Guideline for Crowd Evacuation Simulation
Validation of a Pedestrian Simulator with RiMEA Test Scenarios

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Abstract: This paper introduces a way to verify a microscopic pedestrian simulator. The microscopic pedestrian simulator tested in this paper is developed by our group, which can be used to guide the crowd evacuation and prepare respond plans for emergent situations as reference to city council and law enforcement agency. It is important that the simulation results reveal the true behavior of pedestrian, for certain precaution actions can be taken in order to guarantee the safety of the crowd. Therefore, the simulator has to been tested and verified using different test scenarios. In this paper, we documented the performance of our simulator tested with all 14 scenarios proposed by the RiMEA (Richtlinie für Mikroskopische Entfluchtungs-Analysen) guideline. The test results show that our simulator passes all the tests. Moreover, our pedestrian simulator constantly improves its performance by cooperating with construction companies and government departments running on-site tests with first-hand data. Now it covers emergency scenarios such as fire / smoke and floods.

1 INTRODUCTION

Nowadays, more and more people are moving from small villages to big cities forming metropolises worldwide. The increasing population density and limited living space make metropolises top targets for terror attacks and make them vulnerable to natural disasters. A key task for smart city is to make the city safer to its residents. Central stations, skyscrapers and sport stadiums should be designed to reduce risk by removing congestion, reducing crowd density at hot spots, minimizing evacuation times or maximizing throughput. In those cases, a simulation software which simulates the crowd movement, predicts the evacuation time and identifies the possible bottleneck is very helpful to design smart buildings. As for existing non-smart-buildings, the pedestrian simulator can provide insight in evacuation time and aids to prepare respond plans.

Because of its various applications and convincing results, adopting pedestrian flow simulation is becoming a popular topic in designing public transport systems and large infrastructure facilities (Kneidl et al., 2012) (Gilg et al., 2014) (Lämmel et al., 2008). There are two major types of models adopted by pedestrian behavior simulation: microscopic models and macroscopic models. The so-called microscopic models simulate the behavior of a single pedestrian while the macroscopic models consider flows of pedestrian entities. The macroscopic models are often used to study large scale behavior and typically use network-based models (e.g. (Hamacher and Tjandra, 2002)) or fluid dynamics models (e.g. (Helbing, 1992)). The microscopic models on the other hand are often interested in local small scale behavior of pedestrian flows. The microscopic models can be further distinguished into force models (e.g. (Burstedde et al., 2001)), discrete-choice models (e.g. (Antonini et al., 2006)) and agent-based models (e.g. (Ronald et al., 2007)).

Despite of all the advantages and numerous researches done before, the features mentioned above can only be exploited if the simulation tool fulfills several technical demands: First of all, the simulator should provide results with a well defined accuracy: The simulation results should be investigated and compared with real measurements. For certain cases, the simulation model and parameter should be calibrated in order to achieve better performance. A second critical limitation is the simulation speed, i.e. time needed until a simulation result is available. Moreover, the usability of the software also affects its acceptance. After all, the potential users are most likely to be architects or government officer who are neither familiar with mathematical modeling nor have programing experiences. Therefore, the abstract re-

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sults should be properly visualized to help users link simulated scenarios to real situations.

Based on these prerequisites, our group developed a pedestrian simulation environment named Crowd Control, which has already been used for several evacuation projects in the field of trains and buildings (Köster et al., 2010)(Davidich and Köster, 2012). In the newly released version of our simulator, more scenario-models such as fire / smoke, and flood are integrated, which allow our simulator to meet various simulation demands. In order to ensure its accuracy after the extension, certain tests must be performed. In this paper, we test our newly released simulator with the test scenarios proposed by the RiMEA guidelines (RiMEA e.V., 2009) and document the test results. With the user-friendly graphical interface, we are able to create the test scenario by simple mouse-clicks. The test results show that our simulator passes all the tests within short simulation time. Besides, the 2D and 3D visualization kits of our simulator allow us to check the simulation results; a detailed analysis can be done by exporting the results to Excel, e.g..

