.

**Test method** The test method is a quantitative evaluation of model results, i.e. the comparison between the results produced by the model and the maximum flow rate.

**User's actions** This test may also be susceptible to the type of grid/network in use in the case of fine and coarse network models. For this reason, the tester should demonstrate the sensitivity of the results in relation to a different discretization of the space. This test can be interpreted in two different ways. First, it is a verification test if the model under consideration represents flows through doors using restricted flows. However, it can be instead intended as an external validation requirement if flows are emergent and the tester wants to ensure that a maximum flow rate is not exceeded. An example of the maximum flow rate is the value recommended by the MSC/Circ. 1238 ($1.33pm^{-1}s^{-1}$) [19]. The model tester should document the assumptions adopted in the representation of the flows.

We assigned the population as in an office. 85 young adults and 15 elderly were allocated at specified positions, with speeds sampled from the walking speed distributions embedded in our model.

Since the evacuee flow is discrete, not continuous, we record the number of agents passing through the exit per 8 seconds. So the flow rate $f_t$ at time $t$ is computed as:

$$f_t = \frac{N_t - N_{t-8}}{8w}, \tag{4.1}$$

where $N_t$ is the agent number passing through the exit until current time, and $N_{t-8}$ is the agent number passing through the exit in the last time step. And $w$ represents the width of the exit.

The passing point is regarded as the first point the agent arrived at the exit (as we discussed in Section 3.1.4, an exit is represented as a rectangle with a maximum point and a minimum point). We ran the test 10 times and recorded the maximum flow rate in each test. Among these ten times, there is no maximum flow rate that exceeds the threshold, i.e. 1.33 $ps^{-1}m^{-1}$. Hence, we conclude that our model passes this test.

| | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | $T_6$ | $T_7$ | $T_8$ | $T_9$ | $T_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $f(ps^{-1}m^{-1})$ | 1.125 | 1.125 | 1.125 | 1 | 1.125 | 1.125 | 1.125 | 1.25 | 1.125 | 1 |

Table 4.14: The maximum flow rates of 10 runs

## 4.6 Conclusion

In this chapter, we conduct in total 24 verification tests in five core aspects in the evacuation, i.e. the pre-evacuation time, the movement and navigation, the exit choice, the route availability and the flow constrains. A verification test related to the elevator is not taken into account, since our model does not include any function about the elevator. Among 24 tests, our model successfully passes 23 tests, but fails in Verif.2.8, namely horizontal counter-flows. Such a result indicates that, in general, our model has capability to simulate an evacuation scenario correctly most of time, while the model is unsuitable for simulating a high-density crowd.

# 5 Validation

## 5.1 Exit selection under different lightings

In this section, we validate our model by the experiment mentioned in Section 2.4.1 [29]. In the experiment, participants were divided into two groups. The first group took part in the walking test under the conventional lightings, and the second group participated the walking test under the Nodazzle lighting system. Since we cannot obtain detailed movement time of each participant, neither the standard deviation of the movement times, we can only adopt the exit selection data proposed by the experiment. In the first scenario, i.e. conventional lighting scenario, 14 participants selected the emergency exit and 7 participants selected the main exit. While in the second scenario, i.e. Nodazzle lighting scenario, 18 participants preferred the emergency exit, only 2 participants chose the main exit. However, such an exit preference of evacuees is obviously different from other researches. We consider that it is due to the evacuation message that the participant received in the beginning of his test: "There is a fire. Leave the building via the emergency exit." In this message, the instruction stressed on "emergency exit", which might influence the participant's exit preference. Hence, we modify the exit selection algorithm, such that the main exit preference decreases from 1.3 to 0.7, meanwhile the near exit preference stays at 1.0, for a normal character.

### 5.1.1 Scenario construction

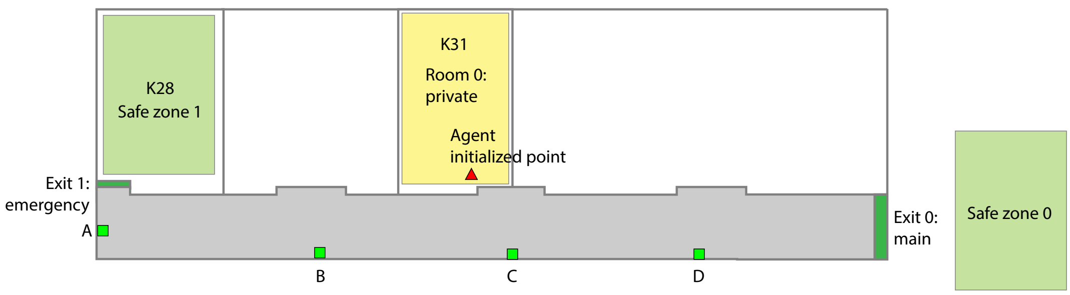
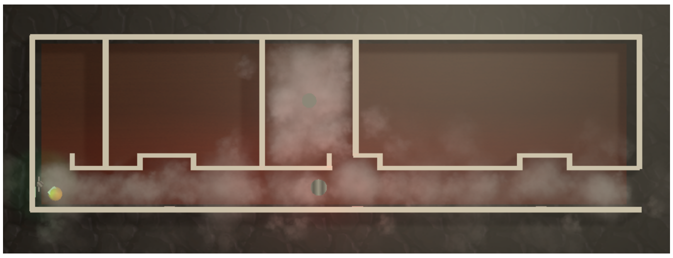



Figure 5.1: Top view of the exit selection validation test

The testing scenario was built according to the real building layout (See Figure 5.1). Two way outs were allocated at the right end of the corridor and at a specified room, respectively. Two smoke points were used to generate smoke diffusing in the corridor, and the extinction coefficient of the smoke was assigned as $1.0m^{-1}$ in white lighting and $0.939414m^{-1}$ (calculated from the formula (3.4)) in red lighting. The room K31 was defined as a private room, which does not automatically generate agents. The only agent in each simulation run was allocated at a specified point (shown in red triangle) in the room. We represented the agent with a normal character, with initial walking speed sampled from the young adult walking speed distribution, body radius 0.239m, main exit preference 0.7 (after modification) and near exit preference 1.0. The pre-evacuation time of the agent was assigned to 0. Since the extinction coefficient of the smoke was specified, when and where the agent moves did not influence his visibility and walking speed, which were calculated from the static extinction coefficient of the smoke in the beginning of the simulation. In addition, the main exit was named Exit 0 and the emergency exit was named Exit 1, and room K28 was defined as Safe zone 1, corresponding to the emergency exit. An area out of the indoor floor was defined as Safe zone 0, corresponding to the main exit. The whole floor, except for Safe zone 0, was regarded as a indoor region.

