

MassMotion Evacuation Model Validation

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Abstract

The thesis purpose is to validate a set of functionalities of MassMotion. MassMotion is an evacuation model that can simulate the pedestrian movement in a 2D environment and visualize it in a 3D environment. Three tests were proposed to examine different functionalities which are: pedestrian walking behaviour where total arrival time, flow rates and density are examined, pre-evacuation times that are produced by MassMotion and the representation of pedestrian behaviour in a cinema theatre experiment, and finally to scrutinize the stair merging ratios where two flows of pedestrian meet at certain place. In addition, uncertainty analysis of the results was also performed for different parameters. Also, behavioural uncertainty of the total arrival time results was examined employing the functional analysis method in corridor test and stair merging test. The benchmark tests that were used is a corridor test which was conducted at Lund University, a cinema theatre which was conducted in Lund, and a stair merging test which was conducted in Japan. Two sets of scenarios were adopted: default input settings and specified input settings. The simulated total arrival time of the specified settings deviates from 0% to 13% compared to the experimental data, while the default settings deviate from 47% to 60%. In addition, the representation of pre-evacuation times was coherent with the benchmark experiment. Finally, the merging ratio percentage in stairs can be in the range of 52% to 66%.

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DISCLAIMER

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Abstract

The thesis purpose is to validate a set of functionalities of MassMotion. MassMotion is an evacuation model that can simulate the pedestrian movement in a 2D environment and visualize it in a 3D environment. Three tests were proposed to examine different functionalities which are: pedestrian walking behaviour where total arrival time, flow rates and density are examined, pre-evacuation times that are produced by MassMotion and the representation of pedestrian behaviour in a cinema theatre experiment, and finally to examine the stair merging ratios where two flows of pedestrian meet at certain place. Furthermore, uncertainty analysis of the results was also performed for different parameters. Also, behavioural uncertainty of the total arrival time results was examined employing the functional analysis method in corridor test and stair merging test. The benchmark tests that were used is a corridor test which was conducted at Lund University, a cinema theatre which was conducted in Lund, and a stair merging test which was conducted in Japan. Two sets of scenarios were adopted: default input settings and specified input settings. The simulated total arrival time of the specified settings deviates from 0% to 13% compared to the experimental data, while the default settings deviate from 47% to 60%. In addition, the representation of pre-evacuation times was coherent with the benchmark experiment. Finally, the merging ratio percentage in stairs can be in the range of 52% to 66%.

الخلاصة

تهدف هذه الرسالة الى التحقق من صحة بعض وظائف برنامج MassMotion. يقوم هذا البرنامج على مبدأ محاكاة حركة إخلاء الأشخاص ضمن بيئة ثنائية الأبعاد وتصويرها في بيئة ثلاثية الأبعاد. ولتحقيق ذلك تم إجراء ثلاثة تجارب حاسوبية تضمن التحقق من وظائف مختلفة من البرنامج. تم في التجربة الأولى التحقق من كل من الزمن اللازم للوصول، معدل تدفق المشاة ونسبة عدد الأشخاص لواحدة المساحة، أما في التجربة الثانية فقد تم التحقق من الزمن السابق لعملية الإخلاء والمحدد من قبل البرنامج وكذلك مقدار صحة توزيع الأشخاص في تجربة دور عرض سينمائي، بينما قامت التجربة الثالثة بالتحقق من نسبة الدمج بين تدفقين من الأشخاص عند نقطة إلتقائهما في مدخل الدرج. بالإضافة الى ذلك فقد تم دراسة تأثير عدة عوامل على درجة عدم التحقق من النتائج، وكذلك مقدار الشك في سلوك الأشخاص بطريقة تحليل التابعية. من أهم التجارب العملية المستخدمة هي تجربة الممر التي اجريت في جامعة لوند، وأيضاً تجربة دور السينما في لوند وكذلك تجربة الدمج في الدرج التي أقيمت في اليابان. تم في الدراسة الحالية استخدام مبدئين: في الأول اعدادات ادخال افتراضية وفي الثاني إعدادات إدخال محددة وقد تراوح زمن الوصول الكلي عند استخدام إعدادات ادخال معينة بين 0 و 13% بينما في الإعدادات الافتراضية تراوح بين 47% و 60%، وكانت نسبة تمثيل الزمن اللازم قبل الحركة مساوية تقريباً للاختبارات العملية. واخيراً، تراوحت نسبة الدمج بين 52% و 66%.

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List of abbreviations

Evacuation Model	A computer simulation model that is used to simulate the movement of pedestrians in an evacuation.
Flow rate	The number of pedestrians that passes a certain point in space where a defined time interval is used. Two units are specified for flow rate. First is related to the width of the opening (person/second/meter). And when it is not related to the width of the opening (person/meter).
Agent	A simulated person in MassMotion model where it is characterized by walking speed and body size(Ronchi et al., 2013).
Pedestrian	A real life person who is characterized by walking speed and body size.
Pre-Evacuation Time	The time when the occupant is prompted about something wrong till the time that this occupant starts moving to evacuate (Kuligowski et al., 2010).
Verification	<i>“The process of determining that a calculation method implementation accurately represents the developer’s conceptual description of the calculation method and the solution of the calculation method” (INTERNATIONAL STANDARD Organization, 2015)</i>
Validation	<i>“The process of determining the degree of which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method” (INTERNATIONAL STANDARD Organization, 2015)</i>

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1 Introduction & Objectives

Structure innovation has been improving throughout history. Recent structures tend to be bigger, taller and more complex. Dramatic changes occurred to the buildings that include electrification, composite buildings, ventilation systems, active and passive fire protection systems, etc. (Rahman, 2010).

Perspective codes which are related to fire engineering were used to determine what the designer could do specifically in the design phase. Perspective codes have been evolving with new regulations and requirements over the existing codes. Therefore, problems were introduced where it became complex, challenging and inefficient to use those codes in the new designs. Therefore, there was a need for a new approach which is the performance-based design approach. The last two decades remarked the development of performance-based design approach (Babrauskas, 2000). Performance-based design can offer a cost effective design that suits the functionality of the structure. This approach can provide an evaluation of the structure related to its occupancy, geometric layout and usage (Hadjisophocleous and Bénichou, 2000). There is no step-by-step method on the way of doing the performance-based design. However, there are some guidelines on the approach such as the method that was explained by Hurley and Rosenbaum in Performance-based fire safety design (2015).

Performance based-design is based on the comparison between RSET (Required Safe Escape Time) and ASET (Available Safe Escape Time). Evacuation models are tools used to calculate the RSET, therefore they are crucial for fire safety assessment and predict the process of evacuation. This includes results such as total evacuation time, arrival times of all occupants, route choice, congestion levels, pre-evacuation time, etc. However, in order to evaluate the capabilities and limitations of these models, they need to go through a process of verification and validation to make sure that the results can be reliable. This is discussed thoroughly in the thesis.

1.1 Background

Fire protection engineers all over the world use different evacuation simulation tools to determine the RSET (Required Safe Egress Time). The ASET/RSET comparison is used to determine whether a building is safe using a performance based design approach. ASET must exceed RSET with a “good enough” margin, in order to state that a building is safe (CFPA EUROPE, 2009). Therefore, evacuation modelling tools should be accurate enough to allow estimating what the real behaviour of people would be. At the moment, there are different types of programs that adopt different modeling techniques, algorithms, etc. The model under scrutiny in the present work is a program developed by Oasys, which is the software house of Arup (Oasys-software.com, 2015). Oasys developed an evacuation model called MassMotion, which can simulate the movement of pedestrian using the social force model by Helbing

(Helbing and Molnár, 1995). As this model was developed and created since 2005, existing validation reports did not cover all features of the model. Thus, there was an interest to examine this model for a set of features that were not deeply analyzed and scrutinize the simulated results.

MassMotion is a 2D model with 3D visualization which can be used to generate different geometries such as floors, escalators, barriers, etc. The model is capable of measuring movement times, flow rates, densities, etc. MassMotion has default settings, and these settings can be varied by user as well in order to comprehend specific settings where needed.

Additionally, the program can produce congestion outputs that can be used to investigate different issues such as overcrowding (Kinsey, 2015). The program is based on a continuous model which considers agents in 2-D planes over several floor plans. As mentioned before, MassMotion uses a social force model; consequently individuals have forces acting upon them including obstacle, goal and neighbor force (Helbing and Molnár, 1995). Regarding exit choice, the model uses by default a quickest path algorithm, for example, it considers the best route for agents to minimize evacuation times which might be longer but faster (Kinsey, 2013) (See Section 3.1.1).

When choosing an evacuation model, the user must check the verification and validation document of the model which will determine whether model is capable of simulating the scenario of interest or not. V&V were the most important factors for a user when choosing an evacuation model according to a survey which was conducted by Ronchi and Kinsey (2011). Verification is the process to evaluate if the program can represent accurately the calculations to represent the concept that the developers want. Validation is the process of determining the degree to which the model can represent reality (Ronchi et al., 2014). MassMotion has gone through different tests to verify and validate the model and therefore calibrating the program accordingly. Most of these tests followed the guidelines and testing procedures that were suggested by IMO Guidelines and the NIST technical Note 1822 (International Maritime Organization, 2007; Ronchi et al., 2013). The studies on verification include pre-evacuation behaviour, travel speed, physicality, decision making, and crowd dynamics. The studies on validation were done to analyze route choice, stair usages, exit choices, flow rates, and total evacuation time. Moreover, uncertainty of the results in a set of selected scenarios was studied. This was done in a report by Michael Kinsey (2015). Variables of interest included the physical behaviour, derivation of mathematical model which describes the conceptual model, implementation of the mathematical model, selection of input data parameters, and lack of knowledge in specific areas (Kinsey, 2015). These studies were explained in Section 3.1.5 thoroughly. As the process of validation is vital, a third party evaluation is an important step to

provide an assessment of the model capabilities and limitations. The third party evaluation avoids bias and contributes to an impartial judgement of the model.

1.2 Purpose and Objectives

The aim of this thesis is to perform a set of exemplary validation exercises of the evacuation model MassMotion. The capabilities under scrutiny were the model representation of pedestrian movement during movement in a corridor, a cinema theatre evacuation, and a stair merging test. The Corridor test examines the flow of people at certain openings' widths, their walking speeds and the density in the corridor. After that, a cinema theatre evacuation with the aim to check the ability of MassMotion to represent the pre-evacuation times for agents. The last test which is the stair merging test scrutinizes the feature of the capability of MassMotion to provide a similar ratio of merging in a stair which occurs when upper floor's occupants descend in a staircase and meet with occupants in the lower floor. The strengths and weaknesses of MassMotion are discussed according to the tests that have been conducted. Also, Uncertainty analysis for different parameters that might affect the results is to be examined. The parameters include model input uncertainty, behavioural uncertainty, and measurement uncertainty. The analysis of behavioural uncertainty was performed using the method based on functional analysis suggested by Ronchi et al (2014).

The objective is to compare the model predictions in different evacuation settings and components in comparison with benchmark validation data-sets. The accuracy of these predictions was analyzed. Additionally, the thesis evaluated the uncertainties observed in the simulation results and how those uncertainties can be investigated.

1.3 Limitations and Delimitations

The limitations of this paper were the following.

First, the direction of pedestrian movement accounted for only one-way flows; therefore counter-flows were not taken into consideration.

In some instances, the geometry of the full-scale experiment cannot be fully represented in evacuation model. Therefore, modifications in the geometry configuration compared to the original experimental one were needed.

Thesis study did not take explicitly into consideration the representation of vulnerable populations, e.g., elderly people and people who have disabilities through the validation tests. Also, movement in elevators was not examined.

Furthermore, agents in MassMotion does not have the explicit ability to group up together, (i.e. no behavioural sub-model for group behaviours is available in the model) thus agents were treated individually.

Complex geometries such as curved ceilings or complex shapes of building have not been taken into consideration. Furthermore, as MassMotion has no own fire/smoke model nor a connection to an existing one, scenarios involving fire-people interactions have not been taken into consideration.

2 Methodology

The methodology employed in this work is presented in this section. This section is divided into five main parts; Literature sources, Benchmark Experiments, Model validation methods, and Uncertainty analysis. The model that is under scrutiny is MassMotion version 8.0.8.2.

2.1 Literature sources

The primary sources for collecting relevant literature were online search engines, especially [Lund's library search engine](#). Also, supervisors provided additional information about validation methods and general information on evacuation modelling as well. Moreover, a report on verification and validation of the model was provided by Kinsey, and the tests that were used are mentioned in Section 3.1.5 (Kinsey, 2015).

The keywords that were used for the literature search were: evacuation modelling, verification methods, validation methods, functional analysis, behavioural uncertainties, walking speeds, and MassMotion.

2.2 Benchmark Experiments

A total of three benchmark experiments were selected to be used in this paper. These experiments were selected to check a set of specific functions of the model as well as other additional criteria regarding the experiments.

The first criterion of selecting the benchmark experiments was that they would provide detailed geometric information of the experiment. The second criterion is that the tests were performed for several times in order to account for behavioural uncertainty, where the results cover the variability of choices that were taken by participants (Ronchi et al., 2014). For each scenario of these experimental trials, the conditions were not changed, i.e. repeated data-sets of the same scenario were available. Lastly, the experiments had several scenarios where these scenarios could be compared between each other. These several scenarios were used to examine the results that the model would represent.

The functions that have been tested were discussed with the supervisors at Arup fire (who are among the end users of the model), and they concerned the capability of the model to represent walking speeds, flow of agents at openings, and representation in certain areas. The second test was conducted to examine the capability of the model to represent pre-evacuation times and the agents' location over time (i.e. Representation of congestion levels). The last test was conducted to examine the merging ratios at stairs in different scenarios, which occurs when upper floor's occupants descend in a staircase and meet with lower floor occupants.

The benchmark experiments selected were: a corridor experiment that was done at Lund University (Frantzich et al., 2007), a cinema theatre experiment that was done in Lund (Bayer

and Rejnö, 1999; Frantzich et al., 2007) and a stair merging experiment that was conducted in Japan (Hokugo et al., 1985; Minegishi et al., 2016)

2.3 Model Validation Method

The validation method that was followed is the same method that was suggested by Lord et al. (2005) which are blind calculation and open calculation (See Section 3.2). The tests that were performed had two different input implementations. Default settings for a blind calculation and specified settings for open calculation. Blind calculations refer to where default settings of MassMotion were compared with the benchmark experiments. In addition, open calculation was performed as well to examine the capability of the model of replicating the experiment with specific settings from the experiment. The method is discussed in Section 3.2.

The main focus amongst two tests that were conducted was the calculation of total arrival time of agents. A method based on functional analysis was used to study behavioural uncertainty associated with the model results (Ronchi et al., 2014). The method included the assessment of model results based on five operators and corresponding criteria; Euclidean Relative Difference (ERD), Secant Cosine (SC), Euclidean Projection Coefficient (EPC), Required Safe Egress Time (TET_j), and Standard Deviation of Required Safe Egress Time (TETs). These criteria are discussed in Section 3.2.2.

The number of repeated simulations for each scenario was decided using a simple convergence factor of difference between progressive averages of 1% for ten consecutive runs. Therefore, the number of simulations of each scenario for each specific variable was different and mentioned in the results. This criterion was determined to ensure that the simulation number was providing results that were sufficiently convergent, i.e. the results were stable and not strongly affected by the number of the simulated runs.

2.4 Uncertainty Analysis

Uncertainties in model results could depend on different components such as Model Input Uncertainty, Measurement Uncertainty, Intrinsic Uncertainty and Behavioural Uncertainty (Hamins and McGrattan, 2007; Ronchi et al., 2014). Those components were be discussed in Section 3.2.1.

Sensitivity analysis have been performed to investigate different parameters in the simulation tests, namely:

- Time intervals: different time intervals for estimating the flow are considered, and the impact of them on the results of flow rates is examined.
- Body Size: the impact of reducing the body size of agents on their movement behaviour is investigated.

- Walking speeds: the reduction of walking speeds on the total evacuation times of the agents in evacuation scenario is investigated.

The theory of uncertainty analysis is discussed in Section 3.2.1, and the analysis is in Section 4.4

3 Literature Study and Fundamentals

This chapter covers the literature which has been considered for the work as well as the methods and assumptions employed. This part is divided into four Sections; Fundamentals of MassMotion, Validation Methods, Uncertainties in Evacuation Modelling and Benchmark Experiments.

3.1 Fundamentals of MassMotion

MassMotion is a simulation model that was developed by Oasys Limited, which is owned by Arup Group Limited. The model can be used in various areas such as evacuation for fire engineers, circulation of people in particular places such as airports and malls, and interactions of vehicle traffic with agents (Zarnke, 2015).

Agents in MassMotion find their destination according to a route choice algorithm. Route choice in MassMotion is based on a conditional state (See Section 3.1.1). MassMotion has the capability of analyzing a large amount of agents, and that amount depends on the computational abilities of the computer in use. However, maximum number of agents that can be simulated is not explicitly mentioned in the model documentation. In general, the order of magnitude of the maximum number of agents is deemed to be approximately 100,000 agents. MassMotion has the functionality of importing CAD layouts. However, geometry and planes must be created on the plans using the 3d modelling software [SketchUP](#) (Zarnke, 2015).

Agents' movement in the model is based on Helbing's social force model that simulates the human behaviour in journeys whether it is in case of an evacuation or circulation (Helbing and Molnár, 1995). MassMotion can create different geometrical components such as floors, stairs, ramps, escalators, barriers, doors, portals and paths. (Kinsey, 2015)

Moreover, MassMotion has both a Graphic User Interface (GUI) where inputs can be calibrated, as well as command lines for input definition.

MassMotion goes through a set of steps in order to complete a simulation. These are shown in Figure 1.

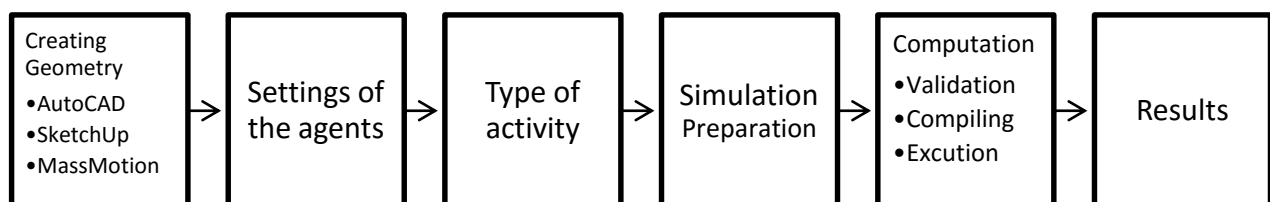


Figure 1 MassMotion Simulation Steps

3.1.1 Route Choice

The representation of route choice in evacuation models accounts for two different levels, namely local level and global level. The local level is where agents in the model rely on their perception of the geometry around them to navigate the space. This type of approach is not common in evacuation models. At a global level, models assume that the agent knows the route from the spawn point to the exit point (Kuligowski et al., 2010; Ronchi and Nilsson, 2016). Global level is instead a common approach which is used in evacuation models.

Evacuation models can adopt different criteria in the calculation of agents' route which are shortest route, fastest route, user-defined, or conditional. Fastest route is the route that will take the least amount of time. The shortest route is the route which assumes the use of the shortest path from the spawn point to the goal point. User-defined is where the user selects which route the agents will choose. Conditional is when agents choose their route based on their interactions with their surroundings such as fire, smoke, actions that were assigned to other agents, etc. (Kuligowski et al., 2010).

MassMotion assigns the route choices during the preparation of the simulation as shown in Figure 1. Agents in MassMotion would select their own route from the spawn point to the goal point. Each agent would have a set of route choices that is based on the behaviour of the agent. This set of routes will be saved in a cost tree, and every agent will have different set of routes. Finally, each agent will select the route that has the least cost to destination based on the cost tree (Kinsey, 2015).

MassMotion assumes that every person is a self-directed agent. Each agent can monitor the surrounding environment around, and it will react accordingly. This means that agents will have the ability to decide their own itinerary based on factors around them and final destination. They will also detect if there is a crowd in their way. These factors will affect each agent's route toward the destination (Kinsey, 2015) .

Different factors affect the agent's route cost which are mentioned in the user guide such as (See Table 1):

Table 1 Route Cost Components (Zarnke, 2015)

Component	Description
Downstream Horizontal Distance	The shortest horizontal distance from target to goal.
Near Horizontal Distance	The horizontal distance from agent to target.
Weighted Downstream Vertical Displacement	The vertical height measured where the agent will go along, and these can be found in escalators, ramps, and stairs.
Queue Time	The time that the agent will take to queue. This can be calculated using the number of the agents queuing and the flow rate to the specific target.
Opposing Flow	The time which is based on the agents coming from the opposite direction.
Closed Penalty	The time in which the target will be closed for the agent.
Backtrack Penalty	The time which if target has been used by the agent.

Following the equation of route cost, the least cost route is to be selected for the agent (see Equation 1). In addition, as agents move between floors, each agent has a local target in each floor. Once the agent reaches a new floor, the route cost to the next local target will be assessed, and best route will be chosen (Zarnke, 2015). Thus, agents will not be aware of any congestion on the following floor. The following formula is used to calculate the total route cost which is calculated in seconds:

$$Cost = \left(W_D * \left(\frac{D_G}{V} \right) \right) + (W_q * Q) + (W_L * L) \quad \text{Equation 1}$$

- Cost* = total travel time (s)
- W_D = Distance weight (-)
- D_G = Distance to final goal (m)
- V = velocity of the agent (m/s)
- W_q = queue weight (-)
- Q = time to reach the local target (ex: Link) (s)
- W_L = geometrical weight (-)
- L = geometrical type (s)

There is also a randomness of costs which are based on agent profile and choice variability. Therefore, MassMotion allows agents to vary and choose their routes to the final goal based on the local conditions at each floor (Kinsey, 2015).