The remaining of the paper is organized as follows: In Section 2 the theoretical background and the simulation model are briefly introduced; In Section 3 the software architecture is sketched; In Section 4 the test scenarios and test results are documented; In Section 5 the performance of the simulator is evaluated and a conclusion is drawn based on the simulation results.

2 SIMULATION MODEL

The simulator tested in this paper is developed based on a discrete, microscopic force model. The simulation model is a cellular automaton on a hexagonal grid (Fig. 1). At each time step each cell has a certain state: It is either empty or occupied by a pedestrian or a fixed obstacle. The positions are updated according to a set of rules (Köster et al., 2010). In comparison to continuous simulation, a discrete model is much faster and does not suffer from artifacts such as instability factors like non realistic oscillatory behavior. In addition, it is easier to include interactions of the pedestrian with dynamic events like closing or opening gates or catastrophic events like fire spread, since calculations can be restricted to discrete events in time. While macroscopic pedestrian simulation is predominantly focused on producing statistical data (like flows and densities), microscopic simulation can help to identify even the behavior of single pedestrians. Of course one has to be aware that the behavior of a specific single individual can never be anticipated, but the interaction of a larger number of individuals can be emulated by microscopic simulation very well (Gilg et al., 2014).

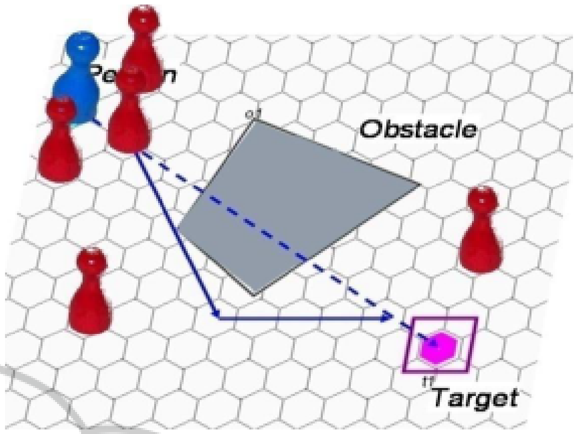


Figure 1: Schematic sketch of a cellular automaton simulating microscopic pedestrian dynamics.

In the simulation model, each pedestrian is initially assigned with an individual velocity, which is considered as a normally distributed variable, whose average and variance are given parameters. In each time step, pedestrians adjust their speed during the simulation as responses to the change of situation. For instance, a pedestrian slows down his movement when the crowd density is too high (for example congestion). The observation area is divided in hexagon cells and each cell is in a certain state for each time step: It is as mentioned above either empty or occupied and an occupied cell cannot be entered. In every time step a person can move one cell forward or stay at the current cell, but cannot move farther than one cell. The update scheme of the cellular automaton has to guarantee, that pedestrians with a higher speed are allowed to move more often than pedestrians with a lower speed. Thus a slow person might not move at each time step compared to faster moving person. Once the set of persons which are allowed to move is determined, they are updated sequentially. The movement rule is similar to the so-called static floor field cellular automaton (Burstedde et al., 2001), in which the movement is determined by a potential f. In the simplest case, the movement rule for a single pedestrian is purely deterministic: Find the unoccupied neighboring cell with the minimal total potential value $f_{total} = f_{navigation}(x;y) + f_{pedestrian}(x;y)$. In this equation, the $f_{pedestrian}(x;y)$ represents the force that the pedestrians repel each other, while the $f_{navigation}(x;y)$ represents the force that the pedestrians are attracted by the target. For more details about the simulation model, please refer to (Köster et al., 2010).