(a) Conventional lighting scenario



(b) Nodazzle lighting scenario

Figure 5.2: Simulation scenarios of walking test

The lighting assignment was as same as the experiment. In the conventional lighting scenario, one lamp with white illumination was arranged in K31, and one exit sign with normal white lighting was set up at 2m height at the end of the corridor, near Exit 1 (position A in Figure 5.1). In the Nodazzle lighting scenario, the same lamp with scenario 1 was arranged in K31 as well. But the exit sign at position A was changed to Nodazzle exit sign, with a blinking green beam irradiating to the ground. Besides, four indicators were assigned at positions A, B, C and D, at 90cm above the ground, pointing to Exit 1. A light with red illumination was installed in the corridor, providing a better visibility in the smoke. The two simulation scenarios are shown in Figure 5.2.

### 5.1.2 Simulation result

We ran simulation in each scenario for 50 times. To compare the simulation result with the empirical result, we denote the simulation as "S", the real experiment as "R", the conventional lighting scenario as "C", and the Nodazzle lighting scenario as "N". For instance, the result in a run of simulation under the conventional lighting is represented as "SC". We recorded the usage of two exits in the simulation (see Table 5.1).

| | RC | RN | SC | SN |
|---|---|---|---|---|
| Main exit | 7 | 2 | 17 | 5 |
| Emergency exit | 14 | 18 | 33 | 45 |

Table 5.1: The number of agents selected two exits

In the conventional lighting scenario, 33 agents selected the emergency exit, while in the Nodazzle lighting scenario, 45 agents selected the emergency exit. We validate quantitatively the ability of the model to correctly represent the exit selection under different lightings by logistic regression. The exit selection is modelled as a function $E(x,y)$ of two variables $x$ and $y$, where $x$ is the lighting type and $y$ is the testing environment:

$$E(x,y) = \frac{1}{1 + e^{-(\alpha+\beta_1 x+\beta_2 y)}} \tag{5.1}$$

where $\alpha$, $\beta_1$ and $\beta_2$ are fitted from the data in Table 5.1. After fitting, we obtain estimated values for these three parameters. The fitted equation is:

$$E(x,y) = \frac{1}{1 + e^{2.21262-1.52537x-0.0215012y}} \tag{5.2}$$

In this equation, we observe that $\beta_2$ is very small, which means $y$ does not influence exit selection $E(x,y)$ seriously. We show the graph of the fitted function $E(x,y)$ in Figure 5.3. Indicated by the figure, the surface fluctuates gently along $y$ axis.

This could be conducted more rigorously with the Wald test in which the null hypothesis $H_0$ and the alternative hypothesis $H_1$ are

$$H_0 : \ \beta_2 = 0, \tag{5.3}$$

$$H_1 : \ \beta_2 \neq 0. \tag{5.4}$$

With the level $\alpha$ of the hypothesis test set to be 0.05, the rejection region of the null hypothesis $H_0$ is given by $z > z_{\frac{\alpha}{2}} = 1.96$. Recall that the level of our test is the highest probability of our test to reject $H_0$ when $H_0$ is actually true. Since our Wald $z$-statistic has value 0.0459935, which lies outside the rejection region, we conclude that it is statistically insignificant to reject $H_0$.

Compared with testing environment $y$, the lighting type $x$ is proved to influence the exit selection of an agent, by using Wald test in which the null hypothesis $H_0$ and the alternative hypothesis $H_1$ are

$$H_0 : \beta_1 = 0, \tag{5.5}$$

$$H_1 : \beta_1 \neq 0. \tag{5.6}$$

With the level $\alpha$ of the hypothesis test set to be 0.05, the rejection region of the null hypothesis $H_0$ is given by $z > z_{\frac{\alpha}{2}} = 1.96$. Recall that the level of our test is the highest probability of our test to reject $H_0$ when $H_0$ is actually true. Since our Wald $z$-statistic has value 3.23955, which lies inside the rejection region, we conclude that it is statistically significant to reject $H_0$.

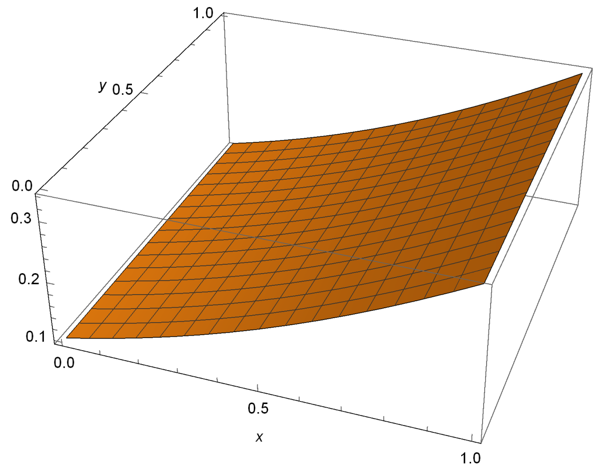
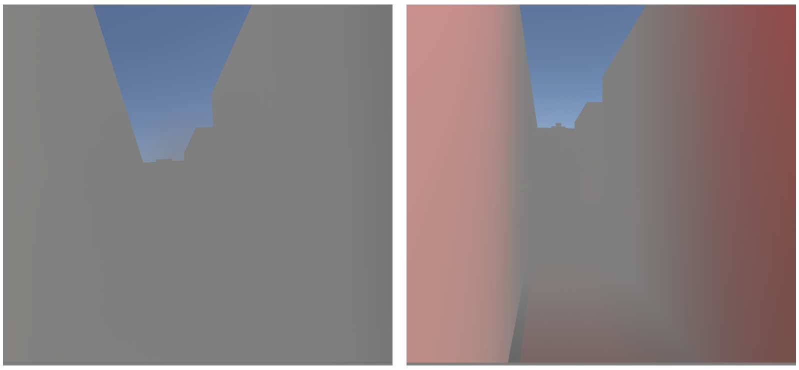



Figure 5.3: $E(x,y) = \frac{1}{1+e^{2.21262-1.52537x-0.0215012y}}$

During the simulation, we also observed several interesting phenomena produced by our model. In the Nodazzle lighting scenario, some agents moved towards the main exit in the beginning, however, the agents noticed an indicator, and then followed the guiding of a sequence of indicators, and finally arrived at the emergency exit. In addition, we also observed a clearer view in the first person view under the Nodazzle lighting scenario (see Figure 5.4), compared with the conventional lighting scenario.