3.1.2 Local Movement

MassMotion uses a model for local movement that was based on Helbing and Molnár (1995) which is the social force model. The social force model assumes different forces on the agents, which results in a total single force which describes the movement motivation of the agent. The social force model has the ability of accelerating or deaccelerating the agent's movement reliant on the surrounding environment (Helbing and Molnár, 1995). Therefore, agents in MassMotion are dynamically modifying their movement speed and route due to change of environment around them, and their interactions with each other.

The equation behind the social force model which represents the sum of repulsive and attractive forces upon the agent is:

$$f_i(t) = \frac{(v_\alpha^0 e_\alpha^0 - v_a)}{\tau_\alpha} + \sum_{\beta(\neq\alpha)} f_{\alpha\beta}(t) + \sum_i f_{\alpha i} \quad \text{Equation 2}$$

The term $\vec{f}_i(t)$ in Equation 2 describes the total force upon the agent to move in a desired direction e_α^0 at a particular time (t) with a particular speed v_α^0 . The first term of Equation 2 describes the acceleration of the agent where the agent adjusts his walking speed that is ideal in a relaxation time τ_α . The last two terms of Equation 2 describe the repulsive forces that act upon the agent to maintain a certain safe distance from other agents β and obstacles i (Helbing and Johansson, 2011; Helbing and Molnár, 1995).

Familiar obstacles or pedestrians have attraction forces, for example, pedestrians be likely to form a group when they are familiar with each other (Helbing and Molnár, 1995). This represents attraction forces which is represented in the first set of variables Equation 2.

The distance between two pedestrians affects the movement of a certain pedestrian. Usually, unfamiliar pedestrians would like to keep a distance from each other. This phenomenon is represented by a repulsive force that affects the walking speed and the density on a specific area. This repulsive force gets stronger when pedestrians get closer to each other (Helbing and Molnár, 1995). This is represented in the second set of variables in Equation 2.

In addition, pedestrians are affected by the distance between them and the obstacles (i.e. walls, handrails, etc.). Pedestrians tend to avoid collision with those obstacles and keep a certain distance. This phenomenon is represented by a repulsive force that also affects the walking speed and density on a specific area. This repulsive force gets stronger when pedestrians get closer to each other (Helbing and Molnár, 1995). This is represented in the third set of variables in Equation 2.

Also, the social force model takes into account the fluctuation for deviations of pedestrian's response to those attractive and repulsive forces. This fluctuation can be added to the total equation of motivation for a pedestrian to move to be (Helbing and Molnár, 1995):

$$\frac{d\vec{w}_\alpha}{dt} := f_\alpha(t) + \text{fluctuations} \quad \text{Equation 3}$$

$f_\alpha(t)$ = The sum of attraction and repulsive forces (The Social Forces)

$\frac{d\vec{w}_\alpha}{dt}$ = The alteration to the pedestrian's velocity

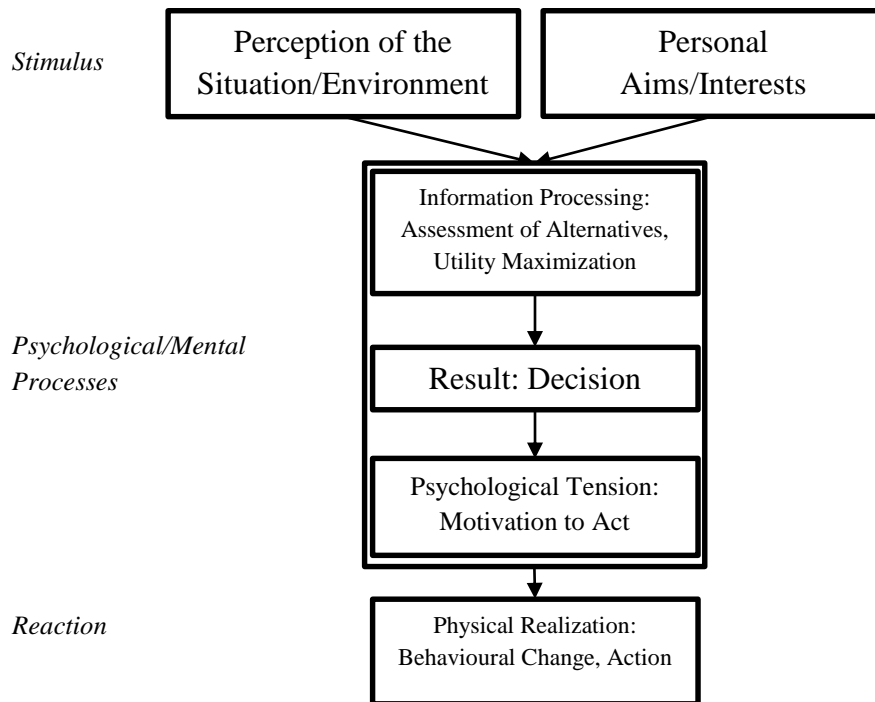


Figure 2 Schematic representation of processes leading to behavioural changes (Helbing, 1998)

Helbing illustrated the process of changing the behaviour of a person which is shown in Figure 2. A specific stimulus which can be simple or complex can result in assessment of alternative decisions. The final decision would motivate the action that a specific person took. Consequently, this will lead to a behavioural change and an action. In addition, there are further forces which are used to adjust the agent's walking acceleration. The components that are generating the forces are more discussed in Table 2.

Table 2 Components that affects the social force model in MassMotion (Zarnke, 2015)

Component	Description
Destination	The main force that will give the agent its desired speed to go toward the destination
Neighbor	It consists of two forces which are cohesion and collision. Cohesion pushes the agents who have similar targets toward each other. Collision pushes the agents who do not have the same targets and will be approaching other agents from the other side.
Drift	A force that will push agents in bias direction when agents approach oncoming agents in the opposite direction in narrow spaces. Also called counter flows.
Orderly Queuing	This force will push agents toward the middle of a target when arriving.
Corner	This force will push agents to swing wide on corners or hug the corner.

The author of the user guide mentioned that the sum of these sources will affect agent walking speed (Zarnke, 2015). However, obstacles are given a repulsive force of its own, but they are used to constrain other forces. Therefore, the sum force will not push agents toward an obstacle. An example of component forces is shown in Figure 3.

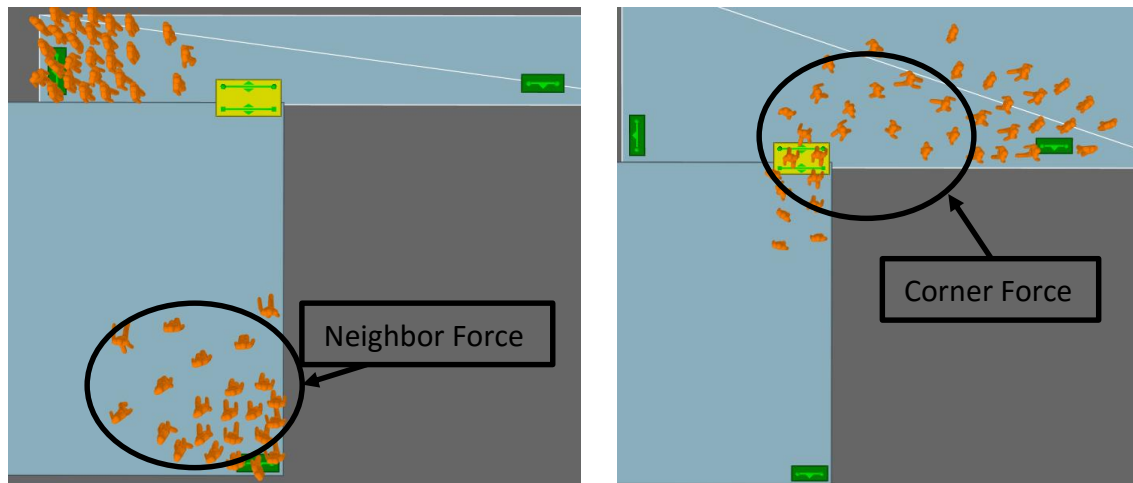


Figure 3 Example of the component forces used in the social force model of MassMotion

3.1.3 Agent Movement

This Section explains how agents move in the building based on the route choice algorithm and social force model implementation that were mentioned before. There are different ways to represent the agents' movement. However, only a set of methods applicable to the continuous approach (since it is the approach used in MassMotion) are discussed here (Kuligowski et al., 2010):

- Density Correlation: Walking speed and flow of agents are assigned based on the density of the area they are occupying. There are different methods to perform this among which the methods presented by Fruin, Paul, and Predtechenskii and Milinskii's (Fruin, 1971; Pauls, 1984; Predtechenskii et al., 1978).
- User's choice: Walking speed, flow and density of agents can be assigned by user.
- Inter-person distance: Agent has a surrounding "bubble" (i.e. comfort area) which gives the agent a minimum distance from other agents and obstacles.
- Conditional: Agents can interact with the condition of the surrounding environment such as fire, interaction with other agents, etc.
- Acquiring Knowledge: It depends on the knowledge of the agents through evacuation and relativity the values will be assigned. However, it is not a real movement algorithm because total arrival time of the agents is not calculated.
- Unimpeded flow: This model will calculate the unimpeded walking speed. The final arrival time is dependent on the calculated arrival time, delays, extra times whether addition or subtraction.

The movement of the agents in MassMotion is also based on Fruin's density correlation (Zarnke, 2015). The data collected was from a non-emergency movement based in the USA. Fruin introduced the concept of Level-of-Service (LOS) standards which provide the model developer with data to determine the quality of the environment of a person's space (Fruin, 1971). This concept was developed first in traffic engineering. There are six categories of Level-of-Service used; LOS A, LOS B, LOS C, LOS D, LOS E, and LOS F. Fruin provided the average area and the average flow of people in each case. LOS A is where people move freely and can negotiate other counter-flow without hindering. LOS B is where people have normal walking speed and can negotiate people in a one-direction flow. Also, reverse-direction can cause minor conflicts which have the potential of lowering the walking speed of people. LOS C is where it is restricted for individual to select their walking speed or pass another person. Therefore, conflicts are considered with high probability. LOC D is where the majority of people have reduced walking speeds, because of the difficulty of passing other slow people. This level illustrates the most crowded areas. LOC E is where it is necessary to have some adjustments of gait and normal walking speeds are restricted. It is very likely that people cannot reverse-flow or cross-flow in this level. Finally, LOC F is where all people's walking speeds are excessively restricted. Forward movement of people is only possible with shuffling. Crossing-flow and reversing-flow are highly implausible (Fruin, 1971). MassMotion has the functionality to provide the values of these levels for each agent. Additionally, based on these levels, maps of average

density can be produced. An example of Level-Of-Services (LOS) generated by MassMotion can be seen in Figure 4.

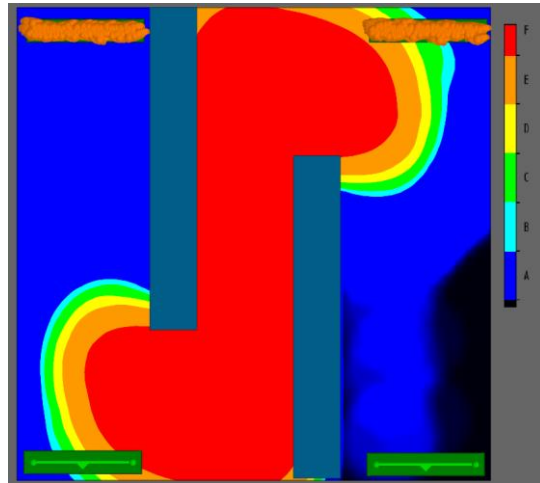


Figure 4 Map of Average Density illustrating Fruin's Level-of-Services.

Agent's movement in MassMotion is dependent on spatial analysis; that means that the results are dependent on the location of objects in the approach map (Zarnke, 2015). Therefore, the agent is always being aware of the route conditions from the location to the destination, and in case of change automatically depending on the floor the agents reach.

Two different maps are created in the preparation of the simulation step (See Figure 5); Obstacle Maps and Approach Maps (Zarnke, 2015).

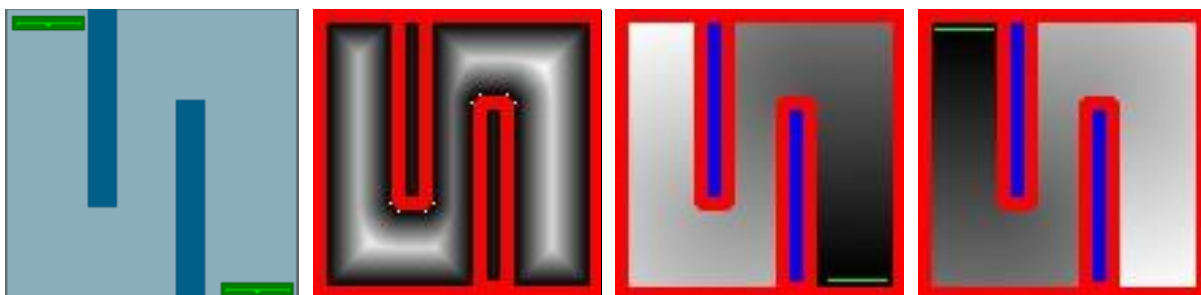


Figure 5 Original Layout, Obstacle map, Two Approach maps (Ordered as 1, 2, 3, and 4)

The obstacle maps represent the walkable space where agents can move in it (see Figure 5). As seen in Figure 5 of number 2, the areas around obstacles and the edges of the floor are marked in red. Thus these areas are not a walkable space. In addition, any obstacle that is created below an elevation of 0.4 m is considered in the obstacle map. Obstacle map also has a gradient of black and white areas, where black areas are the closest distance to the obstacles or the edges where it has a distance of zero. As the distance from the obstacles and the edges increases, the color of the area gets a gradient of black to white (Zarnke, 2015).

Approach maps are also created in the preparation of the simulation. Approach map illustrates the walkable distance to a particular goal. The number of approach maps is dependent on the points of spawn or extraction from the specific floor to another floor. As seen in Figure 5, two portals were created (number 1). Therefore two approach maps are needed (number 3 and 4). The green color is given to the points of spawn or extraction. Black color illustrates a distance of zero from the goal (see Figure 5, number 3 and 4). On the other hand, white color illustrates the farthest distance from the goal (Zarnke, 2015).

3.1.4 Model Space Representation

Models have four types of representations of space, coarse network, fine network, continuous approach, and Hybrid approach as shown in Figure 6 (Ronchi and Nilsson, 2016). A hybrid approach is considered to be a combination of two or more types of networks (Chooramun et al., 2011).

MassMotion uses a continuous approach which represents the geometry as coordinates in which each agent has a specific location in the coordinates system, which provide free movement in the space of the agents. Agents represented in this approach have a body size that can be changed as seen in Figure 6 (Ronchi and Nilsson, 2016). A minimum distance is introduced in this approach which provides the realistic movement of people, to ensure that the agents will not overlap with other agents or obstacles. It is advised that the iteration time step must be sufficiently short to make sure that agents will not walk through obstacles (Ronchi and Nilsson, 2016).

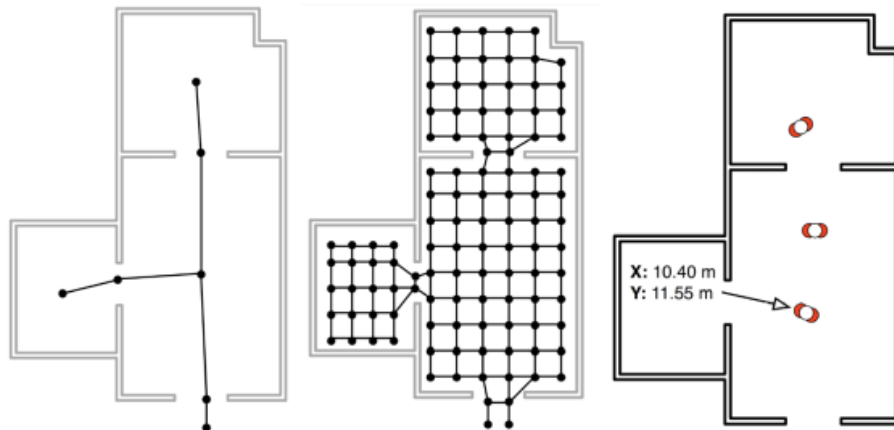


Figure 6 (from left) a coarse network, fine network model and a continuous model, taken from Nilsson (2014) with permission

The continuous model approach has the closest representation of people's movement than the other approaches. As people in real world move freely in the space and avoid collisions with approaching agents or obstacles. Nevertheless, the continuous modelling approach does not

necessarily guarantee a realistic movement behaviour, as it varies upon how movement represented and in what way the model will be used (Ronchi and Nilsson, 2016).

The advantages of the continuous modelling approach are that it is less user-dependent and more realistic when it comes to simulation. An example of that is the solution of counter-flow with a sub-model of route negotiation behaviour. Therefore, in a counter-flow situation, agents negotiate with each other their route choice (Ronchi and Nilsson, 2016).

A continuous approach can require more computational power. Thus, the time of calculation may vary and might be longer (Ronchi and Nilsson, 2016).

3.1.5 Previous Studies

During the process of calibration of MassMotion, program developers have performed a set of verification and validation studies. Many studies were carried out since MassMotion was developed. Verification studies were carried out to check whether the theory behind the model is well applied. The features that were covered so far in the verification tests are pre-evacuation behaviour, walking speed, physicality, decision making, and crowd dynamics. Those studies were based on the verification tests that were suggested by IMO (International Maritime Organization) and the NIST Technical Note 1822 (National Institute of Standards) (International Maritime Organization, 2007; Ronchi et al., 2013)

As mentioned earlier, some tests could not be explicitly conducted because MassMotion does not have a correspondent functionality to represent them. Those tests are related to walking speed reduction in low visibility, elevators, group behaviours of agents, and agents' incapacitation.

A recently published report contains the tests that were conducted for verification tests (Kinsey, 2015). The tests concerning walking speed were: corridor walking speed test, ascending stair walking speed test, and descending stair walking speed test. The tests that were related to the physical movement of agents were movement around corners and movement disabilities. The tests that are related to decision making were assignment of parameters, crowd exit usage, exit allocation, affiliation, and dynamic availability of exits. The tests that are related to crowd dynamics were exit flow rates, counter flow, stair congestion. While most of the tests were following the suggested tests by IMO Guidelines and the NIST technical Note 1822, there were also additional new tests that were performed (International Maritime Organization, 2007; Ronchi et al., 2013). The tests were:

- Stair Merging
 - This test was performed to examine the capability of MassMotion to represent the merging ratios in a staircase, and to examine the impact of density of

occupants on those merging ratios. Stair merging ratio in this test was approximately 1:1.

- Stair Flows
 - This test was performed to examine flow rates of stairs whether it was downward or upward flow, where increasing the width of the stair can lead to the increase of flow rates.

Some other tests will be conducted soon regarding verification as mentioned in the report (Kinsey, 2015).

Validation tests were also conducted with different cases, and they covered different aspects of the model and different scenarios. The data analyzed were to check different features that the program can do such as route choice, exit usage, stairs, and total evacuation time. A study in Toronto, Canada was done in Union Train station to check the impact on commuters' congestion by volume of commuters and arrival patterns of trains. Also, route choices that were taken by occupants to the 14 exits that were available in the station. There were about 10348 occupants. The percentage difference adopting open calculations that was calculated was 0.0% and 2.1%, with a mean of 0.9%, between observed and modelled usage of stair/escalator (King et al., 2014). Another validation study that was conducted included four different buildings, and the simulated data were compared with the observed one (Rivers et al., 2014). The first building was in London, United Kingdom and it was a high-rise office tower with 50 floors and 4 stairwells, and the building is called One Canada Square. This validation test included data for total evacuation time, stair usage, route choice, flow rates, and exit usage. The percentage difference between observation and simulation total evacuation times was up to 10%. The second building was in New York, US in a building called 155 Avenue of the Americas which is a medium-rise office building that consists of fifteen floors with two stairwells, however, only six floors were modeled. Similar data were looked at as the previous test, and MassMotion gave an over predicted evacuation times of 5.6%. The third building was 10 Hanover Square in London, UK, which is a high-rise office building with twenty two floors and two stairwells. MassMotion gave evacuation times that were 1.4% lower than the evacuation time that was conducted in the building. The last building was 85 Broad Street, which is located in London, UK which is a high-rise building that consists of thirty floors and three stairwells. The percentage of difference in evacuation times was 7.3% lower than the observed data. There was a validation test which was not published yet that was mentioned in the report that was done by Michael Kinsey (Kinsey, 2015). MassMotion gave an over prediction of 12.2% than the experimental evacuation time. Additionally, they compared the flow at stair discharge for the most used stairs and the times of the last person to leave every stair.

3.2 Validation Methods

As mentioned earlier, validation is one of the factors that decide the reliability of the model and how much the results produced will match reality (Ronchi et al., 2013). However, validation definition in simulation models is to some extent debatable. The International Standards Organization defines Validation 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” (International Standards Organization, 2008).

Ronchi raises some questions to clear the previous definition. The questions to validate simulation models were how we judge a tool to be accurate, the number and type of tests that should be executed, who can state the approving criteria and how it should be stated, and who should execute the tests that were agreed on whether users, developers or a third party agency (Ronchi, 2014). In addition, evacuation experiments are not that many in real life which makes it harder to get the right data needed to validate a simulation model. Also, some features in a simulation model cannot be implemented due to lack of data in that particular aspect. The main strive is that it is yet difficult to understand the behaviour of occupants fully (Ronchi et al., 2013).

Since acceptance criteria are important in verification and validation, a clear definition must be stated on how do users or developers choose those acceptance criteria. To date, there are no clear acceptance criteria for the simulation models, and this might create issues in the interpretation of evacuation model results (Ronchi, 2014).