3 SOFTWARE ARCHITECTURE

In this section, we will introduce the architecture of our simulator. Figure 2 shows the main components of the software and its data flow. The software comprises a simulation kernel, a graphical user interface, a tool for statistical evaluation and a 3D visualization. The graphical user interface enables the user to create specific scenarios using tools provided by the software. Besides, the scenarios also can be extracted from architectural drawings (Mayer et al., 2014) or data bases. In addition, it is possible to couple the simulation with third party tools, such as Microsoft Excel, which is very useful for processing results and analyzing data. Furthermore, the tool has been calibrated with many real measurements and recently extended by adding more items like fire model, flood model to extend its functionality.

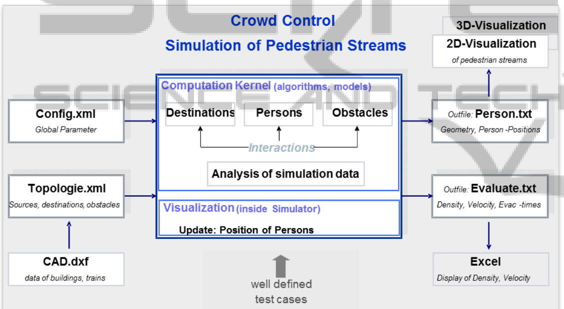


Figure 2: Software Architecture.

Figure 3 shows the graphical user interface, in which user can create a scenario by adding source, destination, walls, obstacles and staircases. Besides, it provides the user possibilities to create more vivid scenarios by add 3D elements, such as trees. The recent version also allows user to add extra dynamic models such as fire spots to simulate the pedestrian behavior under certain emergency situations. All the objects can be configured by adjusting the parameters. For instance, the user can assign a source (the place where a group of pedestrians are generated) with a pedestrian velocity profile. In this way, sources representing pedestrians with different ages can be generated. In this paper, all the test scenarios are created by this graphical user interface.

The created scenarios and the parameter of the simulator are saved as XML files, which contain the topology and model relevant information. Those input files are passed to the computation kernel, which updates the position of persons for each time step.

The simulator generates two types of output files. One type of output file contains the geometry and person position information, which is used to visualize

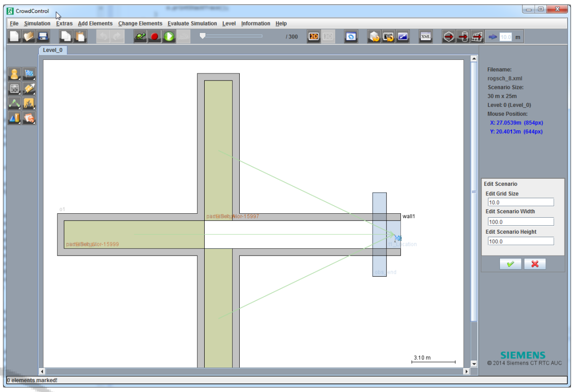


Figure 3: Graphical User Interface.

the crowd movement combined with a 2D or 3D visualization engine. The other type of output file contains the density, velocity and evacuation time information, which can be exported to external software, such as Excel to analyze the results. In 2D visualization, each pedestrian is represented as a colored dot. The color of the dot is determined by the person density, which is shown via a very intuitive coloring scheme green yellow - red for a small, medium or high density. In this way, critical spots can be easily identified by the presence of red color. The 3D visualization is realized by an interface to the 3D-Game-Engine Irrlicht. The computed output file of the simulation storing the geometry and all persons positions at all time steps is directly taken over by the Irrlicht-Engine. The 3D visualization is capable of displaying stairs, doors, narrow corridors, passages, ramps and pillars. It helps the user interpret and analyze the results directly. Similar to the 2D-visualization, crowds or congestion can be seen and discussed directly by that coloring scheme.