Based on the result analysis, we conclude that our model can represent different exit selections of an agent under different lighting situations correctly, as in real life.



(a) Conventional lighting scenario (b) Nodazzle lighting scenario

Figure 5.4: Two scenarios in the first person view

## 5.2 Evacuation time

In this section, we validate our model by the experiment mentioned in Section 2.4.2, with an functional analysis approach.

### 5.2.1 Definitions of validation

Before we discuss validation, we give some definitions which we will use in this section. Suppose we run the model for totally $N$ times in the same scenario with $Q$ agents. In each run, we obtain $Q$ evacuation times (time from the agent receives the first stimuli such as alarm, until the agent passes through an exit) of $Q$ agents. Firstly, the evacuation times are sorted by ascending order, and recorded in a vector called **curve** which is denoted as:

$$\overrightarrow{m} = (m_1, m_2, m_i, \ldots, m_Q). \tag{5.7}$$

In vector $\vec{m}$, $m_1$ represents the evacuation time of the fastest agent, $m_Q$ represents the evacuation time of the slowest agent, and $m_i$ represents the evacuation time of the $i^{th}$ fastest agent.

Since we run the model $N$ times, $N$ curves will be generated. We denote the curve of the $j^{th}$ run as:

$$\overrightarrow{m_j} = (m_{j1}, m_{j2}, m_{ji}, \ldots, m_{jQ}), \tag{5.8}$$

where $m_{ji}$ represents the evacuation time of the $i^{th}$ agent in the $j^{th}$ model run.

The next variable is the arithmetic mean of curves called "average curve" of the runs.

$$\overrightarrow{M_j} = \frac{1}{j} \sum_{k=1}^{j} \overrightarrow{m_k}. \tag{5.9}$$

To write down several terms concretely, $\overrightarrow{M_1} = \overrightarrow{m_1}$, $\overrightarrow{M_2} = \frac{1}{2}(\overrightarrow{m_1} + \overrightarrow{m_2})$, and $\overrightarrow{M_N} = \frac{1}{N}\sum_{k=1}^{N}\overrightarrow{m_k}$. We denote the $k^{th}$ element in vector $\overrightarrow{M_j}$ as $M_{jk}$, where $M_{jk}$ represents the consecutive average evacuation time of the $k^{th}$ fastest agent from the first run until the $j^{th}$ run.

Four types of measures are implemented in our validation, $TET$ (Total Evacuation Time, i.e., maximum evacuation time), $ERD$ (Euclidean Relative Difference), $EPC$ (Euclidean Projection Coefficient) and $SC$ (Secant Cosine). $SD$ (Standard Deviation) is not used because the validity standard of $SD$ is lacking [45]. How to calculate these four measures and their convergence measures $TET_{conv}$, $ERD_{conv}$, $EPC_{conv}$ and $SC_{conv}$ are explained in Appendix C.

After we clarify the definitions, we explain the three basic steps in our validation process. First, we need to analyze the experimental data. Since we only have one group of experimental evacuation time, this group of data will be directly used as comparable experimental result.

Second, $N$ repeated runs of a scenario should be conducted, until $TET_N$, $ERD_{N-1}$, $EPC_{N-1}$ and $SC_{N-1}$ converge, which means that $TET_{convN}$, $ERD_{convN-1}$, $EPC_{convN-1}$ and $SC_{convN-1}$ stay lower than the given thresholds for at least $W$ runs. We apply the standards proposed by Lovreglio [44], where the thresholds are given by

$$TR_{TET} = 0.005;\ \ TR_{ERD} = 0.005;\ \ TR_{EPC} = 0.005;\ \ TR_{SC} = 0.0002 \tag{5.10}$$

The parameter $s$ in $SC_{convN-1}$ and $TR_{sc}$ is assigned to 2 and $W$ is suggested to set as 10.

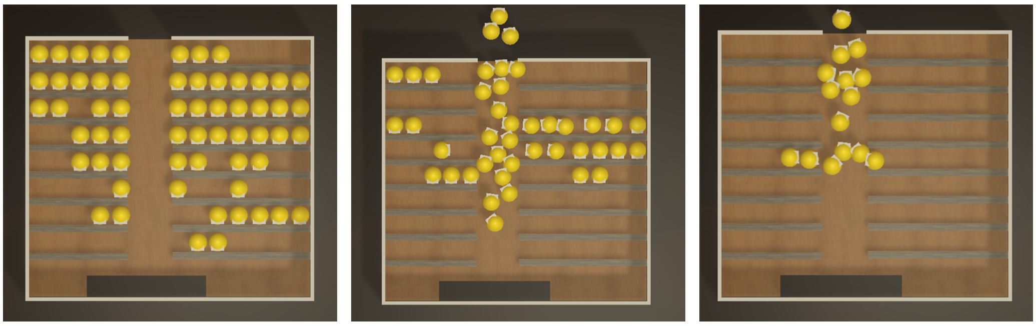
Third, we compare the experimental result with $N$ groups of simulation results by four measures $TET$, $ERD$, $EPC$ and $SC$ as well. In this step, the first comparable curve is the experimental curve. Such an experimental curve is compared with the evacuation time curve $\overrightarrow{m}$ of each run and the average evacuation time curve $\overrightarrow{M_N}$ generated by $N$ runs. After that, for four measures, the best value (nearest to the limit, i.e. $TET_{conv} \to 0^+$, $ERD \to 0^+$, $EPC \to 1$ and $SC \to 1^-$), the worst value (farthest to the limit) and the average value (value of the average curve) should be compared to the thresholds. Galea et al. [45] proposed two sets of standard thresholds, i.e. the less restrictive thresholds (see Equation (5.11)) and the restrictive threshold (see Equation (5.12)).

$$TET_{conv} \le 0.45;\ \ ERD \le 0.45;\ \ 0.6 \le EPC \le 1.4;\ \ SC \ge 0.6\ \ with\ \ \frac{s}{Q} = 0.05 \tag{5.11}$$

$$TET_{conv} \le 0.15;\ \ ERD \le 0.25;\ \ 0.8 \le EPC \le 1.2;\ \ SC \ge 0.8\ \ with\ \ \frac{s}{Q} = 0.03 \tag{5.12}$$

### 5.2.2 Scenario construction

The classroom scenario was built according to Figure 2.3. The only exit was assigned as a main exit. The classroom was defined as a public room and a indoor region. Moreover, an area out of the door was specified as the safe zone. The layout of the simulation scenario is shown in Figure 5.5(a).