The evaluation of the simulation models may not be the easiest task since several sources of errors may rise in the process. The sources of errors may rise in different steps of project such as model inputs, the selection of a model to represent a specific case, calculations done by the model, and how the results would be interpreted (Lord et al., 2005). Therefore, the difference in levels of knowledge among users about models and the simulated scenarios might affect the results of the simulation. In order to make a categorization of calculation methods, three different setups correspond to the degree of user input calibration effort. The three setups are:

- **Blind Calculation:** In this setup, the user is provided with basic information about the project such as the geometry of the structure with the needed components of egress and the type of the structure. The rest of the input are in user’s hands to choose. This kind of setups will assess the ability of users to come up with a valid input for the specific simulated scenario.
- **Specified Calculation:** The user is provided with a specified set of inputs such as the geometry of the structure with the needed components of egress, agents’ characteristics, and the varying range of constants to be used. When using the specific

inputs, the uncertainties related to the scenario will be less, and representation to the reality will be more realistic.

- **Open Calculation:** This setup is the closest to reality since it is based on an experimental study from a real life evacuation or a fire drill. Thus, the uncertainties related to this setup would be the least since the user is trying to replicate the experiment in the simulation model with inputs provided from the experiment.

Evacuation models - whether they are node-based models, grid-based models, or continuous - may require different input parameters and scenario description for each setup of the three setups mentioned above. Also, some models might require the occupants' characteristics while other models might not require that. Finally, a proper description of the scenario is necessary to simulate the scenario for the three different setups.

3.2.1 Uncertainties in Evacuation Modelling

As mentioned previously, uncertainties can affect the results of the simulation models.

Therefore those uncertainties must be defined and limited to minimum values. Simulation models have four categories of uncertainties which are (Hamins and McGrattan, 2007; Ronchi et al., 2014):

- **Model Input Uncertainty:** It is related to the input parameters that are used to do the simulation. The resemblance of walking speeds of occupants from experiments as probability distribution is a common input where users might have uncertainty in it.
- **Measurement Uncertainty:** It is related to the measurement that has been used in the experiment such as measuring the walking speeds of occupants.
- **Intrinsic Uncertainty:** It is related to the model's physical and mathematical assumptions. For example, how the model would represent the walking speeds and the movement of occupants mathematically.
- **Behavioural Uncertainty:** It is related to the variability of human behaviour's (Ronchi et al., 2014). A stochastic representation of human behaviour is important in evacuation since if the same people gathered in the same building in consecutive days where they start from the exact same places, then the results may vary dramatically (Averill, 2011). Therefore, it is crucial that several experimental data-sets are examined to comprehend the variability of occupants' behaviours during evacuation events (Kuligowski, 2013). However, as mentioned earlier, there is a massive need for experimental data-sets, and currently there is only single data-sets for evacuation event (Ronchi et al., 2014). The known methods to study the variability of the data from the simulation models are applied to understand the effect of the behavioural uncertainty. Programmers of

models use probabilistic distribution and algorithms that produce variability of results far from user's control. Consequently, there is a need to implement a process to analyze uncertainty, and that will evaluate the occupant behaviour's variability in evacuation models (Ronchi et al., 2014).

3.2.2 Functional Analysis Concepts

Functional analysis concepts are used in this thesis to evaluate evacuation model results. The original concept of functional analysis comes from the work of Hilbert and others in the beginning of 1900, in which they defined functional analysis as the "generalization of linear algebra, analysis, and geometry". Functional analysis operators were used in different fields such as economics, theoretical physics and engineering and that includes fire engineering (Peacock et al., 1999).

There are five different convergence measures (three of which come from the functional analysis) which are used for the analysis of evacuation model results, namely Euclidean Relative Difference (ERD), Euclidean Projection Coefficient (EPC) and Secant Cosine (SC), TET (Required Safe Egress Time), and Standard Deviation of TET (SD) (Ronchi et al., 2014).

The functional operators examine the vectors and the change between them. For example x and y are dimensional vectors. ERD calculates the normalized difference between those curves. EPC calculates the normalized scalar product of those two curves. While SC measures the difference of the shape of those two curves analyzing the first derivatives of those two vectors. It should be noted that SC includes a skip parameter "s", where it useful to smooth the noise of the data (Galea et al., 2014; Ronchi et al., 2014).

The ERD characterizes "the overall agreement between two curves" (See Equation 4).

$$ERD = \frac{\|\vec{x} - \vec{y}\|}{\|\vec{y}\|} = \sqrt{\frac{\sum_{i=1}^n (x_i - y_i)^2}{\sum_{i=1}^n (y_i)^2}} \quad \text{Equation 4}$$

The EPC studies the minimum problem which can be studied when the derivative of a function approaches zero (Peacock et al., 1999; Ronchi et al., 2014)(See Equation 5).

$$\alpha = EPC = \frac{\langle \vec{x}, \vec{y} \rangle}{\|\vec{y}\|^2} = \frac{\sum_{i=1}^n (x_i y_i)}{\sum_{i=1}^n y_i^2} \quad \text{Equation 5}$$

Secant cosine allows to examine the influence of the number of runs on the probable variances "between the shapes of two consecutive average curves" (Ronchi et al., 2014) (See Equation 6).

$$SC = |SC_j - SC_{j-1}| \quad \text{Equation 6}$$

The last two convergence criteria are to examine the convergence of total arrival time as overall using the following two equations:

$$TET_{convj} = \left| \frac{TET_{avj} - TET_{avj-1}}{TET_{avj}} \right| \quad \text{Equation 7}$$

$$SD_{convj} = \left| \frac{SD_j - SD_{avj-1}}{SD_j} \right| \quad \text{Equation 8}$$

These operators can be used to in understanding behavioural uncertainty analyzing the variability of results of the same scenario. In addition, results from different scenarios can be compared with each other to examine the variability of the results.

3.3 Benchmark Experiments

3.3.1 Corridor Experiment

The following experiment was conducted by Frantzich, Nilsson and Eriksson (2007) in Lund University, to study the pedestrian movement throughout a corridor. Participants were students at the university. The whole experiment was filmed using three video cameras to capture the movement throughout the corridor. There were five different scenarios in this experiment, and the key factor was to use different widths for the opening of the corridor.

The used corridor was 9.6 m long and 1.6 m wide, and the walls were made using boxes and panels which were made of wooden particle boards. The opening at the end was modified using boxes to vary the width of the opening. The boxes and panels were 2.0-2.4 m height.

Additionally, the corridor was not closed from the top so it can be filmed. The plan of the corridor is showed in figures below.



Figure 7 The layout of the corridor and the end opening (Frantzich et al., 2007) with permission.

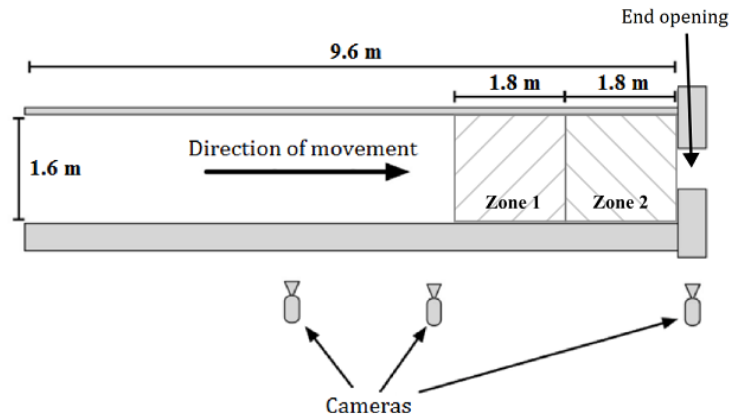


Figure 8: A schematic drawing of the configuration seen from above (Frantzich et al., 2007) with permission.

The total number of participants was 42 students, aged between 20-30 years. The participants were 35 males and 7 females. All participants knew they were taking part of an experiment. Moreover, it was not identified if the participants knew the objective of this experiment.

Participants were lined up in around 2 m wide queue before the corridor. On the first experiment, the objective was to measure the participants' unimpeded walking speeds, so they walked individually throughout the corridor. However on the other experiments, participants walked as a group. Information regarding the experiment scenarios was showed in the following table.

Table 3: Description of the five scenarios in the corridor experiment (Frantzich et al., 2007).

Scenario	Trial numbers	Details	Individual/group
A	83	Completely open corridor	Individual
B	6	Corridor with a 60 cm end opening	Group
C	6	Corridor with a 75 cm end opening	Group
D	6	Corridor with a 90 cm end opening	Group
E	5	Corridor with two 75 cm end openings	Group

The corridor was marked with 13 marks to make 13 small areas so it was easier to calculate each participant's walking speed in the first scenario. On the other scenarios, different measures were calculated such as total movement time, flow through the openings, and density in the zones was marked in Figure 8. The calculated flow was with an interval of 5 seconds and presented as a mean value for each scenario. Deviant flows were excluded from calculations, and only stable flows were included.

3.3.2 Cinema Theatre

The following evacuation experiment was done in the SF cinema theatre which is located in Lund, Sweden in 1999. The experiment was done by Bayer & Rejnö (1999). They have examined how occupants react to different voice alarms. A total of 18 tests were done, however, only two tests were of interest of this thesis. The simulation of this experiment examined the pre-evacuation activities of the agents, and the degree of representation of crowdedness in the initial stages of a fire scenario. The evacuation was not announced, and the occupants inside were not informed before the evacuation. Therefore, the experiment is considered as the initial stage of a fire scenario that could happen in a cinema theatre.

Case A and B had the same alarm which is a pulsing beep with a spoken message. The voice alarm was repetitive until the experiment was done. Both cases had the same number of occupants and the same alarm which makes inputs very similar and it was interesting to examine whether the output can have the same results.

The experiment was done in a theatre which is a 10 m width by 12.5 m length. It consisted of 9 rows where each row has 15 seats (see Figure 9). There is a staircase on each side of the theatre, 0.8 m on the left of Figure 9 and 1.1 m on the right side.

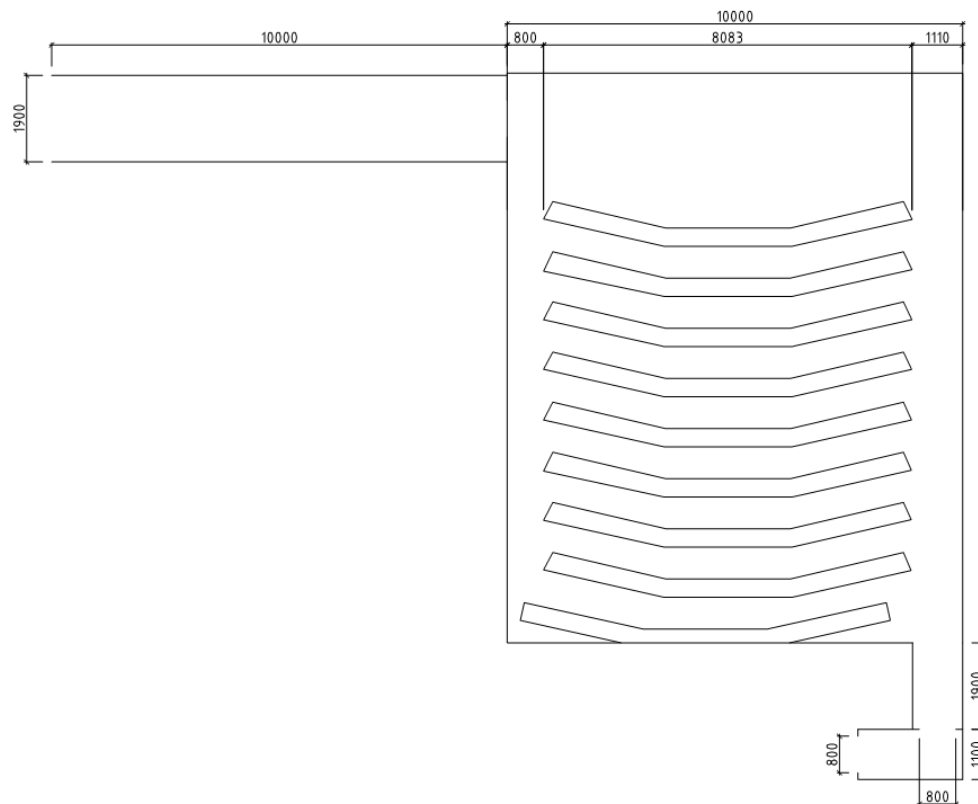


Figure 9 Schematic representation of the cinema theatre layout (original layout is available in(Frantzich et al., 2007) with permission

Two exit doors were available from the theatre. The first one is located on the left front corner and the second one is located on the right bottom (see Figure 9). Those doors were 0.8 m wide and had a standard emergency exit signs.

The theatre was fully booked therefore it had 135 occupants. There was one observer in the theatre and one observer outside the door. After the alarm of evacuation, the locations of occupants were observed after 40s, 50s, and 60s which can be seen in Figure 10. The green dots indicate the occupants who have not started the evacuation process. Red dots indicate the occupants who started evacuating. Pink dots indicate the occupants who were not explicitly observed by the camera. The camera did not cover the area after the dotted line.

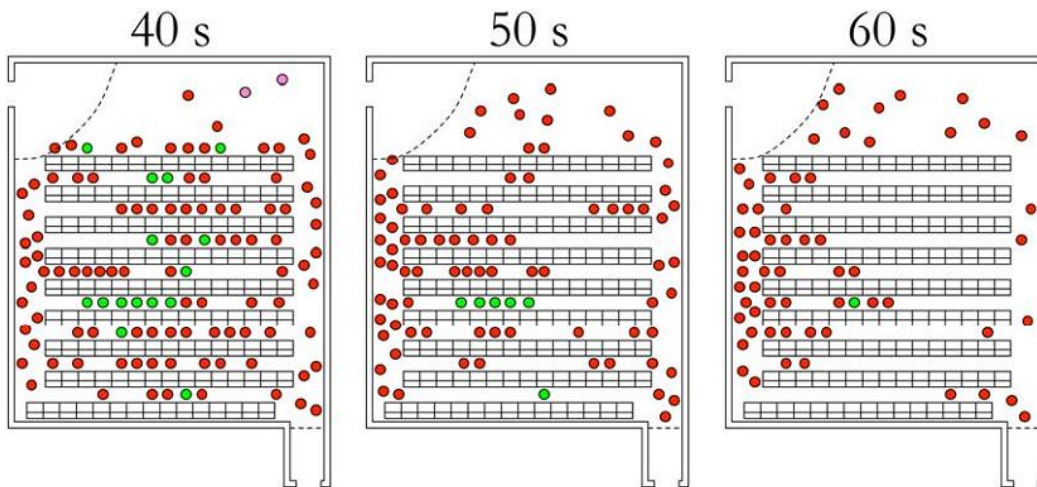


Figure 10 Observed people positions representation (Frantzich et al., 2007) with permission

Additionally, pre-evacuation time of occupants was observed and noted in Table 4 for trial A and Table 5 for trial B.

Table 4 Time in seconds of people who started evacuation in Trial A (Frantzich et al., 2007)

Row	Place														
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
1	35	39	42	28	28	39	38	36	37	38	40	28	32	29	28
2	32	29	31	35	30	27	41	44	39	30	33	33	33	29	27
3	26	25	28	29	35	37	37	38	34	31	36	30	30	30	32
4	26	28	30	25	25	23	41	38	36	40	39	37	39	39	26
5	32	32	34	25	35	30	32	40	46	28	29	28	27	30	30
6	24	34	42	53	56	61	59	58	32	34	37	29	28	28	28
7	30	27	36	38	49	36	37	30	25	28	28	30	33	32	27
8	29	29	28	36	36	35	35	35	28	25	28	25	28	29	32
9	20	27	29	29	32	35	33	28	28	51	35	32	30	28	25

Table 5 Time in seconds of people who started evacuation in Trial B (Frantzich et al., 2007)

Row	Place														
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
1	40	34	35	36	28	32	28	28	26	35	27	35	37	35	41
2	30	32	34	29	31	36	36	27	32	28	28	32	38	35	36
3	45	49	40	32	26	29	28	25	25	30	30	28	25	26	27
4	26	32	31	24	28	34	33	33	27	28	39	33	42	38	28
5	30	30	27	27	25	26	28	28	27	26	28	29	27	29	28
6	21	25	27	30	32	28	23	25	26	30	32	34	36	32	30
7	23	20	39	42	30	30	40	28	41	42	31	31	30	32	35
8	28	29	36	35	28	26	27	32	29	30	34	34	34	31	35
9	37	21	30	32	26	28	29	28	31	32	30	32	27	33	32

3.3.3 Stair Merging

The following experiment was done in Japan by Hokugo et al. (1985) which emphasized on two-way flow in staircases and the merging ratio of occupants. Participants were university students and aged from 18 to 24. In total, there were 115 male and 35 female.

Table 6 Occupants' number in each scenario of Stair Merging experiment

Location	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Corridor	85	86	85	86	86
Upper Floor	68	67	67	65	66
Total	153	153	152	151	152

The layout of the experiment is shown in Figure 11. The experiment had five scenarios in total, and each case had only one trial:

1. The first scenario observed occupants who came first from the upper floor and then people from corridor started moving and merged with them.
2. The second scenario observed occupants who came first from the corridor, and then people from upper floor merged with them.
3. The third scenario observed occupants who came from the corridor and the upper floor at the same time.
4. The fourth scenario is the same as the third scenario. However, the width of the corridor where both merged was decreased by an obstacle at location A to be 1 m (see Figure 11).

- The fifth scenario is the same as the third scenario. However, the width of the corridor where both merged was decreased by an obstacle at location B to be 1 m (see Figure 11).

In addition to the experimental configuration, another simulation was considered in which the exit door of the floor was changed based on a similar study conducted in another evacuation model (Sano, et al., 2015). Flow rate and merging ratios were calculated for each scenario, and there were three different scenarios (See Figure 11, Figure 12, Figure 13 and Figure 14).

The following figures represent the scenarios that had been done:

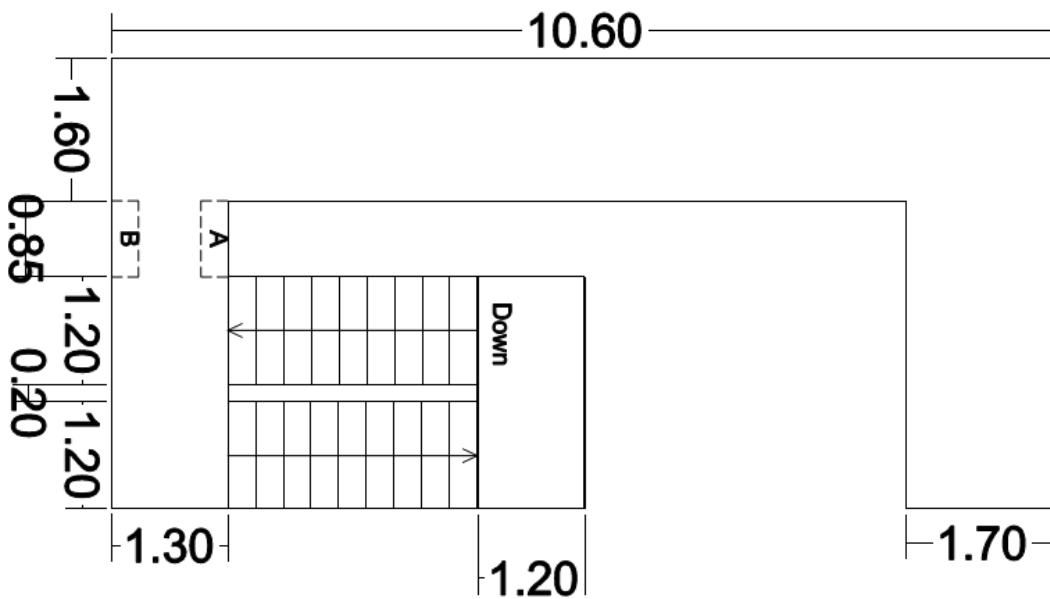


Figure 11 Stair Merging test Layout for Scenario 1-5. Distances are expressed in meters.

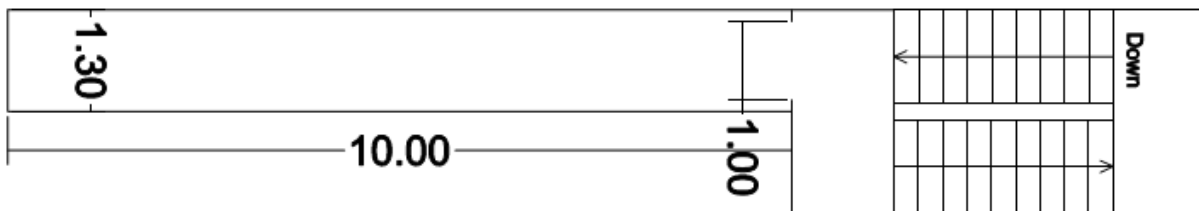


Figure 12 Stair Merging test Layout for Scenario 6. Distances are expressed in meters.

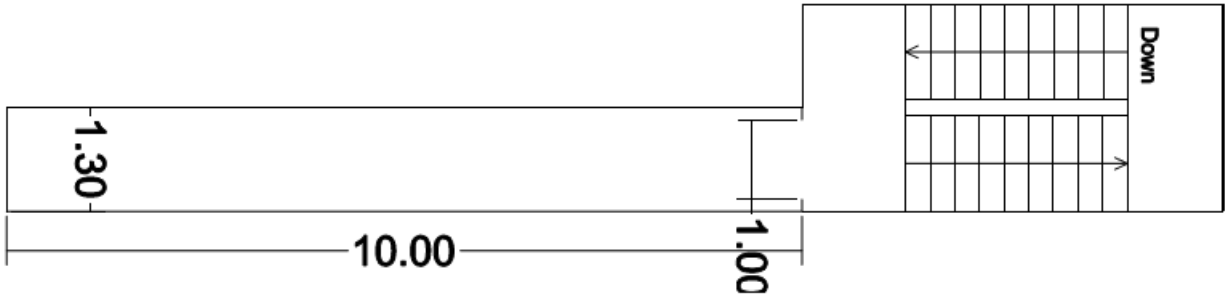


Figure 13 Stair Merging test Layout for Scenario 7. Distances are expressed in meters.