Figure 4 shows an example of a 3D visualization. The user can follow the movement of the persons in a familiar, well known 3D-environment without any delay. The control panel on the right side allows the user to navigate and move in the 3D-Game-Engine to gain a better observation perspective. The zoom functionality enables the user to analyze details of the scenarios. The animation control allows the user to

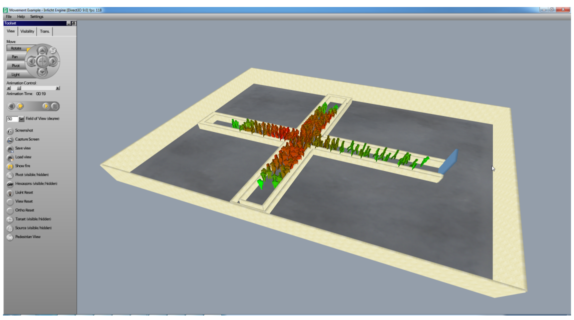


Figure 4: Example of a 3D Visualization.

review the simulation or analyze the situation of a specific time. Using menus under the control panel, the user can even identify and walk as one specific person through the scenario. All those functions are developed to increase the usability, which as mentioned in the first section is very crucial for the acceptance of a simulator.

4 RiMEA TEST SCENARIOS AND TEST RESULTS

As mentioned in the first section, a pedestrian simulation tool must fulfill several technical demands and certain guidelines, such as the IMO (International Maritime Organization) (IMO, 2014) guidelines and the RiMEA (Richtlinie für Mikroskopische Entfluchtungs-Analysen) guidelines (RiMEA e.V., 2009). According to the Rimea guideline, 14 scenarios should be tested in order to check the performance of a person stream simulator and verify its functionality. The test scenarios in this paper are generated according to the Rimea-Standard V.2.2.1. The test results and their corresponding parameters for the concrete application to the Crowd Control simulation tool from Siemens are documented in this paper. Due to the special grid property of our simulator, in addition to the standard RiMEA tests, the tests are repeated several times in different rotation angle and shifted horizontally and vertically to prove the robustness of the simulator. Besides that, the scenarios are tested with different grid sizes.

There are some important assumptions in the RiMEA guideline. The first assumption is the velocity of person group with different ages on the ground. The velocities are defined in the following table 1 (Weidmann, 1992):

Table 1: Velocities on the ground according to Weidmann.

Person Group(Age)	Velocities on the Ground (m/s)	
	Minimum	Maximum
under 30	0.58	1.61
30 to 50	1.41	1.54
Over 50	0.68	1.41
Person with limited mobility	0.46	0.76

The second assumption is the velocity of person group with different ages climbing up and down the staircases. The velocities are defined in the following table 2 (Fruin, 1971):

All tests are repeated several times in order to identify the influence of the basic grid to the simulation results. The tests are repeated in the following orders:

- by rotating the topology in different angles

Table 2: Velocities on the staircase according to Fruin.

Person Group(Age)	Velocities on the Staricase (m/s)			
	Climbing Down		Climbing Up	
	Indoor	Outdoor	Indoor	Outdoor
under 30	0.76	0.81	0.55	0.58
30 to 50	0.65	0.78	0.50	0.58
Over 50	0.55	0.59	0.42	0.42
Person with limited mobility	0.42		0.32	

- by shifting the topology vertically
- by shifting the topology horizontally
- by using different grid sizes for the basic hexagonal grid

The first 3 tests are single pedestrian tests. In the first test, it should be proven, that a person with a given velocity ($1.33m/s$) runs through a 2 m wide, 40 m long corridor within the given time. The expected time is between 26 to 34 seconds. Inaccuracy tolerance of the person position is 0.4 m (body size, 1 second reaction time). Inaccuracy tolerance of velocity is 5%. In the second test, the person retains the same given velocity as the first test climbing up a staircase. It should be proven, that a person climbs up a 2 m wide, 10 m long (the slope length) stair with a defined velocity in a given time range. In the third test, the person retains the given velocity climbing down a staircase. It should be proven, that a person climbs down a 2 m wide, 10 m long (the slope length) stair with a defined velocity in a given time range. Table refres:test1-3 shows the test results of the first 3 test scenarios. From the table, we can see that all the results of repeated tests (shift, rotate topology and change grid size) lie in the given time range.

Table 3: Test Results of RiMEA Test 1-3.