(a) t = 0s (b) t = 15s (c) t = 30s

Figure 5.5: Simulation scenario at time $t = 0s$, $t = 15s$ and $t = 30s$

60 normal characters were manually allocated at positions shown in Figure 2.3. The pre-evacuation times of agents in the scenario were assigned manually with the values offered by Zhang's experiment [46] (see Table 2.1), and all functions related to modifying the pre-evacuation time were disabled. The walking speeds of agents were sampled from the embedded speed distribution in our model. Since the experiment was conducted in China, the body radius of the normal character was changed to 0.2065m [80]. In addition, considering the behaviors of students in the experiment, agents in the simulation did not linger in the room during the pre-evacuation time, instead, they stayed at their seats. Groups were not involved in the simulation, and agents were considered as individuals.

### 5.2.3 Validation Result

**Step 1: Experimental data**

Three steps in the functional analysis validation are conducted successively. Because there is only one group of evacuation times, we have evacuation time curve $\overrightarrow{m_1} = \overrightarrow{M_1}$, as shown in Figure 5.6. This curve is directly used to compare with the simulation curves.

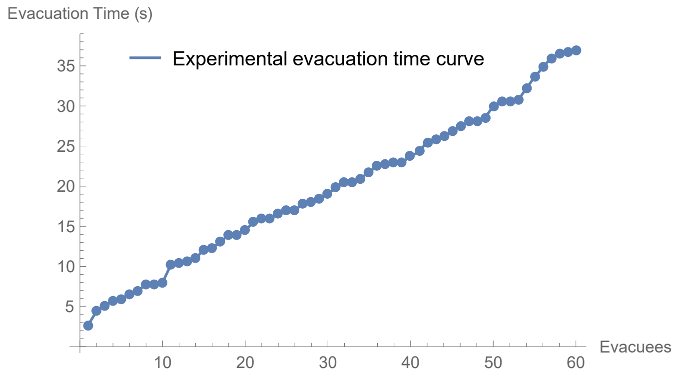
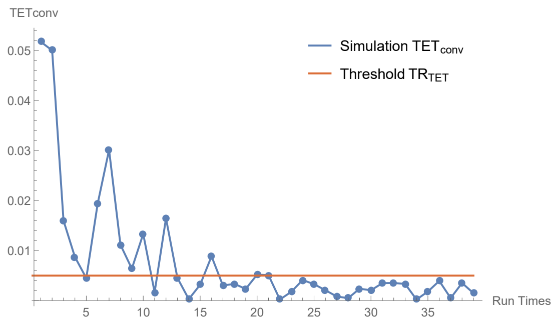


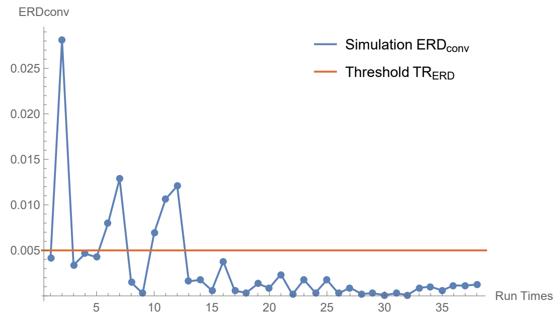

Figure 5.6: Experimental evacuation time curve

**Step 2: Simulation**

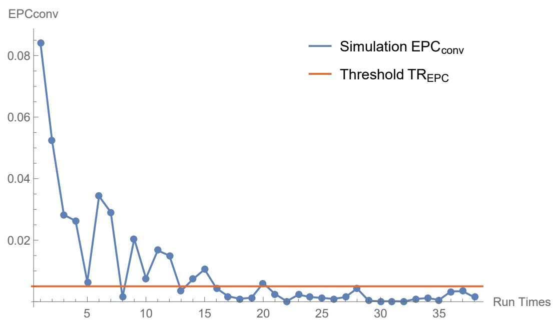
In this step, we run simulations in the same scenario for 40 times. Four measures, $TET$, $ERD$, $EPC$ and $SC$ all converge within 40 runs (see Figure 5.7). $TET_{conv}$ is smaller than the threshold, i.e. 0.005, for 10 times from $22^{th}$ run to $31^{th}$ run. $ERD_{conv}$ is smaller than the threshold, i.e. 0.005, for 10 times from $13^{th}$ run to $22^{th}$ run. $EPC_{conv}$ is smaller than the threshold, i.e. 0.005, for 10 times from $21^{th}$ run to $30^{th}$ run. $SC_{conv}$ with $s = 2$ is smaller than the threshold, i.e. 0.0002, for 10 times from $26^{th}$ run to $35^{th}$ run. After $35^{th}$ run, there is no measure larger than the threshold. Hence, we can conclude that our model can represent stable evacuation times after finitely many times.



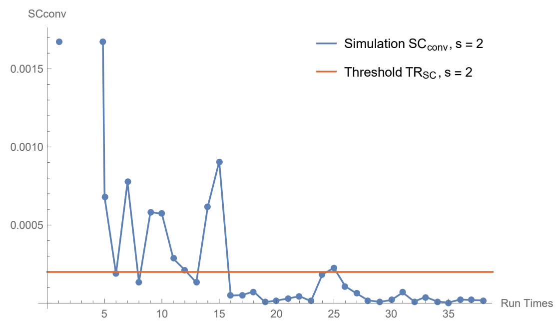

(a) Convergence of TET




(b) Convergence of ERD




(c) Convergence of EPC




(d) Convergence of SC

Figure 5.7: Convergences of four measures

### Step 3: Data comparison

Once the convergence criteria are met, a comparison between the experimental data and simulation results is performed in accordance with standards (5.11) and (5.12).