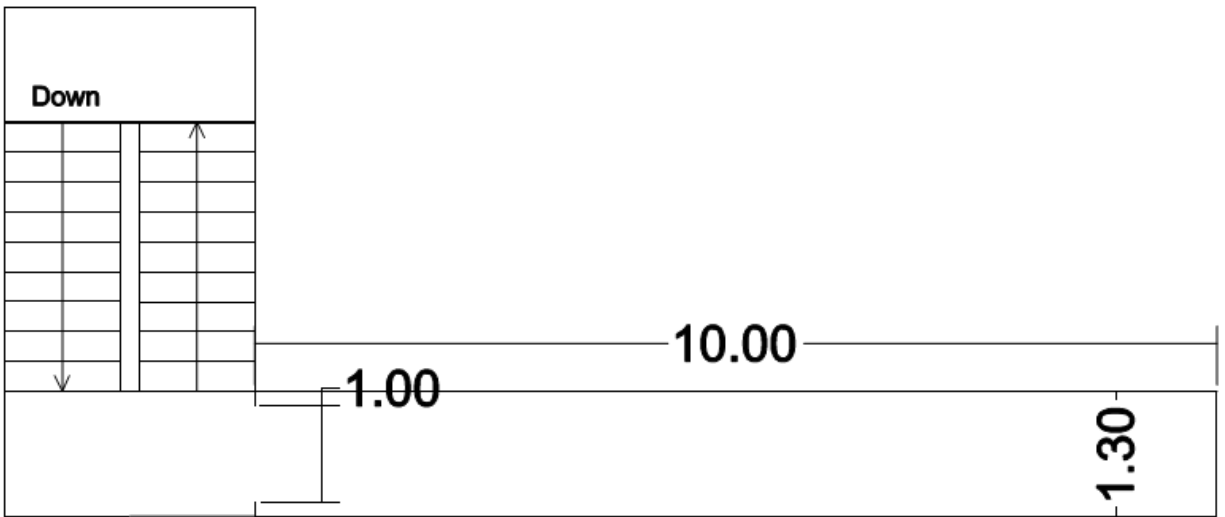


Figure 14 Stair Merging test Layout for Scenario 8. Distances are expressed in meters.

Furthermore, a specific simulation was conducted. Geometry and the number of people were the same as in scenario 3. Fruin's density reduction was turned off to examine the difference in results between those two scenarios which had about the same inputs.

In addition, the stairs created had a rise of 0.18 m and a tread of 0.31 m. As mentioned in the experiment there were 9 treads in total and ten rises while the slope was 30 degrees.

Experimental results were taken into consideration and compared with the results of the simulations performed with MassMotion. Additionally, there are charts of density and flow rate at each second for scenarios 1 to 5 in the original experiment (Hokugo et al., 1985). The same charts were produced with the MassMotion simulations in order to examine the difference between different stages at every second. The results of all experimental scenarios are presented in Hokugo et al. (1985).

4 Validation of MassMotion

4.1 Validation Test 1: Corridor Experiment

As mentioned before in Section 3.3, this experiment was conducted at Lund University (Frantzich et al., 2007). The aim of Scenario A is to inspect the representation of walking speeds in MassMotion. Scenarios B-E considered different opening widths, and the subsequent flow and density are compared to the experiment's results.

4.1.1 Simulation Description:

This validation test is performed with two types of settings, namely default settings, and specified settings. The specified settings were taken from the experiment that was made at Lund University. Default settings are used to examine the unimpeded default speeds within the model. Specified settings are used to examine whether the model can produce the same results as in reality. Both results were compared with the results that were taken from the experiment.

Three areas had to be drawn, to simulate the experiment in MassMotion. The first area consists of 2 m wide by 10 m long and it was drawn before a corridor (Number 1 in Figure 15). This area was made to simulate the queuing of people before entering the corridor. The second area was the corridor itself which was 1.6 m wide and 9.6 m long (Number 2 in Figure 15). The last area was the area where agents exit the simulation which let the agents walk from the opening before they exit (Number 5 in Figure 15).

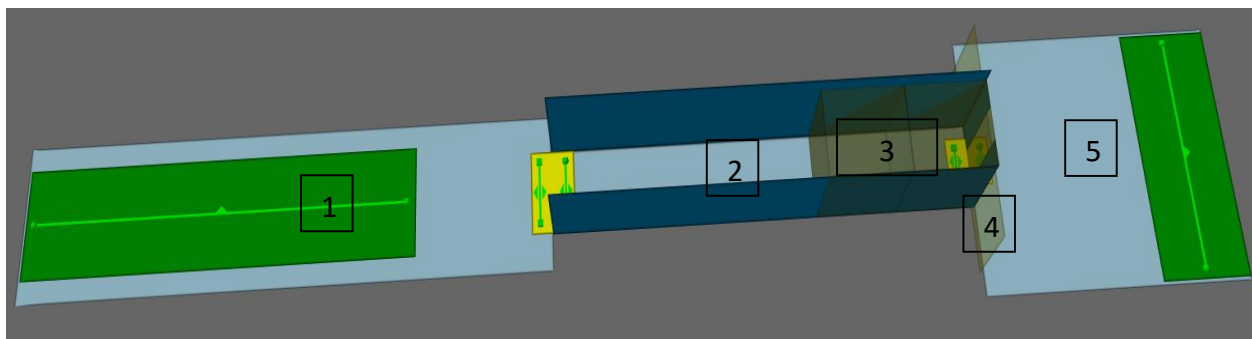


Figure 15 Validation test 1: Corridor Experiment (Scenario B) in the MassMotion Simulator (Refer to Figure 8 for Dimensions)

An analysis sub-area was set at the end opening of the corridor to measure the flow rate of agents (Number 4 in Figure 15). Also, two analysis region were placed as mentioned in Section 3.3.1 before the end opening of the corridor with an area of 1.8 by 1.6 m each (Number 3 in Figure 15). Additionally, the difference between the openings of scenarios is shown in Appendix A in Figure A 1.

Observed walking speeds that were measured from the experiment are presented in Table A 1 in Appendix A. Those walking speeds were used in the specific settings of the scenarios. Scenario A was conducted to observe the walking speeds that MassMotion assigns to agents and examine the probabilistic distribution of MassMotion on walking speeds with a total of 420 observations. Figure 16 compares the experimental and simulation walking speeds. The results were different from the experimental results, and this is because the participants in the experiment were able-bodied Swedish students. It should be noted that MassMotion does not differentiate between walking speeds of female and male agents. Therefore, all agents had the same characteristics except walking speeds which are assigned differently to each agent.

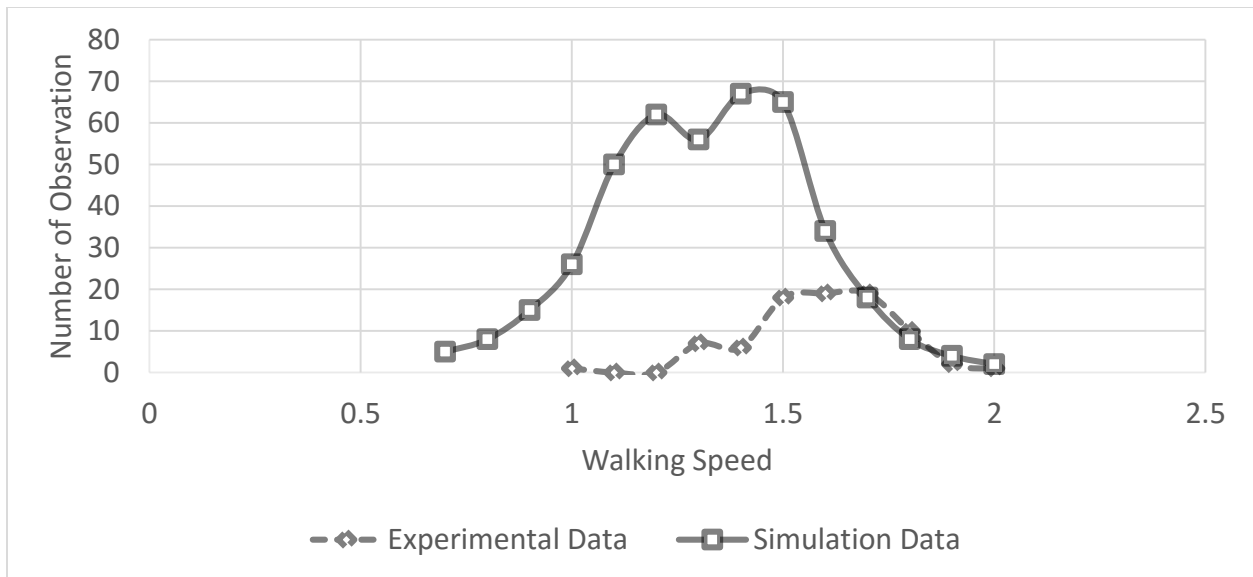


Figure 16 Comparison between Experimental and Simulation Walking Speeds in Validation Test 1: Corridor Experiment Scenario A

As mentioned before, an analysis cordon was used to measure the flow of agents through the end opening. The period of measuring the flow was the stable flow of agents which excludes the beginning of the queue passing through and the end of the end of the queue. In the experiment of Frantzich et al. (2007) the flow was calculated by measuring the number of people during a five second interval, and that number was divided by the length of the time interval. At the end of each trial, a mean of those flows was taken. To compare the results from the simulation, the same method was applied.

To calculate movement time, a difference between the time of the last agent who exits the corridor and the first agent who walked 2.4 m through the corridor, which is how it is done in the experiment.

Two analysis regions were created as seen in Figure 15, to calculate the density of the agents in the corridor,. As in the experiment, the density was set to be calculated in an interval of 1 second. Additionally, only stable flow was considered in the calculation.

Specified settings were also used to compare the results with the default settings. Walking speeds from the experiment were assigned to the agents as seen in Figure 17.

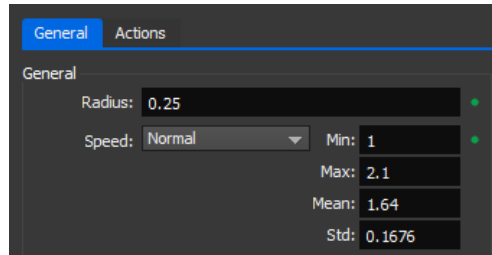


Figure 17 Walking speeds assigned for agents in specified settings of Validation Test 1

Furthermore, Fruin’s density reduction was deactivated. Deactivation of Fruin’s density factor was done by changing the command line concerning Fruin’s density reduction in the input file with an extension of .mm associated with the model. The line that was changed was:

```
<AttrSettingsMovementStandard>
  <Data>
    <EnumString v="MovementStandardFruin" t="3" />
    <EnumValue v="1" t="1" />
  </Data>
<Type v="DataTypeEnum" t="3" />
```

To deactivate Fruin’s density reduction, “MovementStandardFruin” has to be replaced with “MovementStandardNone”.

It should be noted that MassMotion has the capability to cap the flow rate manually, however, the tests performed here is related to validation tests rather than verification. Therefore, the interest was to examine what would be the flow rate and how it would be impacted without capping the flow at the opening.

4.1.2 Results

The following tables show results from the scenarios B-E with default settings which are Tables 3, 4, and 5. The difference between progressive averages is shown in Figure A 2, Figure A 3, Figure A 4, Figure A 5, Figure A 6 and Figure A 7 in Appendix A.

Table 7: Total Arrival Times for Default Settings Scenarios of Validation Test 1

Scenario	Simulation Total Arrival Time Mean (s)	Experimental Total Arrival Time Mean (s)	Time Difference (s)	Time Difference (%)	Number of Simulations
B	79	43	36	59.45%	16
C	66	37	29	55.65%	17
D	52	31	21	50.70%	18
E	45	28	17	46.73%	14

Table 8: Flow Rates for Default Settings Scenarios of Validation Test 1

Scenario	Simulation Flow Mean (p/s)	Experimental Flow Mean (p/s)	Flow Difference (p/s)	Flow Difference (%)	Number of Simulations
B	0.60	1.10	-0.50	58.82%	14
C	0.75	1.30	-0.55	54.09%	18
D	1.03	1.60	-0.57	43.35%	26
E	1.33	1.80	-0.47	30.26%	22

Table 9: Density Results for Default Settings Scenarios of Validation Test 1

Scenario	Zone	Simulation Density Mean (p/m ²)	Experimental Density Mean (p/m ²)	Density Difference (p/m ²)	Density Difference (%)	Number of Simulations
B	1	1.80	1.80	0.00	0.12%	18
B	2	2.38	1.80	0.58	27.89%	18
C	1	1.51	2.00	-0.49	27.93%	29
C	2	2.15	1.80	0.35	17.66%	29
D	1	1.11	1.90	-0.79	52.20%	24
D	2	1.59	1.70	-0.11	6.64%	24
E	1	0.95	1.00	-0.05	5.24%	24
E	2	1.12	1.10	0.02	2.12%	24

Tables 6, 7, and 8 shows the results using specified settings.

Table 10: Total Arrival Times for Specified Settings Scenarios of Validation Test 1

Scenario	Simulation Total Arrival Time Mean (s)	Experimental Total Arrival Time Mean (s)	Time Difference (s)	Time Difference (%)	Number of Simulations
B	44	43	1	2.30%	24
C	37	37	0	0.00%	23
D	27	31	-4	13.79%	19
E	27	28	-2	7.41%	12

Table 11: Flow Rates for Specified Settings Scenarios of Validation Test 1

Scenario	Simulation Flow Mean (p/s)	Experimental Flow Mean (p/s)	Flow Difference (p/s)	Flow Difference (%)	Number of Simulations
B	1.15	1.10	0.05	4.39%	20
C	1.40	1.30	0.10	7.31%	35
D	1.94	1.60	0.34	19.30%	23
E	2.43	1.80	0.63	29.87%	24

Table 12: Density Results for Specified Settings Scenarios of Validation Test 1.

Scenario	Zone	Simulation Density Mean (p/m ²)	Experimental Density Mean (p/m ²)	Density Difference (p/m ²)	Density Difference (%)	Number of Simulations
B	1	1.95	1.80	0.15	8.19%	20
B	2	2.24	1.80	0.44	21.67%	20
C	1	1.87	2.00	-0.13	6.74%	22
C	2	2.04	1.80	0.24	12.34%	22
D	1	1.62	1.90	-0.28	15.89%	30
D	2	1.72	1.70	0.02	0.91%	30
E	1	1.36	1.00	0.36	30.41%	21
E	2	1.52	1.10	0.42	31.99%	21

4.1.3 Analysis

4.1.3.1 Default Settings

The average of the arrival time of the simulation was 17 to 36 seconds longer than the benchmark experiment. Thus, the percentage difference between experimental values and simulation values were 47% to 60% (see Table 7).

The calculated flow rates at the opening of the simulation were lower than the benchmark test with a difference of 0.47 to 0.57 p/s. The percentage difference between experimental values and simulation values were 30% to 59% lower (See Table 8).

The calculated densities were over the two zones of 2.88 m² (See Figure 8). Density differences varied between lower and higher values. The differences were between -0.80 and 0.60 p/m². The percentage differences were between -53% and 28%. It should be noted that four results were below 10% different from the benchmark test (See Table 9).

4.1.3.2 Specified Settings

The difference between the average of the arrival time of the simulation and the benchmark experiment was lower with a range of 1 to -4 seconds. Thus, the percentage difference

between experimental values and simulation values were approximately 3% longer to approximately -14% lower (See Table 10).

The calculated flow rates at the opening of the simulation were higher than the benchmark test with a difference of 0.05 to 0.63 p/s. The percentage difference between experimental values and simulation values were 5% to 30% higher (See Table 11).

The calculated densities were over the two zones of 2.88 m^2 (See Figure 8). Density differences varied between lower and higher values, but in general, it was higher than the benchmark experiment values. The differences were between -0.28 and 0.44 p/m^2 . The percentage differences were between -16% and 32%. It should be noted that three results were below 10% different from the benchmark test (See Table 12).

4.1.3.3 Other observations

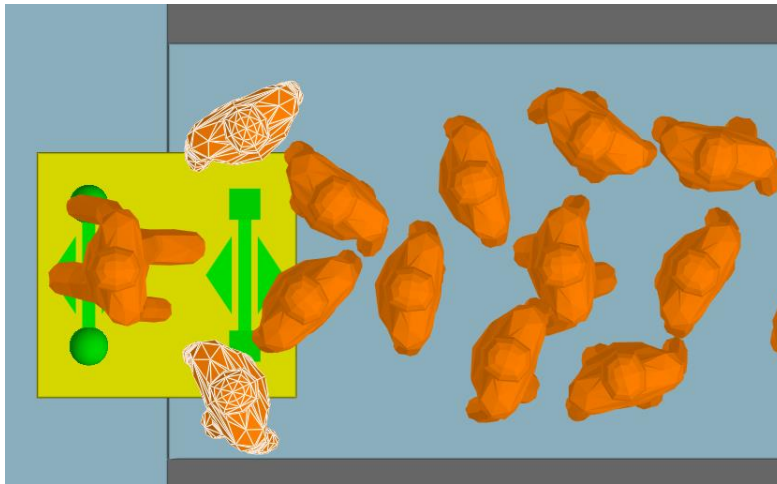


Figure 18 Agents Change their Direction at the Opening of the Corridor for Scenario B with Default Settings

Figure 18 shows that agents queuing at the opening and their movement directions start to fluctuate. This is related to the social force model that is implemented in MassMotion, where there are forces from obstacles and other nearby agents, and then the agent gets stuck in the location of space. The reason for turning direction could be related to the fruín's LOS when there is crowding, people starts shuffling (gaiting). Therefore, agents tend to leave that area faster and not being stuck at corners before the opening. This can be seen in Table 9 where density results tend to be lower than the benchmark test. This can also be the reason for lower flow rates than the benchmark values in Table 8.

Figure 19 shows the same as previous but with specified settings, and that includes deactivating Fruin's LOS. Same fluctuation of directions here, however, the walking speeds of people are relatively faster, therefore, agents who were stuck stay there for a longer time. This might be

one of the reasons why in Table 12 the density differences get higher than the default results and the benchmark values.

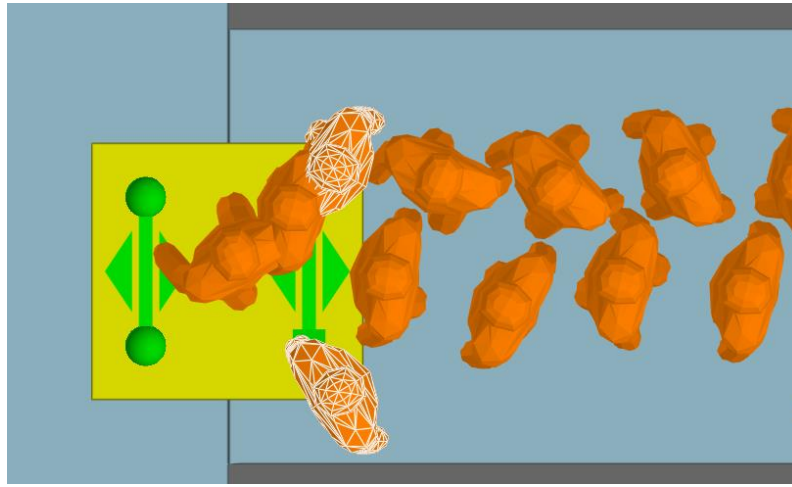


Figure 19 Agents Change their Direction at the Opening of the Corridor for Scenario B with Specified Settings

4.2 Validation Test 2: Cinema Theatre

The objective of this experiment is to compare pre-evacuation times that were assigned by MassMotion to agents with the real experiment that was done in Lund Cinema.

4.2.1 Simulation Description

The cinema theatre was created by floors, links between floors, and blockages to simulate the chairs of the cinema. Three main floors were created; first floor is the cinema theatre floor, top left floor which is the left route exit and the bottom right floor which is the other exit (see Figure 20). The dimensions used in MassMotion were the same as in Figure 9. The distance in between chairs should be 0.5 m, however, because MassMotion is a continuous network model, the distance needed to be 0.7 m. This was analyzed later in the analysis Section.

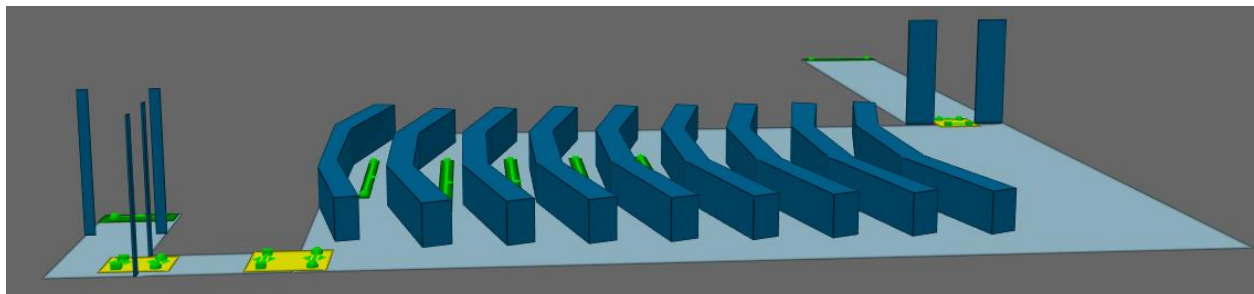


Figure 20 Cinema Theatre Geometry in MassMotion

MassMotion does not have the functionality of viewing pre-evacuation times explicitly. Therefore, pre-evacuation times can be acquired implicitly by using the actions functionality.

The action that was used is shown in Figure 21 for scenario A, and scenario B. Agents would spawn, wait for a certain time and then they will exit the simulation. The pre-evacuation times that were assigned in MassMotion were taken from the results of the experiment and can be seen in Table 4 and Table 5. Normal distribution for each row of the benchmark experiment was taken and applied to that specific row in the simulation.