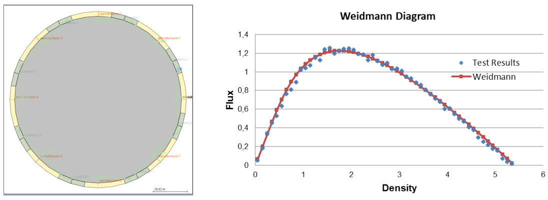
RiMEA Test Number	Tested Time of Simulator (s)		Allowed Time Range (s)	
	Minimum	Maximum	Minimum	Maximum
Test 1	30.27	32.72	26	34
Test 2	11.63	12.89	10.84	14.17
Test 3	8.69	9.25	7.22	9.44

RiMEA test 4 is to check the relationship of a special flow with the person density. The special flow with respect to the person density is given:

$$\Theta_{s,max} = \rho \cdot 1.34 \cdot (1 - e^{-1.913 \cdot (\frac{1}{\rho} - \frac{1}{\iota \cdot 5.4})}) \qquad (1)$$

In order to realize the test, a ring is generated with internal radius 70 meter and external radius 74 meter (Fig. 5(a). 8 person blocks each generates 5000 persons and the persons walk in circles. The ring radius remains constant, but the number of persons increases as time goes by. The test results are plotted in the diagram (Fig. 5(b)). We can see that the test results fit the Weidmann diagram very well.

RiMEA test 5 is to check the reaction time of each person. In this test, 10 persons stand in an 8 m×5 m



(a) Topology (b) Result

Figure 5: RiMEA Test 4.

room with a 1 m wide exit in the middle of the 5 m long wall. The reaction time is to be set uniformly distributed in the interval of 10 s and 100s. We need to verify that each reaction time corresponds to a person. In this test, our simulator generates 10 persons in the interval $[10,100]$, since the first person is not generated at 10 second, the time interval between two persons reaction time is $90/11$. We can compare the reaction time of each person with the expected value $10+i\cdot d$, where i is the index of the person and d is the time interval between two persons reaction time. The simulation results confirm the conclusion.

In RiMEA test 6, 20 pedestrians walk along a 2 m x 10 m corridor and turn left, go further along a 2 m x 10 m corridor. There should be no person go though the walls. To carry out this test, we set three areas outside the corridor (three rectangular areas: outside top left, outside top right and outside bottom) to check if the number of person in each area equals to zero. We also repeated this test to test the robustness of the simulator and all the tests fulfill the requirement. Fig 6 shows one of these tests.

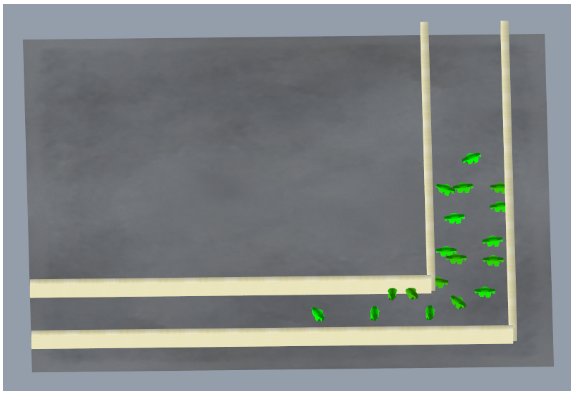


Figure 6: RiMEA Test 6.

In RiMEA test 7, we choose a group of 50 persons and assign the pedestrian velocity according to table 1 listed above. The task is to check if the simulated velocity corresponds to the velocity listed in the table. Fig 7 shows the test results. From this figure, we can see that the minimal velocity and maximal velocity of each group lie in the given range listed in table 1.

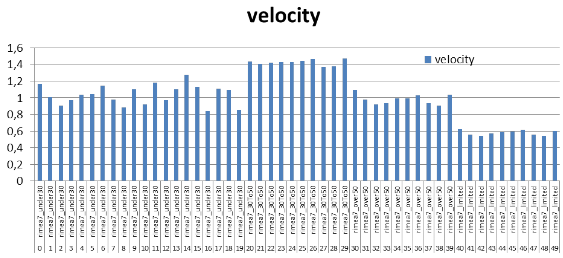


Figure 7: Result of RiMEA Test 7.