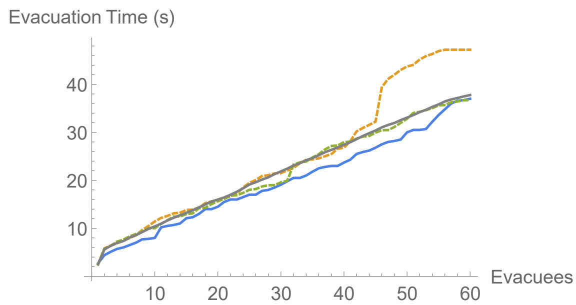



Figure 5.8: TET Comparisons between the experimental curve, the average curve, the best curve and the worst curve

First, we compare TET of the experimental data and simulation results. The best curve is $\overrightarrow{m_{24}}$ with $TET_{conv} = 0.00766$ and the worst curve is $\overrightarrow{m_8}$ with $TET_{conv} = 0.276125$. The average curve is $\overrightarrow{M_{40}}$ with $TET_{conv} = 0.0193$. Comparisons between four curves are shown in Figure 5.8. The best curve and the average curve meet the restrictive threshold and the worst curve meets the less restrictive threshold.

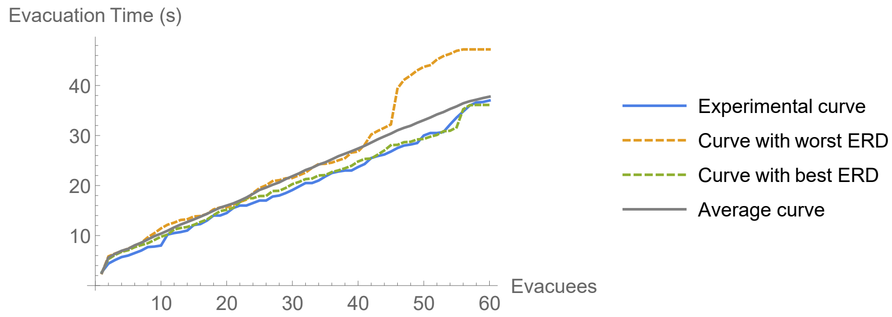



Figure 5.9: ERD Comparisons between the experimental curve, the average curve, the best curve and the worst curve

Second, we compare ERD of the experimental data and simulation results. The best curve is $\overrightarrow{m_{10}}$ with $ERD = 0.0392566$ and the worst curve is $\overrightarrow{m_8}$ with $ERD = 0.31513$. The average curve is $\overrightarrow{M_{40}}$ with $ERD = 0.113028$. Comparisons between four curves are shown in Figure 5.9. The best curve and the average curve meet the restrictive threshold and the worst curve meets the less restrictive threshold.

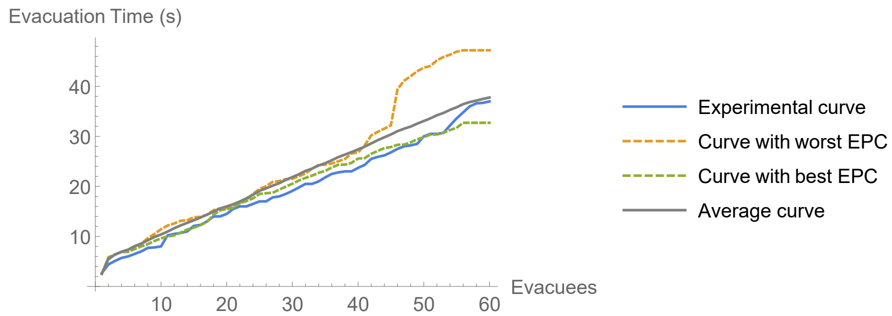



Figure 5.10: EPC Comparisons between the experimental curve, the average curve, the best curve and the worst curve

Third, we compare EPC of the experimental data and simulation results. The best curve is $\overrightarrow{m_{40}}$ with $EPC = 1.00377$ and the worst curve is $\overrightarrow{m_8}$ with $EPC = 1.28158$. The average curve is $\overrightarrow{M_{40}}$ with $EPC = 1.10139$. Comparisons between four curves are shown in Figure 5.10. The best curve and the average curve meet the restrictive threshold and the worst curve meets the less restrictive threshold.

Forth, we compare SC of the experimental data and simulation results. The best curve is $\overrightarrow{m_{10}}$ with $SC = 0.864172$ when $s = 2$ or $\overrightarrow{m_9}$ with $SC = 0.927149$ when $s = 3$. The worst curve is $\overrightarrow{m_8}$ with $SC = 0.631652$ when $s = 2$ and $SC = 0.688795$ when $s = 3$. The average curve is $\overrightarrow{M_{40}}$ with $SC = 0.865709$ when $s = 2$ and $SC = 0.914934$ when $s = 3$. Comparisons between four curves are shown in Figure 5.11. The best curve and the average curve meet the restrictive threshold and the worst curve meets the less restrictive threshold.

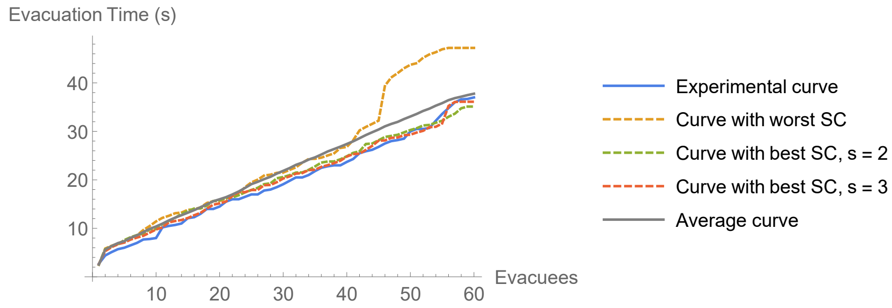
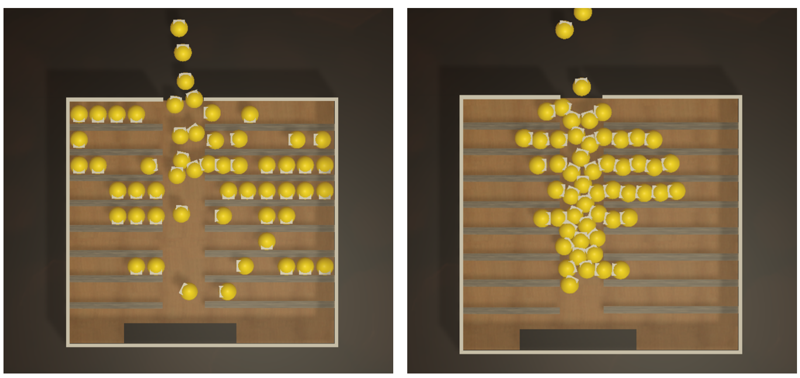