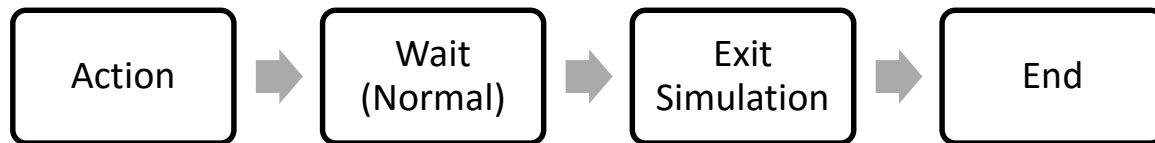


Figure 21 Delay Action that was used to simulate Pre-evacuation time in MassMotion

Walking speeds were not provided in the experiment, hence, there were be no specified settings in this simulation.

4.2.2 Results

Same convergence criterion was taken into consideration in these tests as well. Twelve scenarios were simulated. The difference between progressive averages of scenarios A and B can be seen in Appendix B, in Figure B 1.

Figure 22 shows the comparison between the benchmark test values and the results of the simulation test for each row in Scenario A.

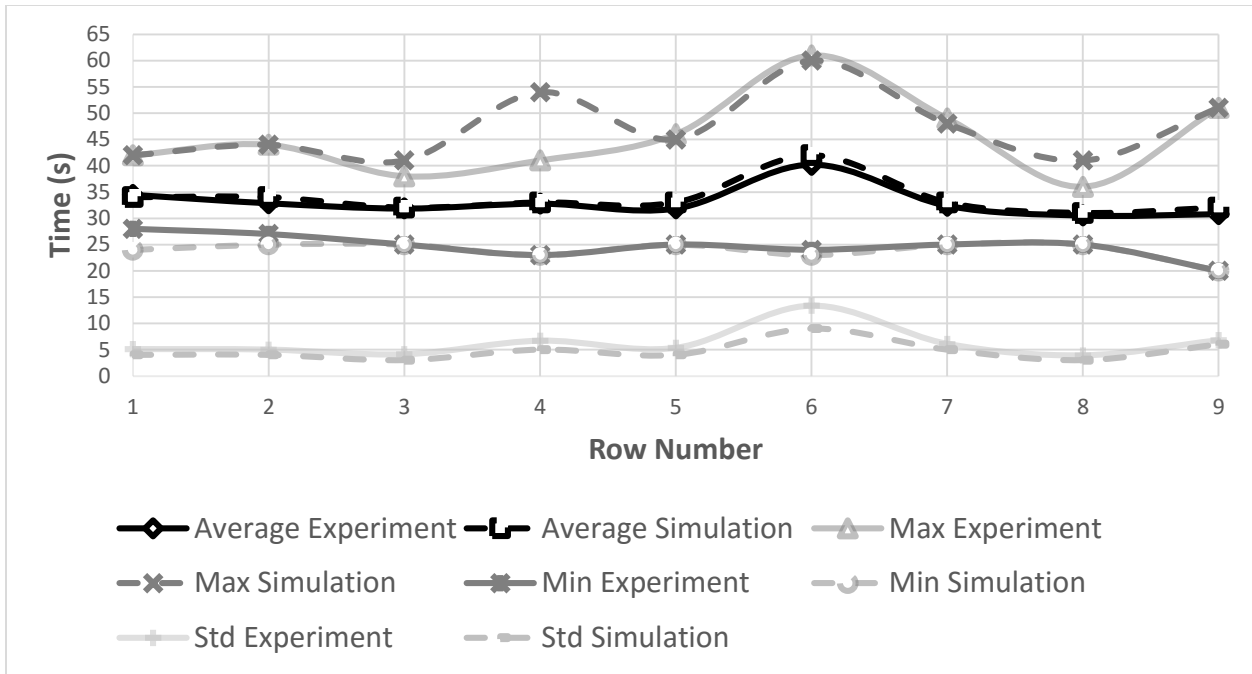


Figure 22 Pre-Evacuation Time for Scenario A in Validation Test 2

Figure 23 shows the comparison between the benchmark test values and the results of the simulation test for each row in Scenario B.

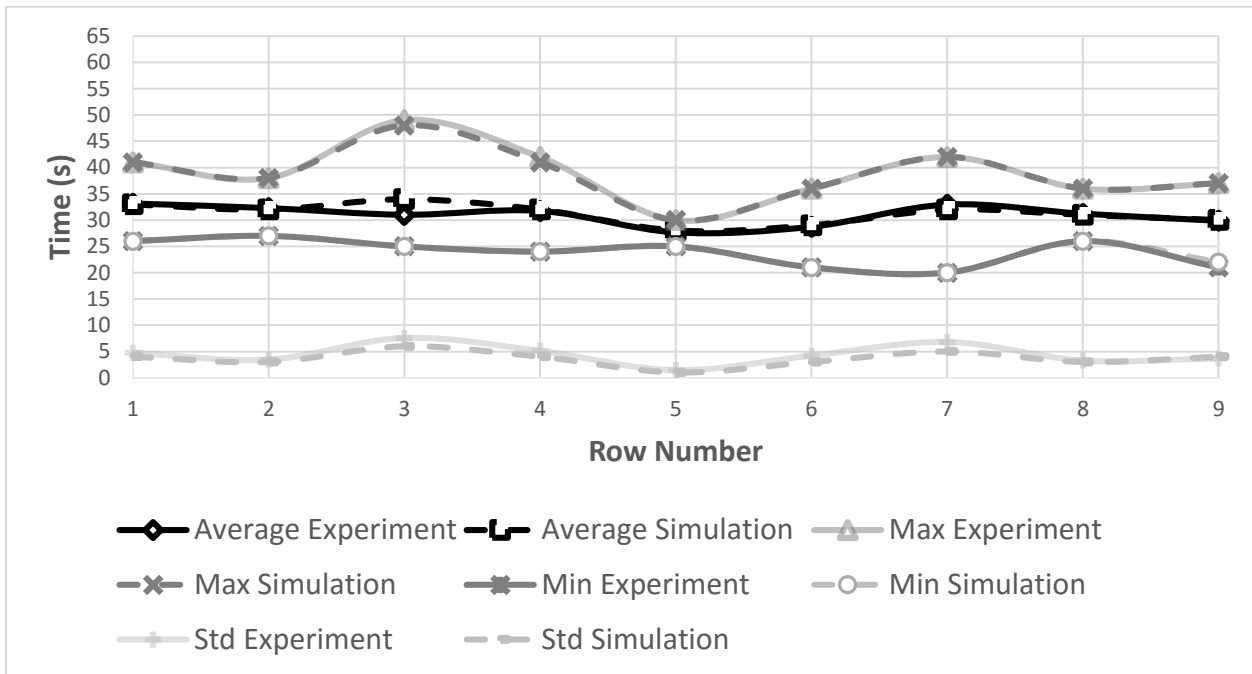


Figure 23 Pre-Evacuation Time for Scenario B in Validation Test 2

4.2.3 Analysis

Scenario A and Scenario B showed that MassMotion is capable of reasonably representing the experimental values of pre-evacuation times. The percentage of differences between benchmark experiment values and simulation test was from 0% to 5%. It is shown that that difference in standard deviation between experimental and simulation result in Scenario A was 27% (See Table B 1 and Table B 2 in Appendix B).

A qualitative comparison between the simulation test and the benchmark experiment shows that MassMotion was able to represent the location of agents during the simulation of the evacuation (See Figure 24). However, a qualitative evaluation of the graphic output of the model shows that the level of crowdedness is higher on the right side of the cinema theatre. This can be related to the default walking speeds that were assigned by the model and the width associated with each passage where it is narrower at the left side of the cinema.

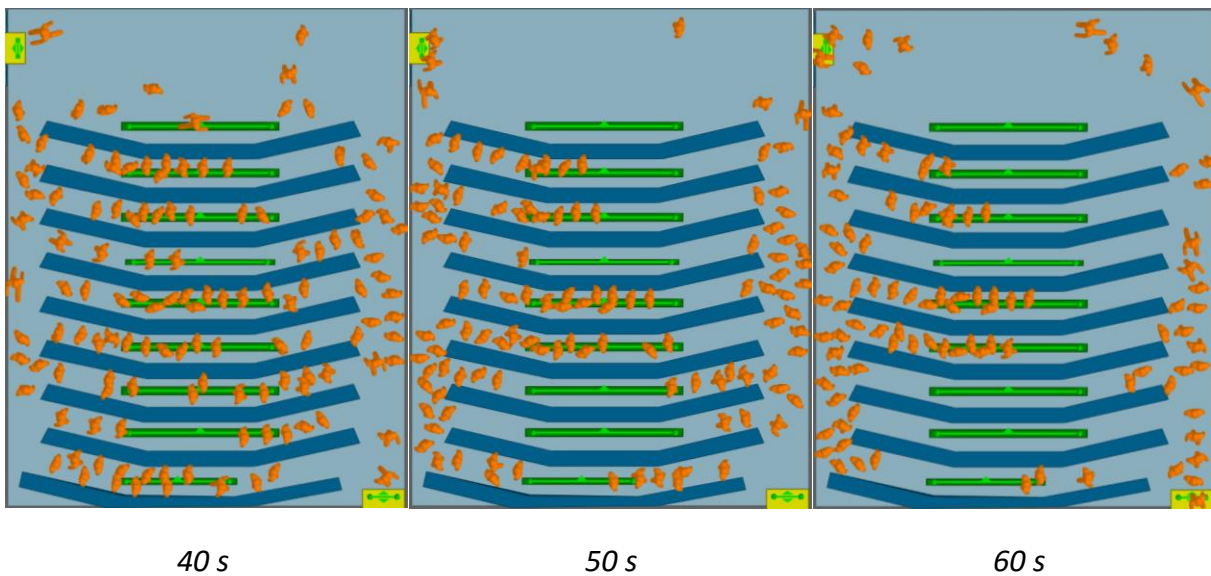


Figure 24 Representation of agents' locations (Scenario A) in the MassMotion Simulations.

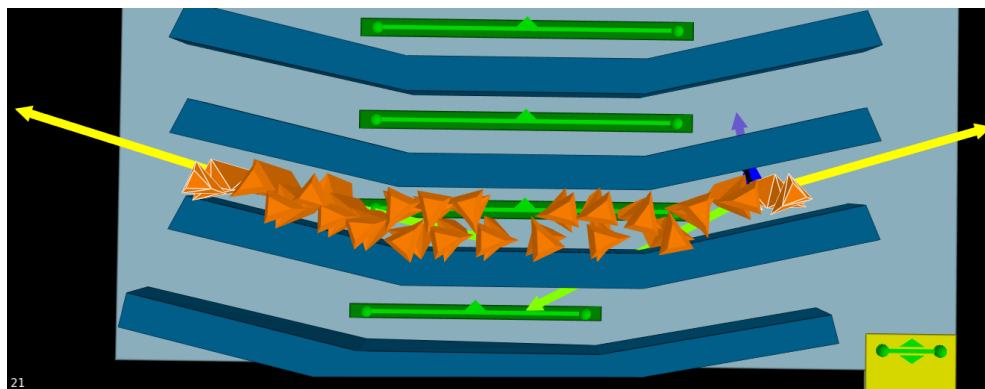


Figure 25 Stuck Agents in Scenario A of Validation Test 2

Figure 25 shows a phenomenon that may occur in force-based continuous models where agents can get stuck in narrow places due to the effect of the forces they are subjected to. As shown in the example in Figure 25, the social forces acting on the agent on the left are equal, and the agent remains stuck, and it shakes in the same location rather than moving. The same behaviour happens for the agent on the right of the same figure. Figure 26 shows the reason behind this issue in continuous models.



Figure 26 Obstacle Map for the Cinema Theatre

Agents get stuck because they cannot negotiate their route with other agents in a narrow area, where all of the agents can be seen shaking (shuffling) in the same position. This can be solved by widening the walkable area between the obstacles, or reducing the body size of the agents.

4.3 Validation Test 3: Stair Merging

This validation experiment was done to examine the merging ratio that MassMotion gives in stair merging. Data experiment was based on an experiment that was done in Japan by Hokugo (Hokugo et al., 1985). The experiment is described in the Section 3.3.3. Another set of tests was performed which was based on the data of Sano et al. (2015). The tests were Scenario 6, 7 and 8. The tests were based on the results of a different evacuation model. (See Section 3.3.3)

Since walking speeds were not provided, only default settings were used as input settings for their configuration. The total tests were nine scenarios including scenario 9 where Fruin's density correlations were deactivated (Fruin, 1971) (See Section 3.3.3).

4.3.1 Simulation Description

In order to simulate all the scenarios, four main geometries had been created. The main geometry which was used in the first five scenarios is shown in Figure 27.

The other scenarios' geometry is shown in Figure C 1, Figure C 2, Figure C 3, Figure C 4 and Figure C 5 in Appendix C. Agents were spawning from two portals. The first portal is the corridor

and the second portal is the portal from the top floor. Corridor portal was created as the width of the corridor which is 1.3 m. Top and bottom portals were created as the stairs width which is 1.2 m.

The number of agents represented in every scenario was kept the same. 85 agents spawned from the corridor portal and 67 agents spawned from the top floor. All agents had the same characteristics except for walking speeds which were assigned by MassMotion with default settings.

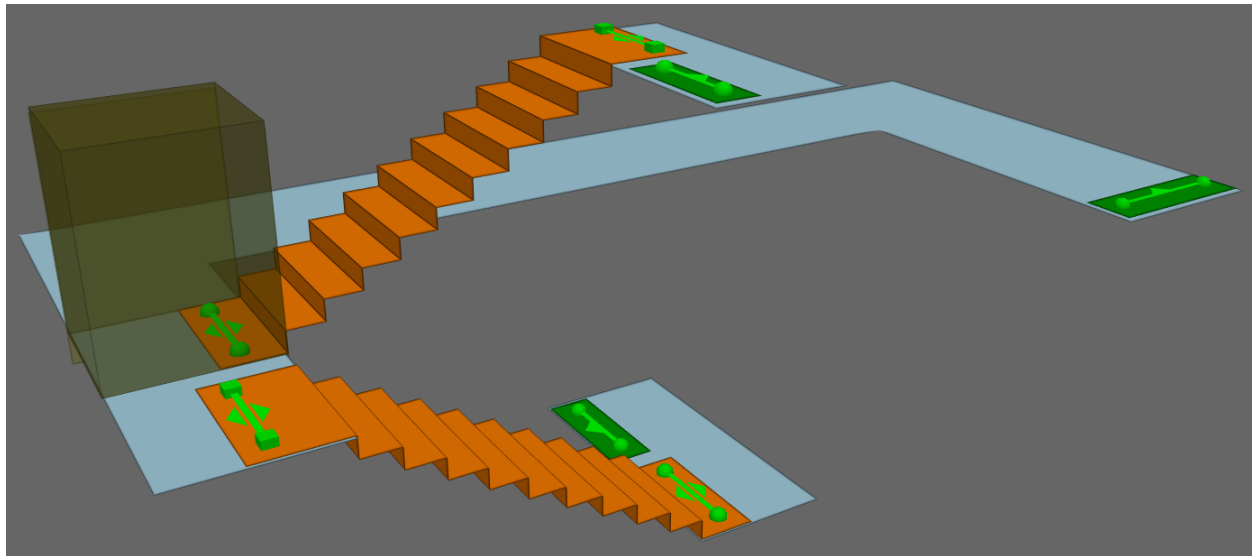


Figure 27 Layout of the MassMotion simulation that was used in scenarios 1-3 of Hokugo et al. experiments (Hokugo et al., 1985)

MassMotion does not have the functionality of representing the handrails of the stairs explicitly. Other settings of the stair components were kept on default settings.

Two analysis cordons were created to measure the flow rate of agents just before they enter the merging area. These cordons count every agent who passes by every second which is the same way that the experiment data was measured. In the experiment, the flow rate was categorized in three different stages which are the first stage, stable stage, and final stage. The same method was followed in analyzing the simulation data. Also, flow rates were translated into specific flow rates which corresponds to the division of flow rate by the width of the corridor or the width of the stairs.

An analysis region was also created at the merging ratio area to measure the density every second as the experiment was done. The method was to count the people in that area every second and get a mean value for the three different stages as well.

The calculation of merging rate was done as in the experiment. The merging ratio is calculated according to the corridor against the upper floor agents. The following equation was used to calculate the merging ratio:

$$\text{Merging Ratio} = \frac{\text{Flow of Corridor}}{\text{Flow of Corridor} + \text{Flow of Top Floor}} \quad \text{Equation 9}$$

The interest in both the experiment and the simulation was the stable stage since flows from both sides became stable and therefore the merging ratio could be evaluated at that stage. The merging ratio from other stages was used to compare the ability of MassMotion to simulate the transition phase of merging behaviour of the experiment.

A total of nine scenarios were done. The first five scenarios corresponded to the scenarios in Hokugo experiment (Hokugo et al., 1985) (See Section 3.3). Scenario 6-8 were following the modifications described in the paper by Sano et al. (2015). Scenario 9 was the same as scenario 3 in which agents came at the same time to the merging point with one exception. This scenario was conducted to check the simulated merging ratio if Fruin’s density reduction was deactivated. Deactivation of Fruin’s density factor was done by changing the command line concerning Fruin’s density reduction in the input file with an extension of .mm associated with the model. The line that was changed was:

```
<AttrSettingsMovementStandard>
  <Data>
    <EnumString v="MovementStandardFruin" t="3" />
    <EnumValue v="1" t="1" />
  </Data>
<Type v="DataTypeEnum" t="3" />
```

To deactivate Fruin’s density reduction, “MovementStandardFruin” has to be replaced with “MovementStandardNone”.

The results of the simulation were matched with the results of the experiment in which charts of the results were created to compare density of the merging area, flow rates in corridor and stairs, and the total time in which the simulation was finished.

4.3.2 Results

Table 13 shows the merging ratios of all the scenarios that were simulated. Difference between progressive averages to obtain the flow rates for all scenarios is shown in Figure C 6 in Appendix C.

Table 13 Averaged Flow Rates and Merging Ratio of all Scenarios

Stage	N	Corridor Flow		Stairs Flow		Sum Flow		Merging Ratio	
		Flow (p/s)	Specific Flow (p/s/m)	Flow (p/s)	Specific Flow (p/s/m)	Flow (p/s)	Specific Flow (p/s/m)	Flow (%)	Specific Flow (%)
First Stage	1	0.82	0.63	0.95	0.79	1.77	1.42	46.51%	44.53%
	2	1.00	0.77	0.67	0.56	1.67	1.33	60.06%	58.13%
	3	0.78	0.60	0.85	0.71	1.63	1.31	48.06%	46.07%
	4	0.48	0.48	0.85	0.70	1.32	1.18	36.02%	40.32%
	5	0.63	0.63	0.81	0.68	1.44	1.30	43.52%	48.04%
	6	0.54	0.54	0.87	0.72	1.41	1.27	38.57%	42.97%
	7	0.53	0.53	0.75	0.58	1.28	1.11	41.36%	47.83%
	8	0.65	0.65	0.67	0.51	1.31	1.16	49.19%	55.72%
	9*	1.48	1.14	1.46	1.22	2.94	2.36	50.28%	48.28%
Stable Stage	1	0.83	0.64	0.40	0.33	1.23	0.98	67.44%	65.66%
	2	0.83	0.64	0.54	0.45	1.36	1.08	60.54%	58.61%
	3	0.90	0.69	0.44	0.37	1.34	1.06	66.96%	65.16%
	4	0.73	0.73	0.53	0.45	1.26	1.17	57.59%	61.97%
	5	0.72	0.72	0.55	0.45	1.27	1.18	56.93%	61.33%
	6	0.66	0.66	0.56	0.47	1.23	1.13	54.03%	58.51%
	7	0.70	0.70	0.58	0.45	1.28	1.15	54.36%	60.76%
	8	0.57	0.57	0.70	0.54	1.27	1.11	44.98%	51.52%
	9*	1.23	0.94	0.94	0.78	2.17	1.73	56.58%	54.61%
Final Stage	1	0.65	0.50	0.23	0.19	0.88	0.69	73.89%	72.31%
	2	0.46	0.35	0.76	0.63	1.22	0.99	37.73%	35.87%
	3	0.53	0.41	0.65	0.54	1.18	0.95	44.82%	42.85%
	4	0.59	0.59	0.33	0.28	0.93	0.87	64.28%	68.35%
	5	0.41	0.41	0.33	0.27	0.74	0.69	55.95%	60.38%
	6	0.72	0.72	0.19	0.16	0.91	0.88	79.04%	81.91%
	7	0.65	0.65	0.28	0.22	0.94	0.87	69.77%	75.01%
	8	0.86	0.86	0.31	0.24	1.18	1.10	73.55%	78.33%
	9*	0.75	0.57	0.39	0.33	1.14	0.90	65.38%	63.55%

4.3.3 Analysis

Table 13 shows that merging ratios varied between 51% and 65% at the stable stage depending on the specific flows. Therefore, it can be concluded that the merging ratio of MassMotion varies in that region.

MassMotion can generate an instantaneous density map where critical areas can be spotted. Figure 28 shows the instantaneous density at different times of scenario 3. Red areas show the denser areas where blue has the least density.

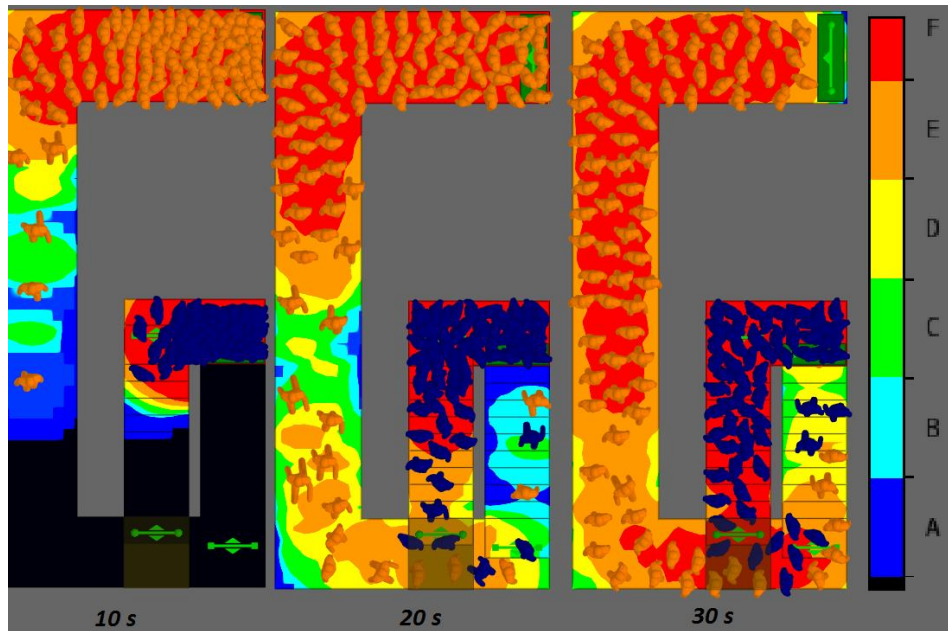


Figure 28 Instantaneous density map of Scenario 3 of stair merging test

Another set of maps can be created to examine the overall average density. Figure 29 shows the average density of the stairs. These maps are better to identify and interpret the critical areas (as can be seen in Figure 29 the critical areas were mostly the merging areas).