In RiMEA test 8, a test topology with three floors is given (Fig. 8). Each room contains 4 persons and has a 1 meter wide door. This topology is adopted to test the influence of parameter in each person on the total evacuation time. If the parameter of each person is changed, the total evacuation time should also change correspondingly. In this test, the persons are assigned with different velocities for each simulation run. We need to check if the evacuation time is within the given tolerance. We also repeat the tests with different topology orientation and location, the evacuation time variation is under the given tolerance.

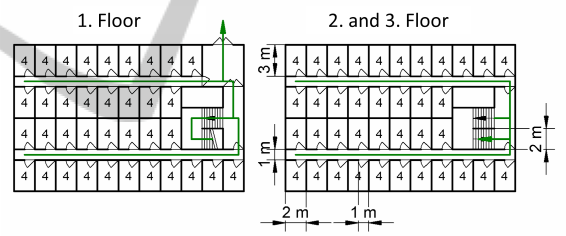


Figure 8: Topology of RiMEA Test 8.

In RiMEA test 9, 1000 persons with same figure size and no reaction delay are uniformly distributed in a public room with four exits. The topology of the test room is shown in the following picture (Fig. 9). Assume that people in this group are all adults and their velocities are set according to table 1. In the first test, the time of the last people leaves the room is documented. Then two exits are closed and the test is repeated to check the time of the last people leaves the room again. Then we calculate the ratio of the evacuation time with four doors open and the evacuation time with two doors open. If the ratio lies between 0.4 and 0.6, the simulator passes the test. In our test, the ratio lines between 0.49 and 0.56.

For RiMEA test 10, we construct a test topology (Fig. 10) with a corridor, 12 rooms each with a 0.9 m door are located along the corridor. 23 adults with no reaction delay and defined velocity according to the Table 1 are scattered in rooms. The people in room 1, 2, 3, 4, 7, 8, 9 and 10 are assigned to use the main

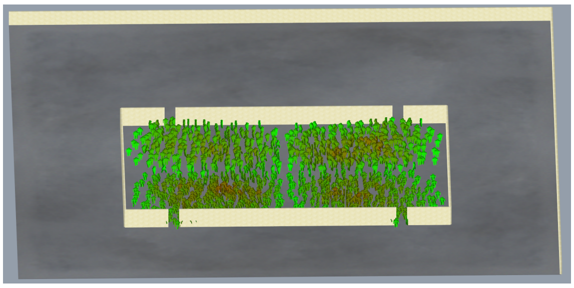


Figure 9: RiMEA Test 9 with 4 Doors Open.

exit and the remaining people are assigned to use the second exit. The expected result is that the people behave just like the assignment and leave the region using the assigned exit. We set a tripwire in the corridor. The tripwire is located between room 5 and room 11, which separates two exits. If the number of persons who cross this line is 0, it means that persons use the assigned exit to leave the room. In all the tests, no person crosses the tripwire.

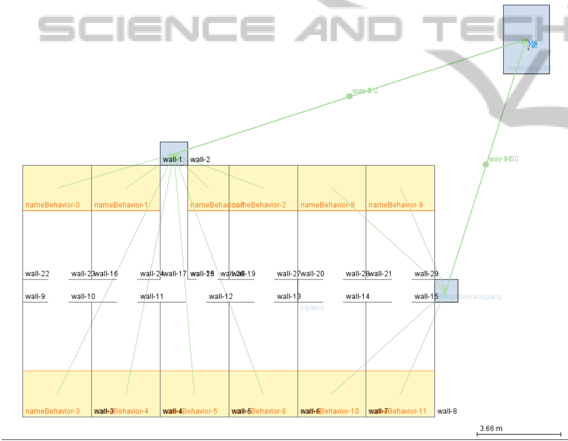


Figure 10: Test Topology for RiMEA Test 10.