Figure 5.11: SC Comparisons between the experimental curve, the average curve, the best curve and the worst curve

Among 40 times of simulation runs, the $8^{th}$ run behaves worst in all measurements. Nevertheless the $8^{th}$ run meets the less restrictive criteria. The best curves and the average curves satisfy the rigorous standards. Hence, we can conclude that our model can represent the evacuation time correctly most of the time. More than that, an arbitrary run of simulation can still meet the less restrictive criteria.

### Observations

Except for the evacuation time, we observe an interesting phenomena in the simulation which is dubbed "faster is slower" [81]. In the validation scenario, we manually assign the pre-evacuation times for agents according to the experimental data. However, when we disable the pre-evacuation times, we find that the evacuation times does not become shorter. Instead, they are longer than the former situation. As shown in Figure 5.12, in the scenario with pre-evacuation times, a continuos pedestrian flow is formed near the exit, while in the scenario without pre-evacuation times, every agent wants to evacuate quickly, yielding a blockage at the front row. The pedestrian flow is intermittent and the agents in the back rows need a long time to pass through the exit.



(a) with pre-evacuation times (b) without pre-evacuation times

Figure 5.12: Evacuation with and without pre-evacuation times

We run the scenario without pre-evacuation times for 20 times, and generate an average evacuation time curve for this scenario (see Figure 5.13) to compare to the average curve in validation scenario. As indicated by the figure, in the scenario without pre-evacuation times, the first few agents have shorter evacuation times than in the scenario with pre-evacuation times. But from the $28^{th}$ agent, the agents move slower and slower. It implies that proper pre-evacuation times might shorten the evacuation times to some extent.

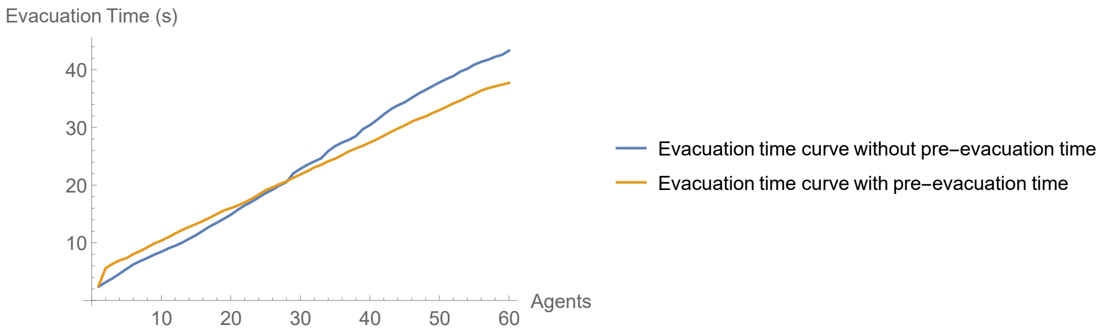



Figure 5.13: Comparisons between evacuation times with and without pre-evacuation times

# 6 Conclusion

In this thesis, we propose an improved evacuation model based on our small project research [1], which can be applied in a multi-layered environment, involving smoke and different lighting setups. The model can represent evacuation behaviors qualitatively and quantitatively, with embedding existing knowledge in the evacuation research field. The model considers an evacuee as an active and intelligent agent, who has receptors to precept the environment and feedback strategies to response to the environment. The agent has a set of initial parameters, while some events in the environment are recognized as triggers to modify the parameters of agents. Such a mechanism allows dynamic varieties during the evacuation, i.e. dynamic environment perceptions, dynamic exit selections (the agent changes his target exit according to the surrounding environment), dynamic pre-evacuation times and dynamic path plannings.

Through a set of verification tests, the model is proved to correctly represent the evacuation process in five aspects, i.e. the pre-evacuation time, the movement and navigation, the exit choice, the route availability and the flow constrains. In addition, two validation tests are conducted based on two existing experiments. The validation result indicates that the model has capabilities to represent the exit selection under different lighting systems and the evacuation time accurately.

However, our model still has some unsolved shortcomings that will need to be addressed in the future. First, the model is considered unsuitable for simulating the crowd in a high density. As we observed in Verif.2.8, two counter-flows might block each others from passing through to the opposite positions. Second, the weighted region and deviation in the smoke functions cannot be used in the same time since they are based on two different path planning approaches in the bottom level. Third, because the testing standard of it is still lacking, the evacuation behaviors in a multi-layered environment has not been fully tested yet. Last, the smoke growing equation in our model is rough. Introducing a scientific smoke model might be a valuable direction of the future work.

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# Appendices

# A [Evacuation character]

This appendix lists default values for features of six types of characters, i.e. the normal character, the visitor, the elderly, the disabled agent, the staff and the nurse.

| Normal Character | |
|---|---|
| Body radius (m) | 0.239 |
| Preferred speed $S_p$ (m/s) | Sample from Weibull distribution with $\alpha =$ 10.14 and $\beta = 1.41$ |
| Ascending speed (m/s) | $(-0.0136 * degree + 0.8728)\, S_p$ |
| Descending speed (m/s) | $(-0.0142 * degree + 0.9644)\, S_p$ |
| Initial visibility | 1.0 |
| Initial accumulated toxicity | 0.0 |
| Pre-evacuation time (s) | Sample from Log-normal distribution with $\mu = 4.30008$ and $\sigma = 0.628501$ |
| Main exit preference | 1.3 |
| Near exit preference | 1.0 |
| Need help | No |
| Inform others | No |
| Help others | No |