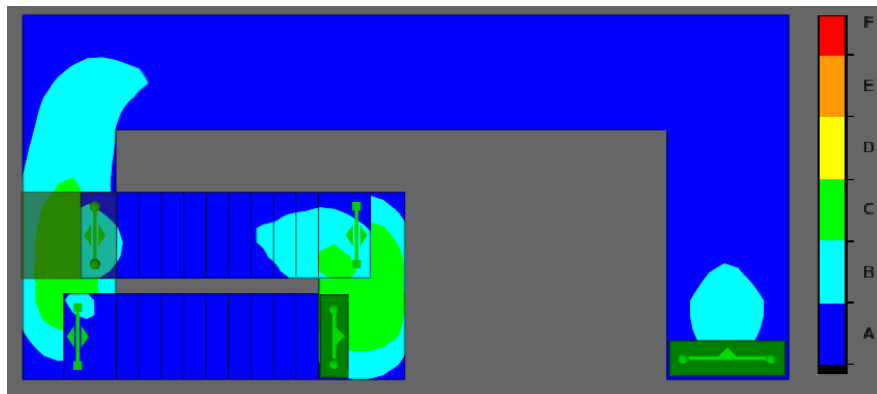


Figure 29 Average Density Map of Scenario 3 for Validation Test 3

4.3.3.1 Scenario 1

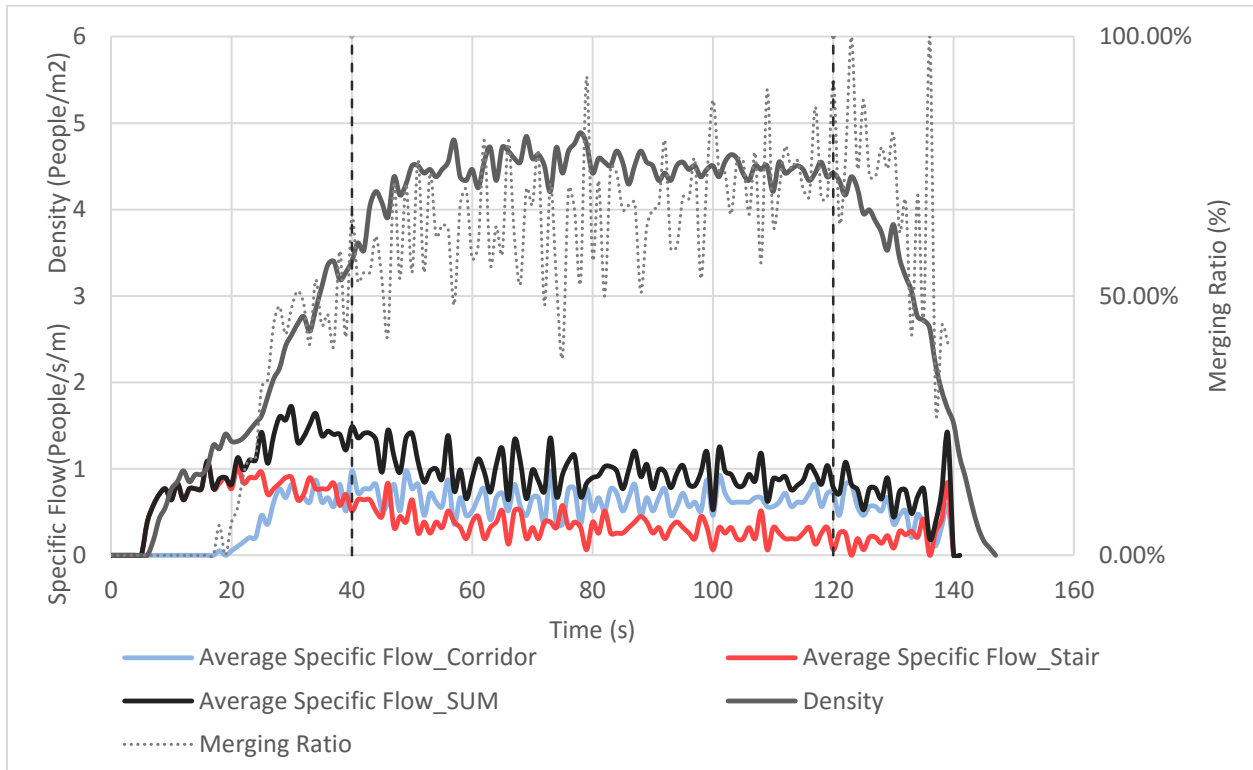


Figure 30 Merging Stairs Simulation for Scenario 1 for Validation Test 3 (Refer to Equation 9)

The average merging ratio at the point area of merging was approximately 65.66% at the stable stage (See

Table 13). The experimental specific flow for scenario 1 is 47.30% (See Table C 1 in Appendix C). The instantaneous merging ratio varied between 50% and 75%. It should be noted that merging ratio started from 0% which is expected since the agents in the upper floor started flowing through the merging area first. Density was stabilized after the steady stage in between 4 and 5 agents/m² (See Figure 30).

The average specific flow of the upper floor was approximately 0.33 agents/s/m, where the average specific flow of the corridor was approximately 0.63 agents/s/m (See

Table 13). The experimental values were 0.88 occupants/s/m and 0.79 occupants/s/m relatively (See Table C 1 in Appendix C). The instantaneous average flow of upper floor varied between 0.2 agents/s/m and 0.9 agents/s/m. The instantaneous average flow of the corridor varied between 0.35 agents/s/m and 0.95 agents/s/m (See Figure 30).

4.3.3.2 Scenario 2

The average merging ratio at the point area of merging was approximately 58.61% at the stable stage (See

Table 13). The experimental specific flow for scenario 2 is 51.30% (See Table C 1 in Appendix C). The instantaneous merging ratio varied between 30% and 80%. It should be noted that merging ratio started from 100% which is expected since the agents in the corridor started flowing through the merging area first. Density was stabilized after the steady stage in between 4 and 5 agents/m², however, density started from 2 agents/m² and then started to increase (See Figure 31).

The average specific flow of the upper floor was approximately 0.45 agents/s/m, where the average specific flow of the corridor was approximately 0.64 agents/s/m (See

Table 13). The experimental values were 0.78 occupants/s/m and 0.82 occupants/s/m relatively (See Table C 1 in Appendix C). The instantaneous average flow of upper floor varied between 0.2 agents/s/m and 0.9 agents/s/m. The instantaneous average flow of the corridor varied between 0.3 agents/s/m and 1.15 agents/s/m (See Figure 31).

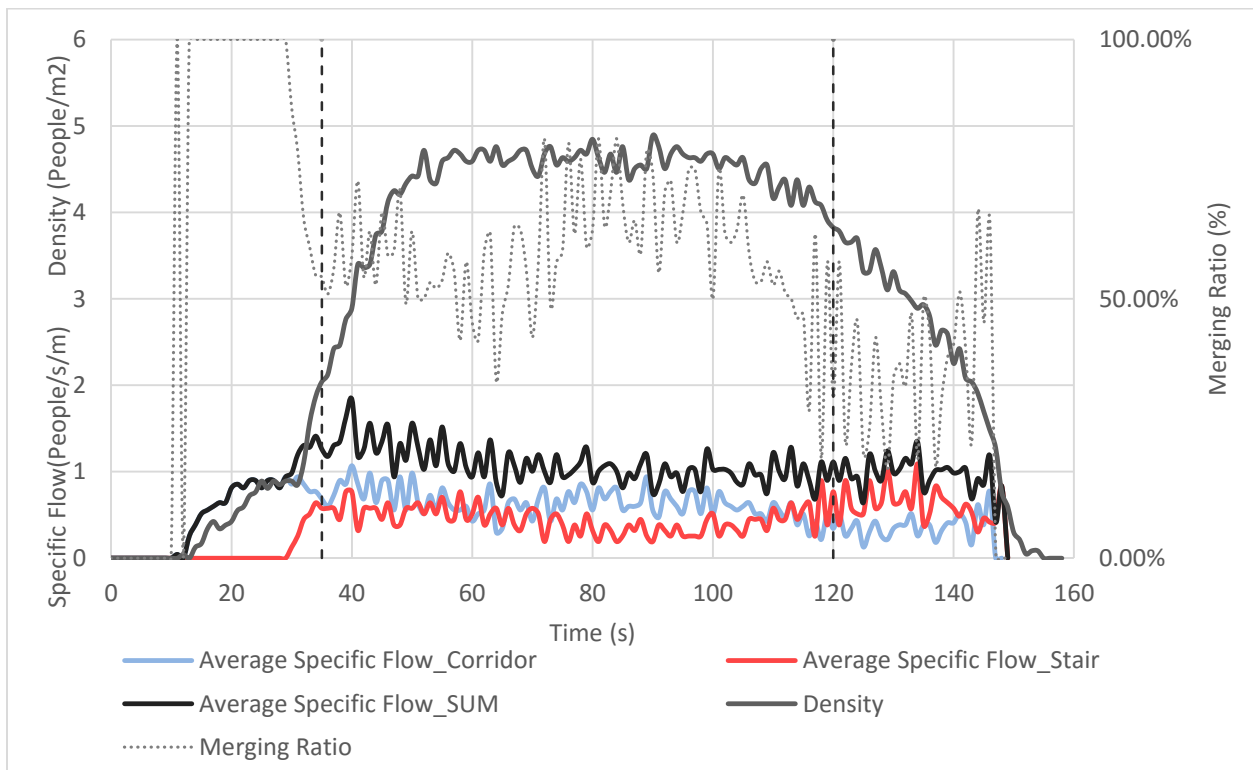


Figure 31 Merging Stairs Simulation for Scenario 2 for Validation Test 3

4.3.3.3 Scenario 3

Scenario 3 has different settings where agents from both portals merge at the merging point at the same time. The average merging ratio at the point area of merging was approximately 65.16% at the stable stage (See

Table 13). The experimental specific flow for scenario 3 is 59.60% (See Table C 1 in Appendix C). The instantaneous merging ratio varied between 50% and 90%. Density was stabilized after the steady stage in between 4 and 5 agents/m², however, density started from 3 agents/m² and then started to increase (See Figure 32).

The average specific flow of the upper floor was approximately 0.37 agents/s/m, where the average specific flow of the corridor was approximately 0.69 agents/s/m (See

Table 13). The experimental values were 0.63 occupants/s/m and 0.93 occupants/s/m relatively (See Table C 1 in Appendix C). The instantaneous average flow of upper floor varied between 0.0 agents/s/m and 0.80 agents/s/m. The instantaneous average flow of the corridor varied between 0.45 agents/s/m and 1.1 agents/s/m (See Figure 32).

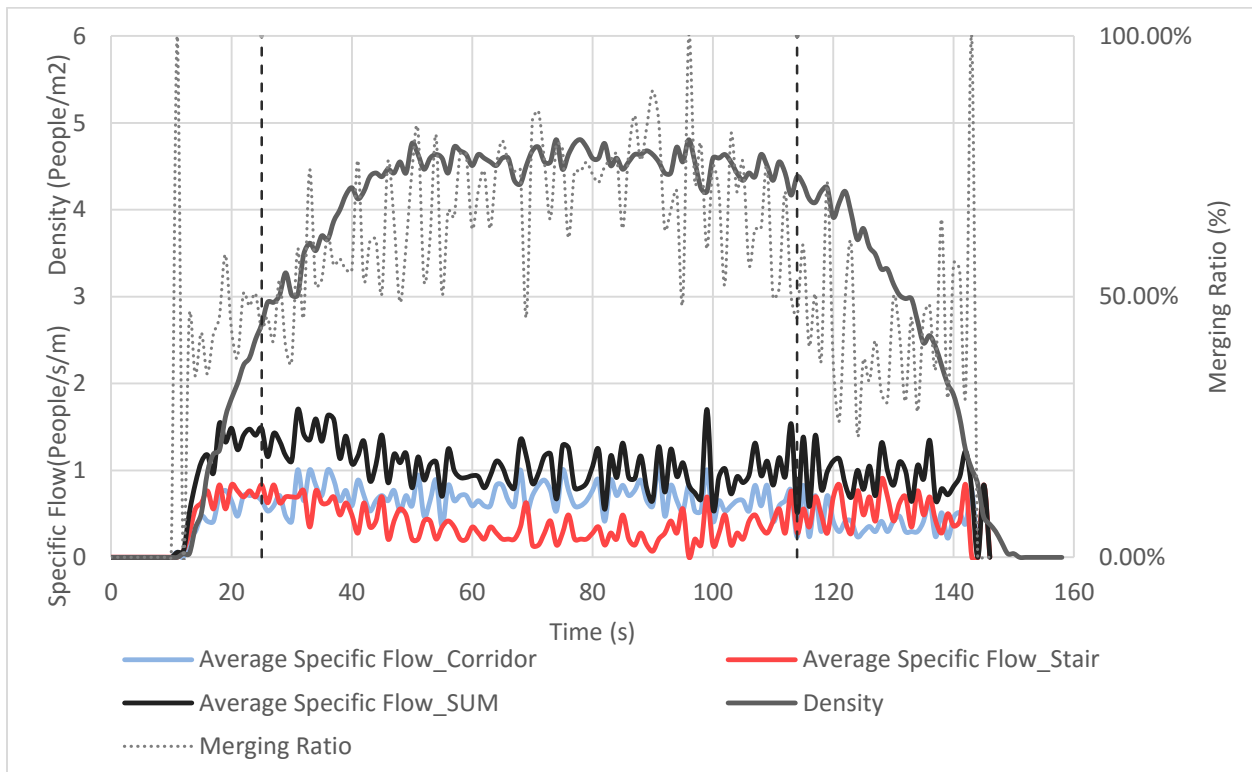


Figure 32 Merging Stairs Simulation for Scenario 3 for Validation Test 3

4.3.3.4 Scenario 4

In Scenario 4, agents also arrive at the same time however, the corridor width is reduced to be 1 m (See Figure 11). The average merging ratio at the point area of merging was approximately 61.97% at the stable stage (See

Table 13). The experimental specific flow for scenario 4 is 62.30% (See Table C 1 in Appendix C). The instantaneous merging ratio varied between 45% and 85%. Density was stabilized after the steady stage to be approximately 4 agents/m², however, density started from 2 agents/m² and then started to increase (See Figure 33).

The average specific flow of the upper floor was approximately 0.45 agents/s/m, where the average specific flow of the corridor was approximately 0.73 agents/s/m (See

Table 13). The experimental values were 0.63 occupants/s/m and 1.04 occupants/s/m relatively (See Table C 1). The instantaneous average flow of upper floor varied between 0.17 agents/s/m and 0.83 agents/s/m. The instantaneous average flow of the corridor varied between 0.45 agents/s/m and 1.2 agents/s/m (See Figure 33).

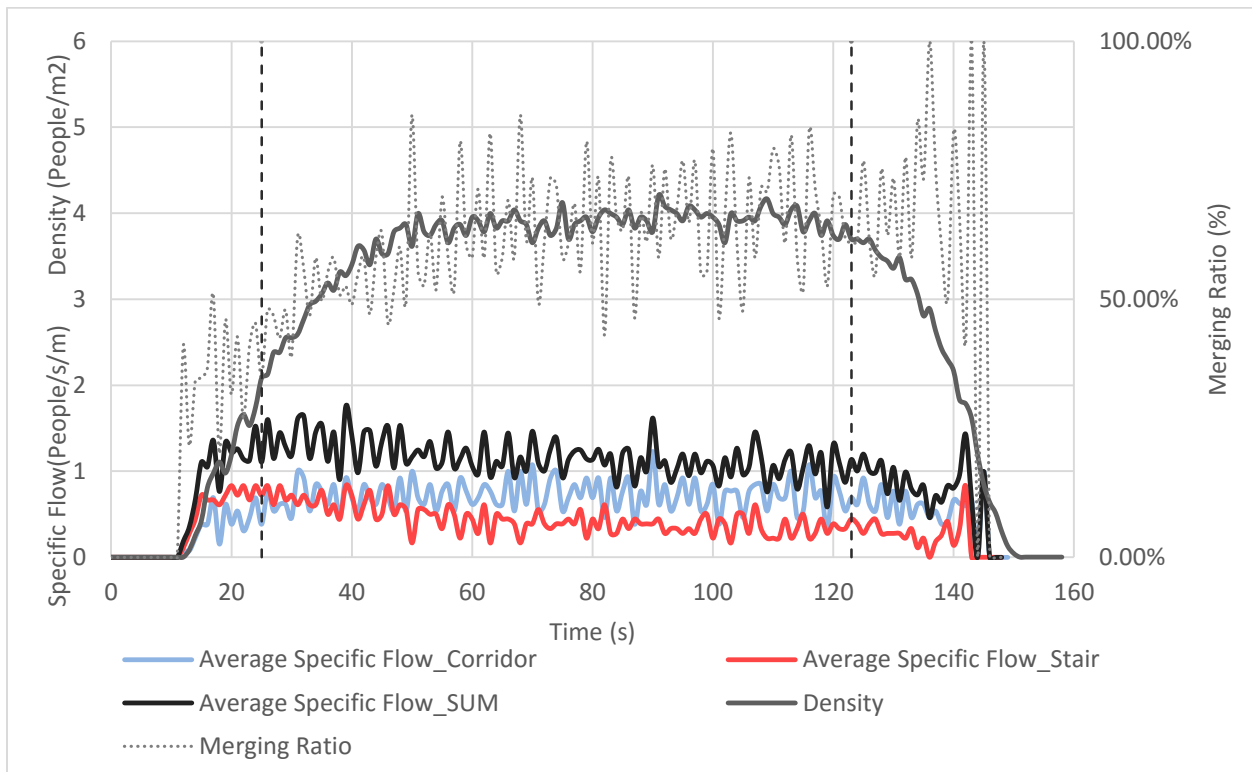


Figure 33 Merging Stairs Simulation for Scenario 4 for Validation Test 3

4.3.3.5 Scenario 5

In Scenario 5, agents also arrive at the same time however, the corridor width is reduced to be 1 m (See Figure 11). The average merging ratio at the point area of merging was approximately 61.33% at the stable stage (See

Table 13). The experimental specific flow for scenario 5 is 59.90% (See Table C 1 in Appendix C). The instantaneous merging ratio varied between 45% and 87%. Density was stabilized after the steady stage in between 4 and 5 agents/m², however, density started from 2 agents/m² and then started to increase (See Figure 34).

The average specific flow of the upper floor was approximately 0.45 agents/s/m, where the average specific flow of the corridor was approximately 0.72 agents/s/m (See

Table 13). The experimental values were 0.61 occupants/s/m and 0.91 occupants/s/m relatively (See Table C 1). The instantaneous average flow of upper floor varied between 0.2 agents/s/m and 1.00 agents/s/m. The instantaneous average flow of the corridor varied between 0.50 agents/s/m and 1.15 agents/s/m (See Figure 34).

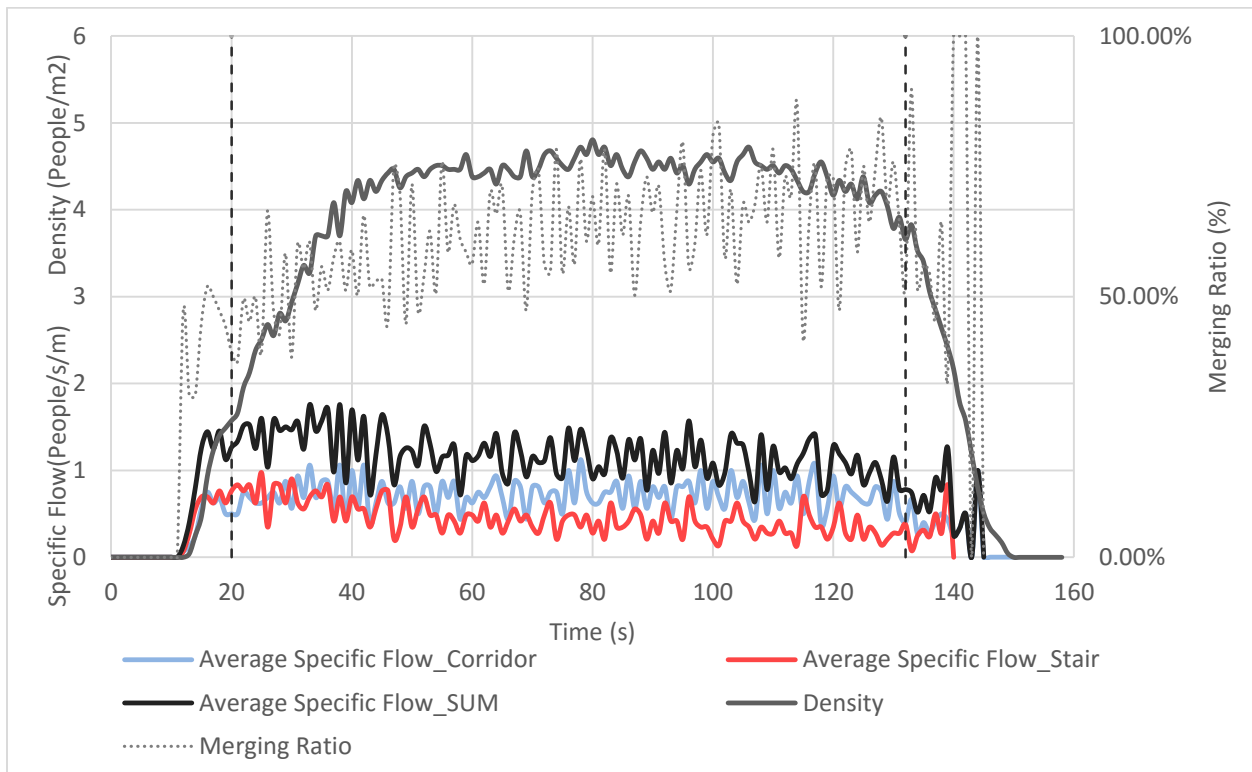


Figure 34 Merging Stairs Simulation for Scenario 5 for Validation Test 3

4.3.3.6 Scenario 6

In Scenario 6, agents also arrive at the same time however, the entrance of the corridor was changed. The width of the entrance is 1 m (See Figure 12). The average merging ratio at the point area of merging is 58.51% at the stable stage (See

Table 13). The experimental specific flow for scenario 6 is 48.00% (See Table C 1 in Appendix C). The instantaneous merging ratio varied between 30% and 85%. Density was stabilized after the steady stage in between 3.5 and 4 agents/m², however, density started from 2 agents/m² and then started to increase (See Figure 35).