RiMEA test 11 is about the choice of emergency route. The test topology is a public room with two exits: exit 1 and exit 2 (Fig. 11). 1000 adults with no reaction delay are gathered on the left side of the room (achieve the maximal person density). The velocities of the people are set according to the Table 1. The people should leave the room through two exits. The expected result is that the people prefer to leave the room through a nearer exit (in this case, exit 1), but if the exit 1 is over-crowded, people should choose the alternative exit (exit 2) to leave the room.

In this test two tripwires are defined to count the number of persons crossing these lines. The number of the persons who cross the tripwire 1 stands for the number of persons who leave the room with exit 1, and the number of the persons who cross the tripwire 2 stands for the number of the persons who leave the room with exit 2. The test criteria is to check the number of persons using exit 1 and exit 2 respectively. The simulator passes the test if two criteria are satisfied:

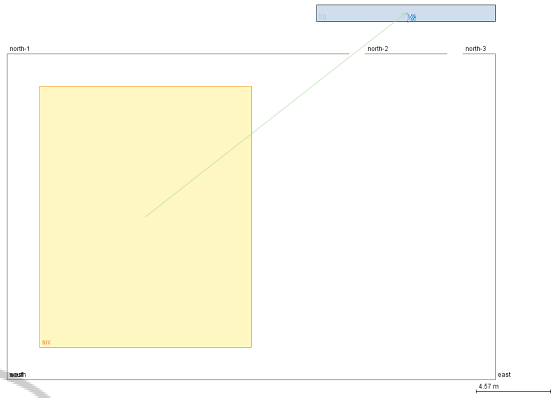


Figure 11: Test Topology for RiMEA Test 11.

1. More persons use exit 1 than exit 2;
2. At least 20% of the persons use exit 2;

In all the repeated tests, the ratio of the persons using the exit 2 lies between 22.6% and 42.4%, the simulator passes this test as well.

The test topology of RiMEA test 12 is two rooms connected by a narrow corridor (Fig. 12). 150 adults with no reaction delay are gathered on the left side of room 1 and room 2 has an exit. These 150 people in room should leave the room through exit in room 2. Since the corridor is very narrow, the person flow is limited. The expected result is that the crowded condition occurs only in room 1 but not in room 2. For this test, we select two areas (one is in room 1 right before the narrow corridor and the other is in room 2). The person density of these two areas are checked to see where the crowded condition occurs. The simulation results show that the maximal person density in region 2 lies between 1.40 to 1.96, while the average person density in region 1 lies between 3.33 to 4.63, which confirms the expectation that the crowded condition occurs only in room 1 but not in room 2.

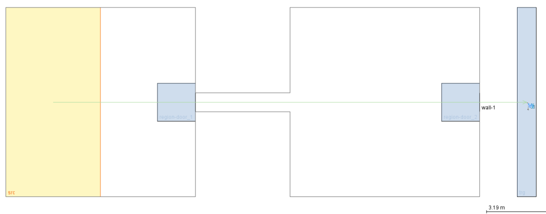
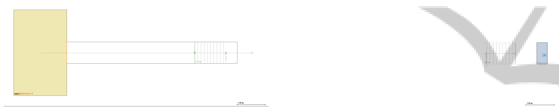


Figure 12: Test Topology for RiMEA Test 12.

The test topology of RiMEA test 13 is a room connected to a staircase toward upstairs by a corridor. 150 adults with no reaction delay and velocity according to Table 2 are gathered in the room. These people leave the room by taking the staircase. The expected result is that the crowded condition occurs at the exit of the room to the corridor. Besides, people are crowded in front of the staircase and the situation becomes worse as the time goes by, since the person flow over the staircase is smaller than the corridor. The test topology is constructed in two levels: at the first level, there is a room, source, a corridor and a staircase; at the second level, there is a staircase and a target area (Fig. 13). For this test, we define two areas in the test topology. Area 1 is located at the room exit and area 2 is located in front of the staircase. We count the person density of these two areas to check if the maximal person density is larger than 3 (definition of crowded situation). The test results show that the maximal person density at the room exit lies between 3.24 and 4.28. The maximal person density in front of the staircase lies between 3.78 and 4.72. The person density of both areas exceeds the threshold of the definition of crowded situation.