Table A.1: Evacuation characters: normal character

| Visitor | |
|---|---|
| Main exit preference | 3.5 |
| Others | As the same as the normal character |

Table A.2: Evacuation characters: visitor

| Elderly | |
|---|---|
| Body radius (m) | 0.241 |
| Preferred speed $S_p$ (m/s) | Sample from Uniform distribution from 0.71 to 1.85 |
| Ascending speed (m/s) | $(-0.0152 * degree + 0.9244)\, S_p$ |
| Descending speed (m/s) | $(-0.0165 * degree + 1.0054)\, S_p$ |
| Others | As the same as the normal character |

Table A.3: Evacuation characters: elderly

| Disabled agent | |
|---|---|
| Body radius (m) | 0.375 |
| Preferred speed $S_p$ (m/s) | Sample from Uniform distribution from 0.10 to 1.77 |
| Ascending speed (m/s) | $(-0.0152 * degree + 0.9244)\, S_p$ |
| Descending speed (m/s) | $(-0.0165 * degree + 1.0054)\, S_p$ |
| Need help | Yes |
| Others | As the same as the normal character |

Table A.4: Evacuation characters: disabled agent

| Staff | |
|---|---|
| Pre-evacuation time (s) | 0.3 * Sample from Log-normal distribution with $\mu = 4.30008$ and $\sigma = 0.628501$ |
| Near exit preference | 2.0 |
| Inform others | Yes |
| Others | As the same as the normal character |

Table A.5: Evacuation characters: staff

| Nurse | |
|---|---|
| Pre-evacuation time (s) | 0.2 * Sample from Log-normal distribution with $\mu = 4.30008$ and $\sigma = 0.628501$ |
| Near exit preference | 3.5 |
| Inform others | Yes |
| Help others | Yes |
| Others | As the same as the normal character |

Table A.6: Evacuation characters: nurse

# B [Suggested verification tests]

This appendix lists all verification tests we conducted in chapter 4 in five aspects, i.e. the pre-evacuation time, the movement and navigation, the exit choice/usage, the route availability and the flow constrains.

| Core component | Sub-element | suggested tests | Test code | Type of test |
|---|---|---|---|---|
| Pre-evacuation time | Pre-evacuation time distributions | NIST Test 1.1 | Verif.1.1 | AN_VERIF |
| | pre-evacuation time in a public room | New test | Verif.1.2 | EB_VERIF |
| | pre-evacuation time in a building with staff | New test | Verif.1.3 | EB_VERIF |
| | pre-evacuation time in smoke | New test | Verif.1.4 | EB_VERIF |
| | pre-evacuation time with red lighting | New test | Verif.1.5 | EB_VERIF |
| Movement and navigation | Speed in a corridor | Modified IMO Test 1 | Verif.2.1 | AN_VERIF |
| | Speed on stairs | Modified NIST Verif.2.2 | Verif.2.2 | AN_VERIF |
| | Movement around a corner | Modified IMO Test 6 | Verif.2.3 | AN_VERIF |
| | Assigned demographics | NIST Verif.2.4 | Verif.2.4 | AN_VERIF |
| | Reduced visibility vs walking speed | NIST Verif.2.5 | Verif.2.5 | AN_VERIF |
| | Evacuee's incapacitation | NIST Verif.2.6 | Verif.2.6 | AN_VERIF |
| | Elevator usage | Modified NIST Verif.2.7 | Verif.2.7 | AN_VERIF |
| | Horizontal counter-flows | Modified NIST Verif.2.8 | Verif.2.8 | EB_VERIF |
| | Group behaviors | NIST Verif.2.9 | Verif.2.9 | EB_VERIF |
| | People with movement disabilities | Modified NIST Verif.2.10 | Verif.2.10 | EB_VERIF |
| | Deviation in smoke | New test | Verif.2.11 | EB_VERIF |

Table B.1: Suggested verification tests for evacuation models

| | | | | |
|---|---|---|---|---|
| Exit choice/Usage | Exit route allocation | NIST Verif.3.1 | Verif.3.1 | AN_VERIF |
| | Social influence | NIST Verif.3.2 | Verif.3.2 | EB_VERIF |
| | Affiliation | NIST Verif.3.3 | Verif.3.3 | EB_VERIF |
| | Group coherence | Lubaś test | Verif.3.4 | EB_VERIF |
| | Environment perception | New test | Verif.3.5 | EB_VERIF |
| | Following the indicator | New test | Verif.3.6 | EB_VERIF |
| Route availability | Dynamic availability of exits | Modified NIST Verif.4.1 | Verif.4.1 | AN_VERIF |
| Flow constrains | Congestion | Modified NIST Verif.5.1 | Verif.5.1 | EB_VERIF |
| | Maximum flow rates | Modified IMO Test 4 | Verif.5.2 | EB_VERIF |

Table B.2: Suggested verification tests for evacuation models

# C [Definition of $TET$, $ERD$, $EPC$, $SC$ and their convergences]

This appendix explains the definitions and the calculations of four measures in Lovreglio's validation approach [44], i.e. the total evacuation times (TET), the Euclidean relative difference (ERD), the Euclidean projection coefficient (EPC) and secant cosine (SC).

**Convergence measure 1: Total evacuation times (TET)**

TETs represent the highest values of the curves, i.e. the evacuation times of the slowest evacuees in several runs. We calculate consecutive averages of TETs as following:

$$TET_{avj} = \frac{1}{j}\sum_{k=1}^{j} m_{kQ}, \qquad when \quad 1 \leq j \leq N. \tag{C.1}$$

where $m_{kQ}$ is the evacuation time of slowest evacuee in the $k^{th}$ run. It is should be noticed that $TET_{avj}$ and $m_{kQ}$ are both scalars. Applying the law of large numbers, the consecutive $TET_{avj}$ can be interpreted as a series converging to an expected value ($\mu$ of the total evacuation time distribution). Hence, a measure of convergence of the series can be performed.