The average specific flow of the upper floor was approximately 0.47 agents/s/m, where the average specific flow of the corridor was approximately 0.66 agents/s/m (See

Table 13). The experimental values were 1.18 occupants/s/m and 0.79 occupants/s/m relatively (See Table C 1). The instantaneous average flow of upper floor varied between 0.11 agents/s/m and 1.00 agents/s/m. The instantaneous average flow of the corridor varied between 0.40 agents/s/m and 1.25agents/s/m (See Figure 35).

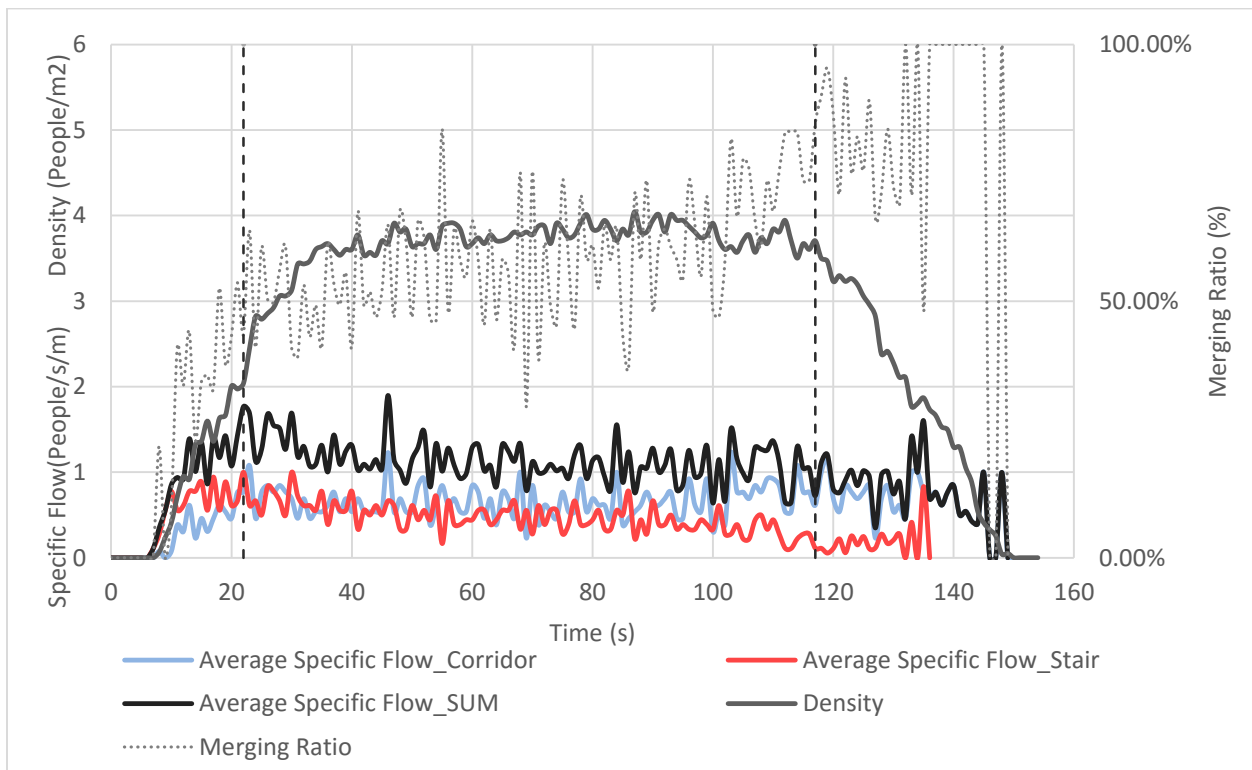


Figure 35 Merging Stairs Simulation for Scenario 6 for Validation Test 3

4.3.3.7 Scenario 7

In Scenario 7, agents also arrive at the same time, however, the entrance of the corridor was changed. The width of the entrance is 1 m (See Figure 13). The average merging ratio at the point area of merging is 60.76% at the stable stage (See

Table 13). The experimental specific flow for scenario 7 is 45.80% (See Table C 1 in Appendix C). The instantaneous merging ratio varied between 30% and 90%. Density was stabilized after the steady stage in between 4 and 4.5 agents/m². However, density started from 2 agents/m² and then started to increase (See Figure 36).

The average specific flow of the upper floor was approximately 0.45 agents/s/m, where the average specific flow of the corridor was approximately 0.70 agents/s/m (See

Table 13). The experimental values were 1.19 occupants/s/m and 0.76 occupants/s/m relatively (See Table C 1 in Appendix C). The instantaneous average flow of upper floor varied between 0.10 agents/s/m and 0.80 agents/s/m. The instantaneous average flow of the corridor varied between 0.20 agents/s/m and 1.4 agents/s/m (See Figure 36).

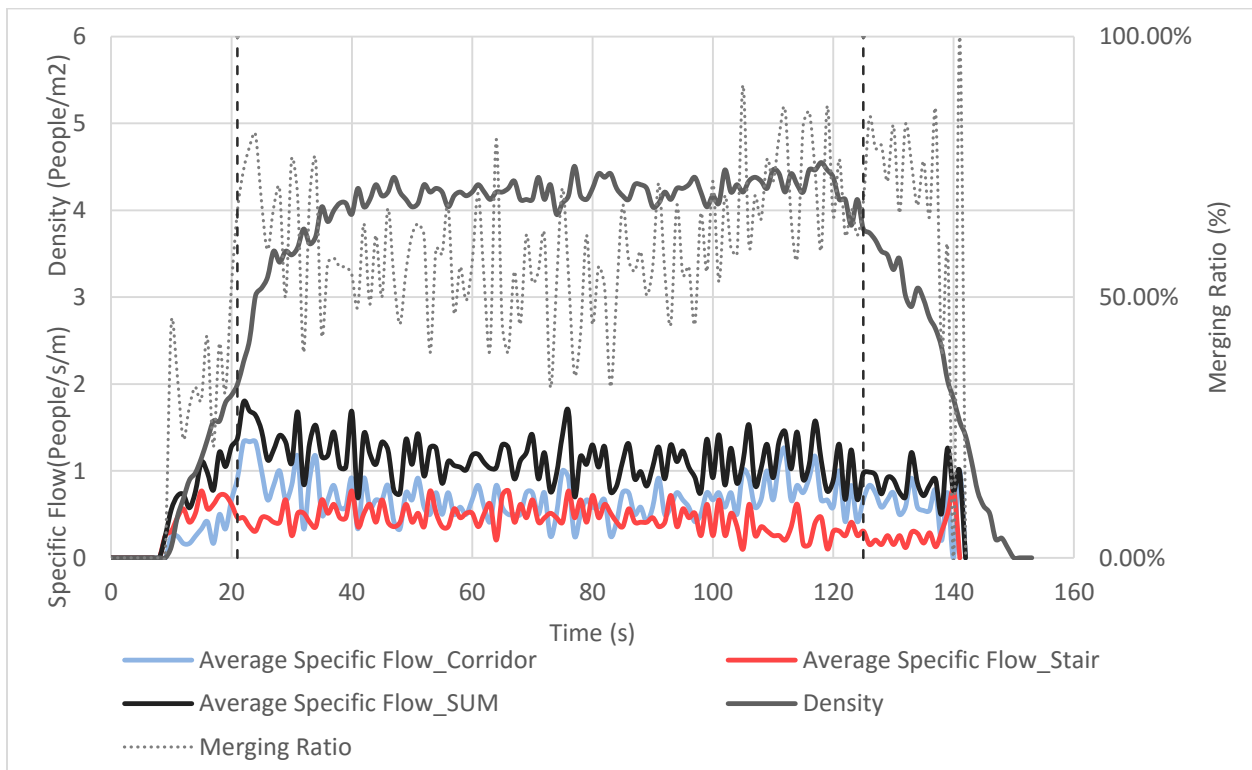


Figure 36 Merging Stairs Simulation for Scenario 7 for Validation Test 3

4.3.3.8 Scenario 8

In Scenario 8, agents also arrive at the same time, however, the entrance of the corridor was changed. The width of the entrance is 1 m (See Figure 14). The average merging ratio at the point area of merging was approximately 51.52% at the stable stage (See

Table 13). The experimental specific flow for scenario 4 is 38.60% (See Table C 1 in Appendix C). The instantaneous merging ratio varied between 25% and 70%. Density was stabilized after the steady stage in between 4.5 and 5.0 agents/m². However, density started from 3.5 agents/m² and then started to increase (See Figure 37).

The average specific flow of the upper floor was approximately 0.54 agents/s/m, where the average specific flow of the corridor was approximately 0.57 agents/s/m (See

Table 13). The experimental values were 1.2 occupants/s/m and 0.65 occupants/s/m relatively (See Table C 1 in Appendix C). The instantaneous average flow of upper floor varied between 0.20 agents/s/m and 0.85 agents/s/m. The instantaneous average flow of the corridor varied between 0.20 agents/s/m and 1.0 agents/s/m (See Figure 37).

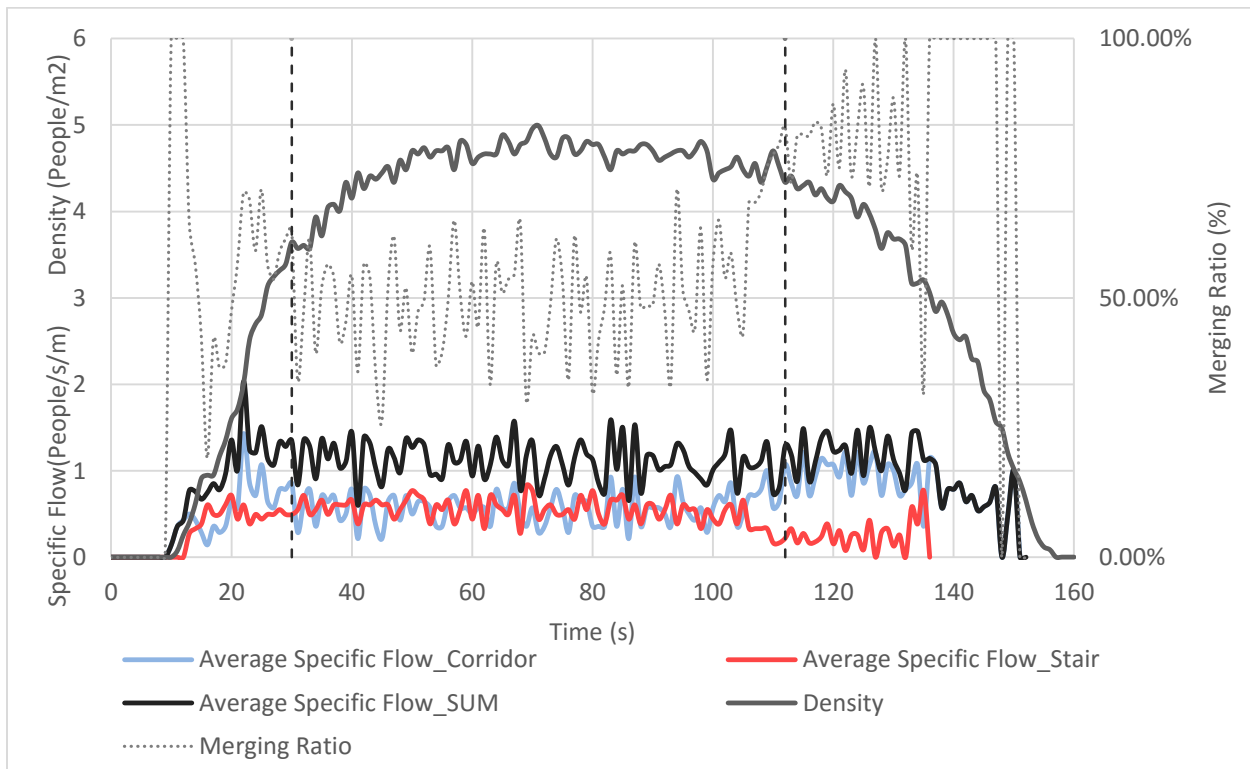


Figure 37 Merging Stairs Simulation for Scenario 8 for Validation Test 3

4.3.3.9 Scenario 9

Scenario 9 has the same geometry and settings as Scenario 3 except of one parameter which is Fruin's density correlation. Fruin's density correlation in Scenario 9 is deactivated (See

Section 3.3.3). The average merging ratio at the point area of merging was approximately 54.61% at the stable stage (See

Table 13). The simulation test specific flow for scenario 3 is higher by 10% which is 65.16% (See Table C 1 in Appendix C). The instantaneous merging ratio varied between 35% and 80%. Density was stabilized after the steady stage in between 4.0 and 5.0 agents/m². However, density started from 3 agents/m² and then started to increase (See Figure 38).

The flow rates, in general, were higher in Scenario 9 where the average specific flow of the upper floor was approximately 0.78 agents/s/m. And the average specific flow of the corridor was approximately 0.94 agents/s/m (See

Table 13). The simulation test values for scenario 3 are 0.37 occupants/s/m and 0.69 occupants/s/m relatively (See Table C 1 in Appendix C). The instantaneous average flow of upper floor varied between 0.25 agents/s/m and 1.6 agents/s/m. The instantaneous average flow of the corridor varied between 0.6 agents/s/m and 1.4 agents/s/m. Also, it should be noted that the average specific flow for both stair and corridor starts to be high and decrease with time. In addition, the total evacuation time was drastically less than the other scenarios (See Figure 38).

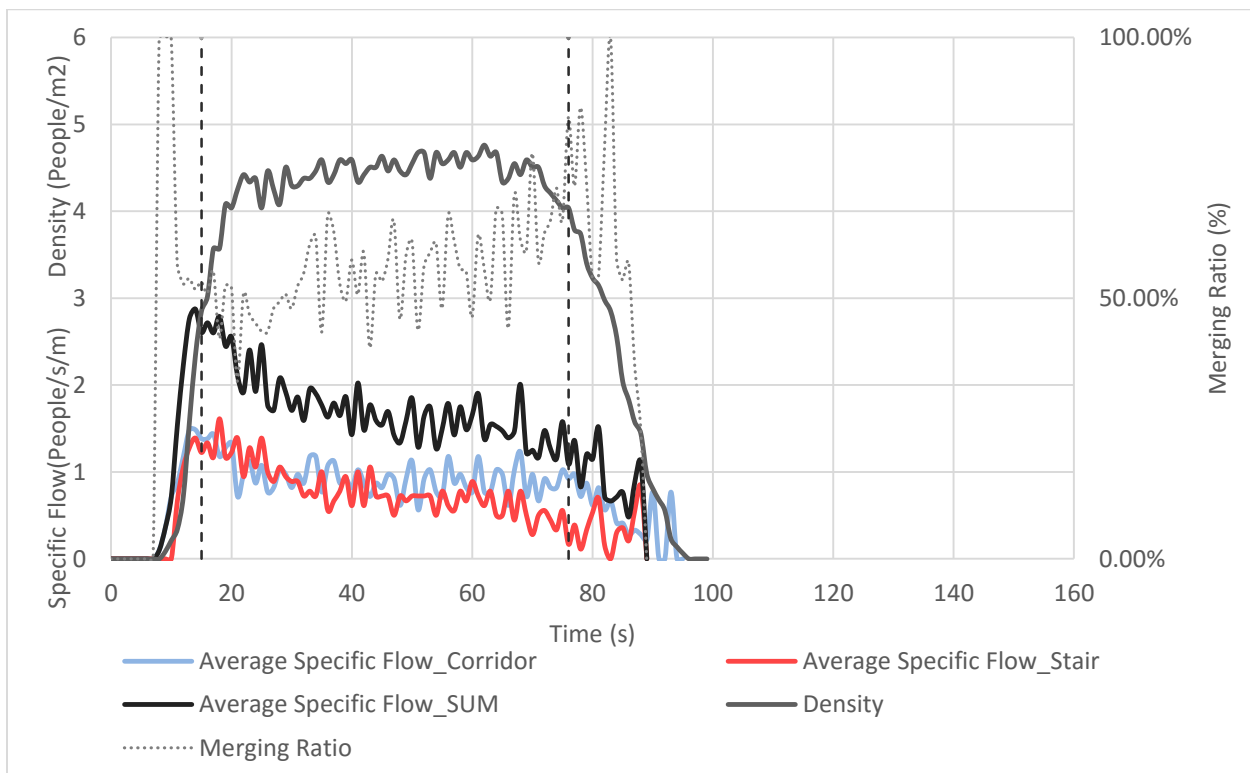


Figure 38 Merging Stairs Simulation for Scenario 9 for Validation Test 3

Table 14 A comparison between flow rates in Stair Merging Test for the stable stage

		Simulation		Experimental		Corridor Flow		Stairs Flow	
		Corridor Flow	Stairs Flow	Corridor Flow	Stairs Flow	Flow Difference (p/s)	Flow Difference (%)	Flow Difference (p/s)	Flow Difference (%)
		Flow (p/s)	Flow (p/s)	Flow (p/s)	Flow (p/s)				
Stable Stage	1	0.83	0.40	1.03	1.05	-0.20	21.21%	-0.65	89.27%
	2	0.83	0.54	1.06	0.94	-0.23	24.80%	-0.40	54.32%
	3	0.90	0.44	1.21	0.75	-0.31	29.66%	-0.31	51.49%
	4	0.73	0.53	1.04	0.75	-0.31	35.66%	-0.22	33.64%
	5	0.72	0.55	0.91	0.74	-0.19	23.12%	-0.19	30.21%
	9	1.23	0.94	1.21	0.75	0.02	1.33%	0.19	22.59%

A comparison of flow rates between simulation and experimental results is shown in Table 14. The corridor flow rate shows a difference of approximately 20% to 36%. On the other hand, the flow difference in the stairs is approximately 30% to 90%. Scenario 9 which had a deactivation of Fruin’s LOS functionality shows a difference in the flow rate of the corridor of approximately 1.5% and in the stairs of approximately 23%.

4.4 Uncertainty Analysis

This section addresses the uncertainties related to the validation tests conducted. The analysis is based on the four uncertainties that were mentioned in Section 2.4. A set of selected variables which might influence results to a larger extent were analyzed to test the sensitivity of results to selected model inputs.

4.4.1 Model Input Uncertainty

Uncertainties are introduced when assuming the input parameter of evacuation simulations. There are two groups of uncertainty related to this issue. The first group is related to the agents’ demographics such as walking speed, body size or gender. MassMotion does not have a library of occupants’ demographics (e.g. walking speed and age of agents), therefore an implicit sensitivity analysis about occupants’ demographics was performed. Walking speed and body size of the agents are analyzed in the sensitivity analysis in Section 4.4.1.1 and Section 4.4.1.2.

The other group of model input uncertainties is related to the geometry of the simulation test that was created in MassMotion. Despite that the experimental descriptions were detailed, there are in some instances possibilities for interpretations. For example, the size of the spawn and the exit areas, the location of the spawn and the exit areas, and the slope of floors. There is no sensitivity analysis regarding this point because the experimental layouts that were used had specific descriptions about the layout.

4.4.1.1 Walking Speeds

The stair merging test has been used, to perform an example analysis of the impact of walking speeds on model results. Walking speed's distributions which were assigned by MassMotion were decreased by 25%. For example, if the walking speed distribution is from 1.5 to 2 m/s then it is adjusted to 1.125 to 1.5 m/s. In addition, functional analysis methods were used to compare the total evacuation time. The scenario that was used is Scenario 3 where it is described in Section 3.3.3.

Table 15 Total Evacuation Time comparison between Reduced speeds scenario and Original Speeds scenario

Total Evacuation time Mean, Reduced Speeds (s)	Total Evacuation time Mean, Original speeds (s)	Time Difference (s)	Time Difference (%)	Number of Simulations, Reduced	Number of Simulations, Original
184.60	167.35	17.25	9.80%	25	20

Table 15 gives a comparison between reduced walking speeds and original walking speeds. The average total evacuation time increased from 165 s to 185 s, which is approximately 10 % increase. In addition, the average standard deviation of the average total evacuation times increased from 2.10 s to 2.65 s, which is approximately 22% increase.

In addition, a comparison between Figure 59 and Figure 39 shows that the results are not converging at the beginning of the simulation test in Figure 39, however, at the end of the simulation, there is a convergence in the results. A comparison between Figure 40 and Figure 60 shows that there is a higher behavioural uncertainty in the reduced speed scenario compared to the default speed scenario. However, the behavioural uncertainty is not major in the reduced speed scenario since most of the criteria converge quickly. Only SDj crossed the 5% criteria which is normal in the functional analysis for SDj to be a bit higher than the other criteria.