(a) Level 1 (b) Level 2

Figure 13: Test Topology of RiMEA Test 13.

The last RiMEA test refers to the simulator configuration. The test topology is shown below (Fig. 14). The start area and the targeted area are located at the second floor and marked with different colors. The start area is marked as red and the targeted area is marked as green. They are further connected by two staircases and a long corridor on the ground floor. The task is to check how a pedestrian chooses his route: he chooses a long route which is on the same floor or a short route though the staircases and the corridor on the ground floor. For different simulators, different choices can be made (short, long, mixed or configurable). Our simulator supports the version "short". That means all persons select the shortest path. In this test, we construct a two levels topology: the first level has two staircases and no other obstacles; the source and target areas are located at the second floor. Besides the staircases to downstairs, there is a corridor connecting these two areas at the same level (Fig. 15). The simulator passes the test if no person crosses the tripwire set in the second floor corridor. The tests are repeated by rotating, shifting the topology as well as changing the cell size to verify the robustness of the simulator. In all tests, the number of persons who cross the tripwire equals to zero.

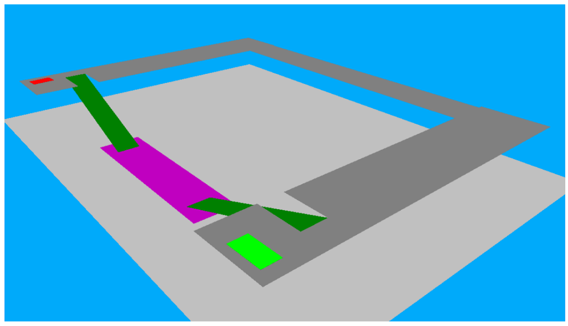


Figure 14: Test Topology for RiMEA Test 14.

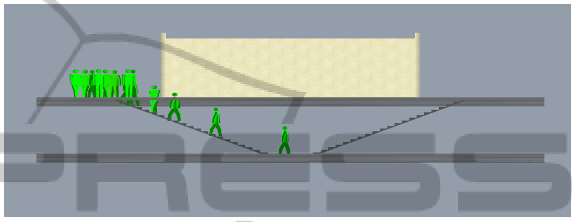


Figure 15: Constructed Topology for RiMEA Test 14.

5 CONCLUSIONS

In this paper, all tests listed in the RiMEA guideline are implemented and used to test the Crowd Control Simulator Version 2.2. The tests are repeated by rotating, shifting the topology as well as changing the cell size to verify the robustness of the simulator. The test results show that the simulator passes all the tests, which indicates its reliability and robustness. All of the mentioned RiMEA test cases are part of a larger test suite containing additional internal test cases, which compares the simulation results automatically with given result values. These test cases should be checked after each software update.

Our simulator offers architectures, city planners, authorities and other potential users a powerful tool to get precise and valuable simulations results, in order to improve the infrastructure planning and the safety of passengers. This new version of the simulator not only allows the user to create a test scenario by using its graphical user interface, but also interacts with BIM (Building Information Modeling) model to improve the performance of the building (Mayer et al., 2014). With the newly integrated emission model (such as fire, smoke) and flood model, the simulator can calculate an optimal escape route for emergent situation provided that the building is equipped with sensors and detectors. There are enough applications for a robust reliable pedestrian behavior simulation tool like our Crowd Control Simulator. It is highly desirable to complement the RiMEA tests with scenarios based on measured data. However, collecting this data and finding appropriate measures for qualitative assessment of simulation results is still an open field of research. It is also the interests of the authors to collect more test scenarios, on which different models can be tested, compared and calibrated.

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