A measure of convergence of two consecutive $TET_{avj}, TET_{avj+1}$ is obtained by calculating $TET_{conv}$ (see equation C.2). This convergence measure assumes that the best approximation of the expected value is the last average total evacuation time. This measure is useful to evaluate the impact of an additional run on the average predicted total evacuation time.

$$TET_{convj} = \left| \frac{TET_{avj} - TET_{avj-1}}{TET_{avj}} \right|, \qquad for \quad 2 \leq j \leq N. \tag{C.2}$$

**Convergence measure 2: Euclidean Relative Difference (ERD)**

Instead of measuring difference between highest values of two curves, ERD compares two curves globally. We calculate ERD of the $j^{th}$ run as:

$$ERD_j = \frac{\| \overrightarrow{M_j} - \overrightarrow{M_{j+1}} \|}{\| \overrightarrow{M_{j+1}} \|} = \sqrt{\frac{\sum_{k=1}^{Q} [M_{jk} - M_{(j+1)k}]^2}{\sum_{k=1}^{Q} [M_{(j+1)k}]^2}}, \qquad for \quad 1 \leq j \leq N-1 \tag{C.3}$$

The consecutive $ERD_j$ can be interpreted as a series converging to the expected value equal to 0 (the case of two curves identical in magnitude). Hence, a measure of the convergence of the series is possible. A measure of the convergence of two consecutive $ERD$, corresponding to two consecutive average curves $\overrightarrow{M}$, can be obtained by calculating $ERD_{conv}$. It is defined as the absolute value of the difference of two consecutive Euclidean Relative Difference, $ERD_j$ and $ERD_{j-1}$.

$$ERD_{convj} = \left| ERD_j - ERD_{j-1} \right|, \qquad when \quad 2 \leq j \leq N-1. \tag{C.4}$$

Calculation of $ERD_{convj}$ permits estimation of the impact of the number of runs on the overall differences between consecutive average curves. $ERD_{conv(N-1)}$ represents therefore a tool to understand the behavioral uncertainty associated with multiple runs of an evacuation scenario.

**Convergence measure 3: Euclidean Projection Coefficient (EPC)**

Similar with ERD, Euclidean projection coefficient measures the differences between two curves by all the discrete points on the curves. It corresponds to the coefficient $a$ when the derivative of the function $|\vec{x} - a\vec{y}|$ equals to zero (see Equation C.5).

$$EPC = \arg\mathrm{Min}_{a\in R}|\vec{x} - a\vec{y}| = \frac{<\vec{x},\vec{y}>}{\|\vec{y}\|^2}. \tag{C.5}$$

We apply it to the curves of evacuation times. $\vec{x}$ is replaced by curve $\overrightarrow{M_j}$ and $\vec{y}$ is replaced by curve $\overrightarrow{M_{j+1}}$. Then we calculate EPC of the $j^{th}$ run as:

$$EPC_j = \frac{<\overrightarrow{M_j}, \overrightarrow{M_{j+1}}>}{\|\overrightarrow{M_{j+1}}\|^2} = \frac{\sum_{k=1}^{Q} M_{jk}M_{(j+1)k}}{\sum_{k=1}^{Q}[M_{(j+1)k}]^2}, \qquad for \quad 1 \le j \le N-1 \tag{C.6}$$

The consecutive $EPC_j$ can be interpreted as a series converging to the expected value 1 (the best possible agreement between two consecutive $EPC$). Hence, a measure of convergence of the series can be performed. We express $EPC_{convj}$ in Equation C.7.

$$EPC_{convj} = \left|EPC_j - EPC_{j-1}\right|, \qquad for \quad 2 \le j \le N-1. \tag{C.7}$$

$EPC_{convj}$ permits estimation of the impact of the number of runs on the possible agreement between two consecutive average curves. $EPC_{conv(N-1)}$ is therefore another indicator of the behavioral uncertainty associated with multiple runs of an evacuation scenario.

**Convergence measure 4: Secant Cosine (SC)**

Secant cosine represents a measure of the difference between the shapes of two curves. This is investigated by analyzing the first derivative of both curves. For $n$ data points, a multi-dimensional set of $n-1$ vectors can be defined to approximate the derivative. This produces Equation C.8 [23]:

$$SC = \frac{\sum_{i=s+1}^{n}\frac{(x_i-x_{i-s})(y_i-y_{i-s})}{s^2(t_i-t_{i-1})}}{\sqrt{\sum_{i=s+1}^{n}\frac{(x_i-x_{i-s})^2}{s^2(t_i-t_{i-1})}\sum_{i=s+1}^{n}\frac{(y_i-y_{i-s})^2}{s^2(t_i-t_{i-1})}}}, \tag{C.8}$$

where $t$ is the measure of the spacing of the data, i.e. $t_i - t_{i-1} = 1$ if there a data point for each evacuee; $s$ represents the number of data points in the interval; $n$ is the number of data points in the data-set. When $SC$ equals to 1, the shapes of the two curves are identical. Depending on the value of $s$, the equation provides a level of smoothing of the data and thus better measures large-scale differences between vectors. Nevertheless, $s$ should not be too large, so that the natural variations in the data could be kept.

We apply this equation to the curves of evacuation times. $\vec{x}$ is replaced by curve $\overrightarrow{M_j}$ and $\vec{y}$ is replaced by curve $\overrightarrow{M_{j+1}}$. Then we calculate SC of the $j^{th}$ run as:

$$SC_j = \frac{\sum_{k=s+1}^{Q} \left[M_{jk} - M_{j(k-s)}\right] \left[M_{(j+1)k} - M_{(j+1)(k-s)}\right]}{\sqrt{\sum_{k=s+1}^{Q} \left[M_{jk} - M_{j(k-s)}\right]^2 \sum_{k=s+1}^{Q} \left[M_{(j+1)k} - M_{(j+1)(k-s)}\right]^2}}, \qquad \text{(C.9)}$$

when $1 \leq j \leq N - 1$.

Convergence measures can be developed for $SC$. The consecutive $SC_j$ can be interpreted as a series converging to the expected value equal to 1 (the case of two identical shapes of consecutive curves). Hence, a measure of the convergence of the series can be performed and it is presented in Equation C.10.

$$SC_{convj} = \left|SC_j - SC_{j-1}\right|, \qquad when \quad 2 \leq j \leq N - 1. \qquad \text{(C.10)}$$

$SC_{convj}$ allows understanding of the impact of the number of runs on the possible differences between the shapes of two consecutive average curves. $SC_{conv(N-1)}$ represents therefore a variable to understand the behavioral uncertainty associated with multiple runs of an evacuation scenario.