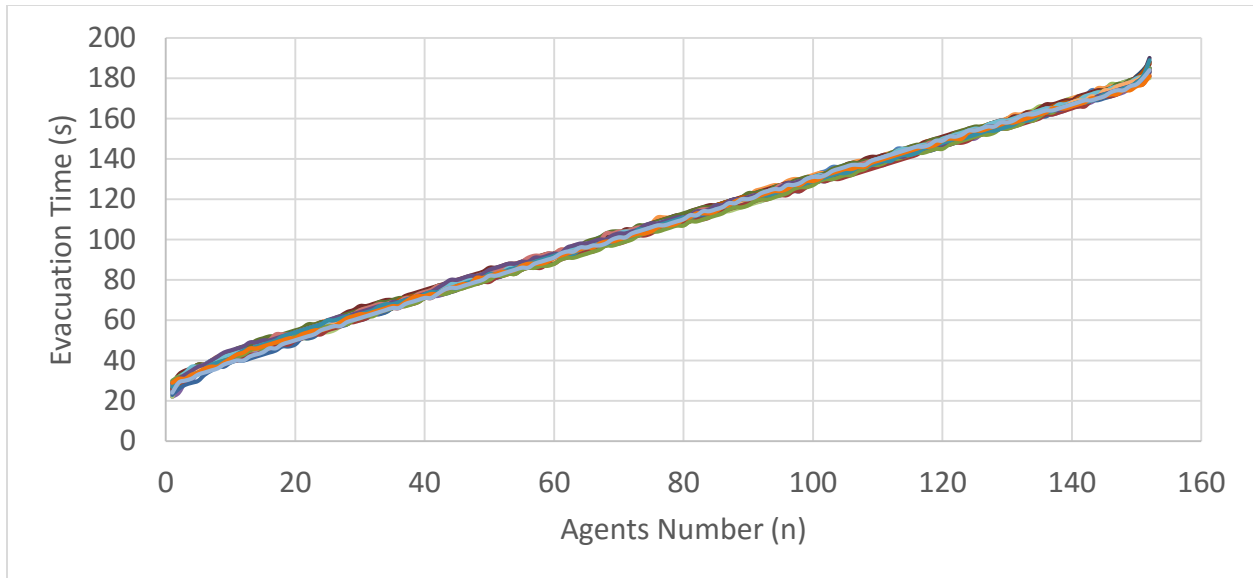


Figure 39 Total Arrival Times for Scenario 3 with Reduced Speeds for Validation Test 3

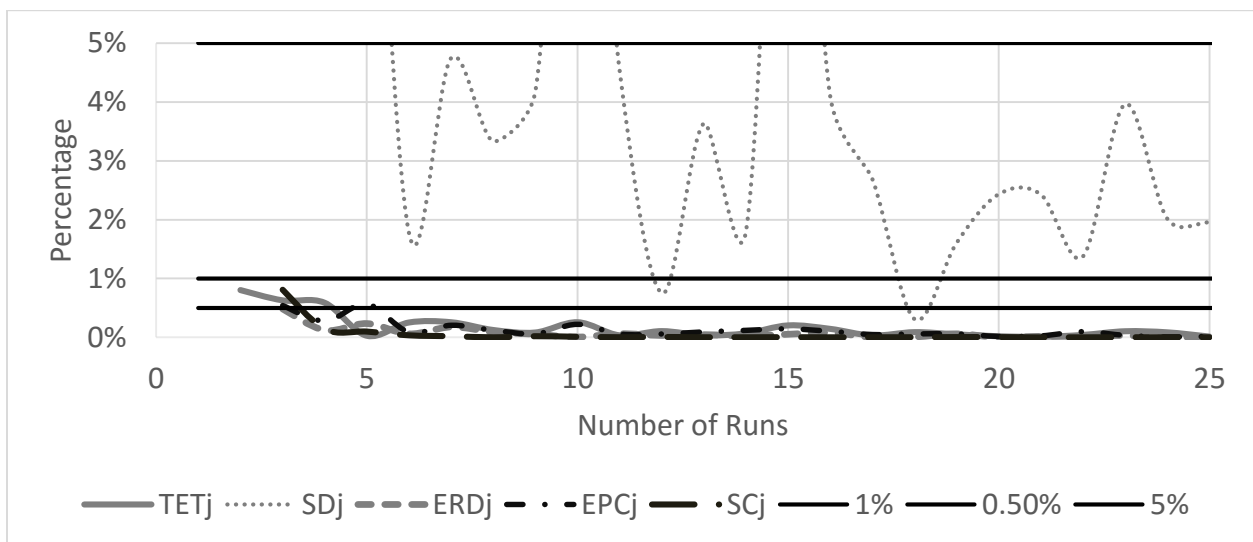


Figure 40 Functional Analysis Method for Stair Merging Test of Scenario 3 Reduced Speeds

4.4.1.2 Body Size

In this analysis, the impact of the body size on the results was examined. The used simulation test is the corridor test scenario B that was described in Section 3.3.1. Only specified input settings were used in this analysis.

The profiles in MassMotion are user-defined and therefore there is no default settings for different demographics of agents. The default body size in MassMotion is 0.25 m. This value was be decreased by 20% and the impact on the total arrival time was analyzed. The body size that is used in this test is 0.20 m. In addition, the flow rate of the opening and the density of

the two zones before the opening are analyzed. The convergence method that is used in analyzing walking speeds is based on functional analysis, while the analysis of flow rates and densities is based on progressive average values.

Table 16 Comparison between Reduced body size and Original body size in Scenario B

Total Arrival time Mean, Reduced body size (s)	Total Arrival time Mean, Original body size (s)	Time Difference (s)	Time Difference (%)	Number of Simulation, Reduced	Number of Simulations, Original
40.47	45.50	-5.03	11.70%	38	24

Table 16 shows that the average total arrival time for the reduced body size is decreased by 11.70% from 45.50 seconds to 40.47 seconds which is expected since smaller body sizes increase the flow of agents through the opening.

In addition, Table 17 shows the flow rates at the opening of the corridor, and the comparison to the original body size flow rate. The difference between the two flow rates was increased by 0.19 with a percentage of 15.84% from 1.11 p/s to 1.30 p/s.

Table 17 Reduced and original body size flow rate, Scenario B Specified Settings

Scenario	Reduced Body Size Flow Mean (p/s)	Original Body Size Flow Mean (p/s)	Flow Difference (p/s)	Flow Difference (%)	Number of Simulations
B Specified	1.30	1.11	0.19	15.84%	18

Table 18 Reduced and original body size density values at Zone 1 and Zone 2, Scenario B Specified Settings

Scenario	Zone	Reduced Body Size Density Mean (p/m²)	Original Body Size Density Mean (p/m²)	Density Difference (p/m²)	Density Difference (%)	Number of Simulations
B	1	2.27	1.95	0.32	15.22%	21
B	2	3.06	2.24	0.82	30.89%	21

The last output corresponds to the values of densities at the two zones before the opening. Table 18 shows the comparison between reduced body size and original body size density values at the two zones. It shows an increase of 15.22 % and 30.89% in zone 1 and zone 2 relatively. Zone 1 has a density value of 2.27 p/m² which is higher than the original value of 1.95

p/m^2 by 0.32. Zone 2 has a density value of $3.06 p/m^2$ which is higher than the original value of $2.24 p/m^2$ by 0.82. The increase in flow rates and density values are reasonable since body size of the agents got reduced.

Also, the functional analysis method was used to examine the impact on behavioural uncertainty when changing the body size. A comparison between Figure 41 and Figure 45 shows that the reduced body size scenario has less variance than the original body size scenario. Also, a comparison between Figure 42 and Figure 46 shows that the reduced body size scenario has larger behavioural uncertainty than the original body size. TETj crossed the 0.5% criterion many times before it converged. Also, SDj crossed the 5% criterion many times before it converged. Other criteria converged quickly under the 1% criterion.

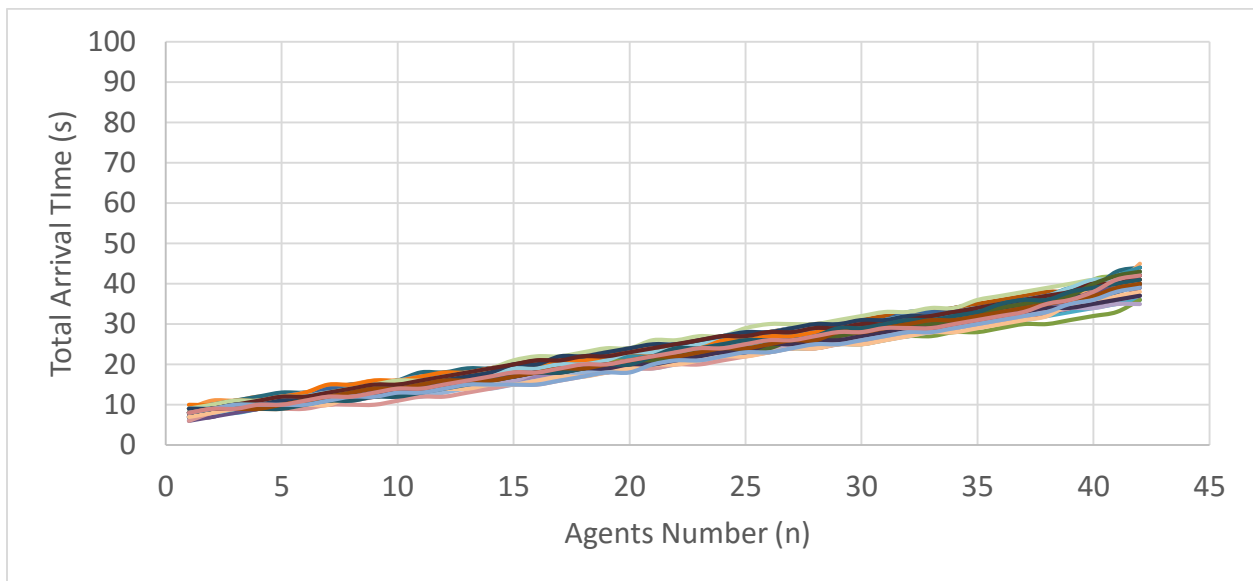


Figure 41 Total Arrival Times for Scenario B with Reduced Body Size for Validation Test 1

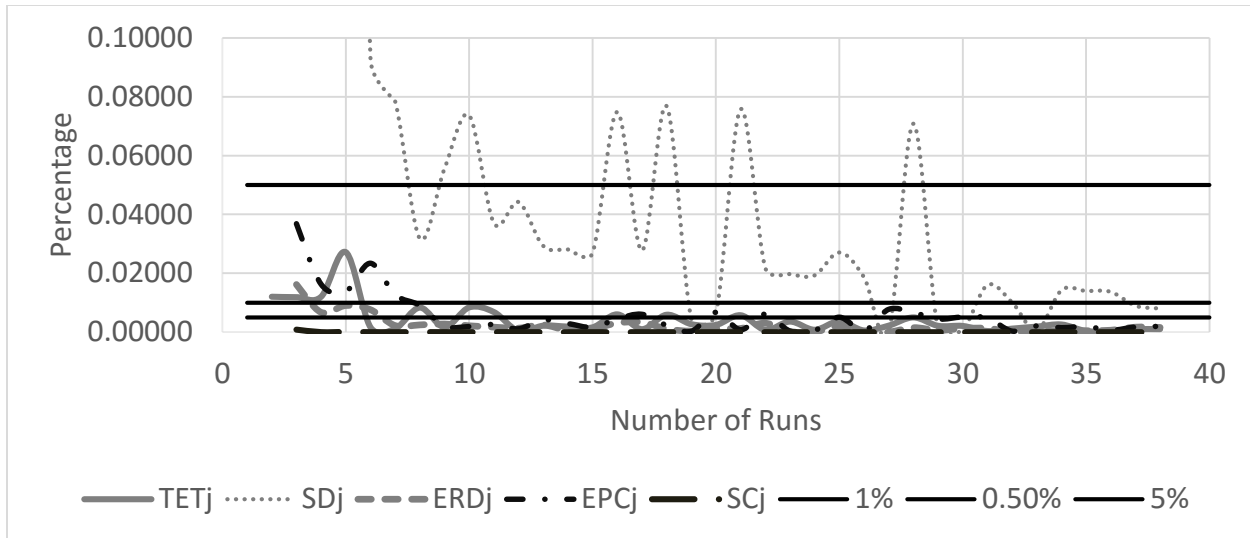


Figure 42 Functional Analysis Method for Corridor Test of Scenario B Specified Settings Reduced Body Size

4.4.2 Measurement Uncertainty

Numerous uncertainties are related to benchmark experiments such as the measurement method, the equipment, and the analysis of the results. Measurement method depends on the researchers that performed the experiments. Also, this will depend on the calibration of the equipment used in the experiment. In addition, the results that were taken from the experiments are generally interpreted and coded by the researchers themselves before getting published. Therefore the magnitude and the impact of these uncertainties are not elucidated, and it cannot be determined. However, the selected experiments provided a detailed documentation about the process and the equipment of performing the experiments. Therefore this is an attempt to reduce the uncertainties related to measurement in experiments.

An example of this uncertainty is the time interval that was used in the flow calculations of the corridor experiment. Also, the researchers of the corridor experiment were only interested in a steady flow. Thus the beginning and the end of the measurements were excluded in the experiment. Another assumption of these parameters would give a different flow rate. Consequently, when the same method is implemented in MassMotion, the chosen length of the time interval might lead to uncertainties in results. Different time intervals were used in the sensitivity analysis in Section 4.4.2.1 in order to examine the uncertainty regarding this subject.

Uncertainties can be also related to the information that were given to the participants before the experiment was performed. This will affect the behaviour of the participants if they were told about the objective of the experiment. For example, the participants might change their walking speeds if they were told that the objective of the experiment is to measure their

walking speeds. Therefore to minimize this uncertainty, experiments might be an informed or an uninformed. In addition, participants may alter their behaviour when performing several trials of the same type of experiment.

4.4.2.1 Time Intervals

The last sensitivity analysis is focused on the calculations of the flow rates at the corridor's opening. The simulation scenario to be used is Scenario B specified settings, which is the closest to the experimental value (See Section 4.1).

The experimental method that was used in Section 4.1 used the steady flow rate on a five seconds segment. To scrutinize the influence the time interval, an increase and a decrease of 10 seconds to the whole time interval is to be done. This value is to be distributed as a 5 seconds at the beginning and a 5 seconds at the end of the time interval. The original time interval is 10-40 seconds.

Table 19 shows the results of the time interval impact on the results. When the time interval increased by 10 seconds to be 5-45 seconds, the flow rate decreased by 0.13 to be 1.02 p/s with a percentage of 12.3%. On the other hand, when the time interval decreased by 10 seconds to be 15-35 seconds, the flow rate increased by 0.09 to be 1.24 p/s with a percentage of 7.2%.

Table 19 Time Interval Sensitivity analysis

Scenario	Time Interval	Changed Flow Mean (p/s)	Original Flow Mean (p/s)	Flow Difference (p/s)	Flow Difference (%)	Number of Simulations
B Increased Time Interval	5-45	1.02	1.15	-0.13	12.27%	13
B Decreased Time Interval	15-35	1.24	1.15	0.09	7.18%	20

4.4.3 Intrinsic Uncertainty

Intrinsic uncertainty is associated with the model's formulations of mathematical, physical and behavioural relationships between agents and agents and the environment. This uncertainty is difficult to be determined (Hamins and McGrattan, 2007). An example of this uncertainty might be the geometry around the agent and how the agent is be affected by it. A related example as well is the social force model that was implemented in MassMotion, and the way it can reproduce in the behaviours observed in real experiments. As it is difficult to measure the impact of this uncertainty and the scope of this thesis is limited, it was excluded.

4.4.4 Behavioural Uncertainty

Behavioural uncertainty is associated with the possible variability of human behaviour, and it is observed when repeated trials of the same experimental evacuation scenario are investigated.

This is reflected in the used of distributions/stochastic variable in evacuation models.

Therefore, it impacts the comparison between the simulation results and the experiment results. Usually, it is preferable to have a large set of trials as it includes a larger portion of the possible behaviour of occupants. This will create a variety of behaviours, and the evaluation of results will be more realistic. Despite that the conditions of the experiment were the same, the outcome results of participants might change in each different trial. This was presented in Section 3.2.1. The experiments that were selected had single trial and multiple trials, and the uncertainties regarding the single trial are to higher than the multiple trials. Consequently, functional analysis method has been used to examine the variation of behaviours of agents.

4.4.4.1 Corridor Test

All scenarios that were done were examined for behavioural uncertainty analysis, where two settings were used: Default settings and Specified settings. The criteria used for the functional analysis were: 0.5% for TETj, 5% for SDj, and 1% for ERDj, EPCj, and SCj for ten consecutive runs.

4.4.4.1.1 Scenario B

4.4.4.1.1.1 Default Settings

Scenario B with Default settings took 52 runs to converge applying the method based on functional analysis. Figure 43 shows the arrival time in Scenario B where default settings were used. It can be seen that there are a variance in the total arrival time in this scenario. Moreover, Figure 44 shows that the behavioural uncertainty in this scenario is quite high. SD Convergence criterion crossed the 5% criterion many times. In addition, TETj criterion crossed the 0.5% criterion many times as well. Other criteria converged rapidly below the 1% criterion.

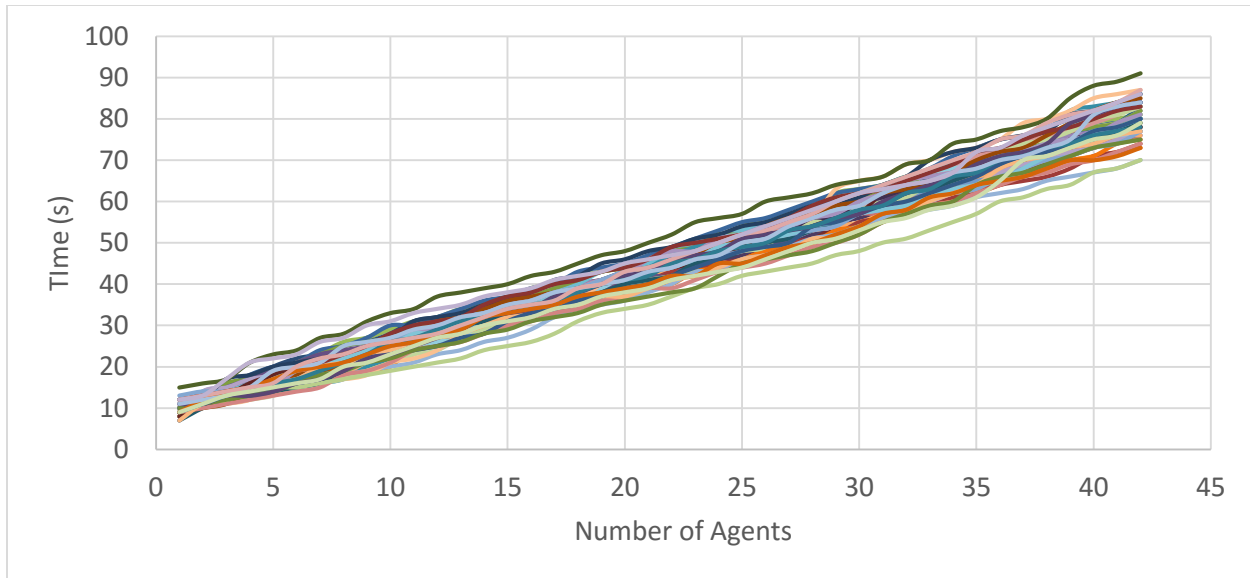


Figure 43 Total Arrival Times for Scenario B with default settings for Validation Test 1

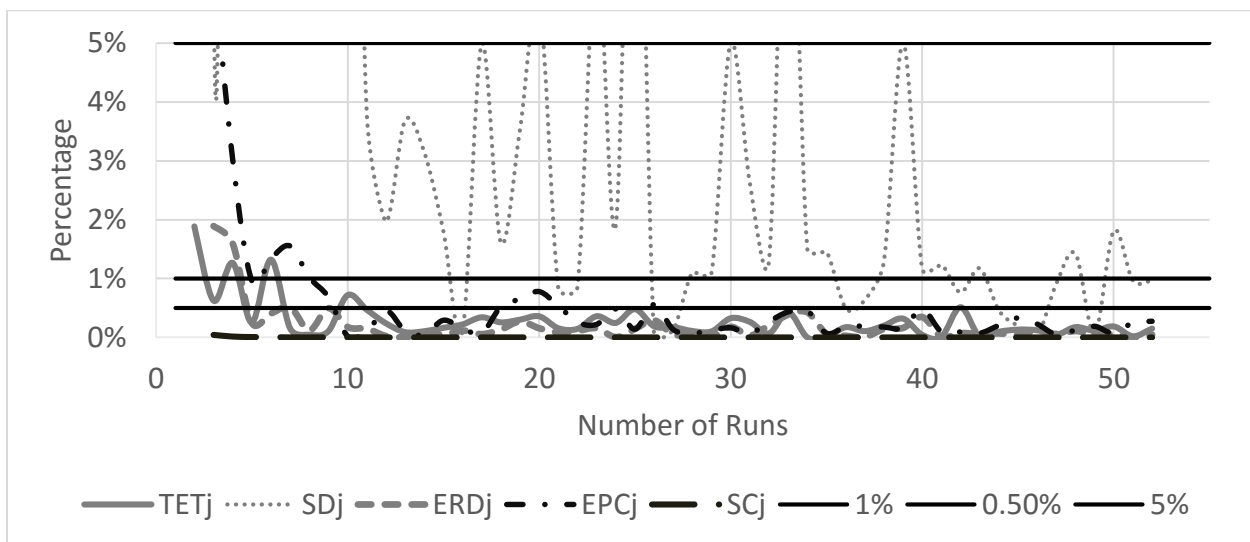


Figure 44 Functional Analysis Method for Corridor Test of Scenario B Default Settings

4.4.4.1.1.2 Specified Settings

Scenario B with Specified settings took 24 runs to converge using the functional analysis operators, which is approximately the half number of runs than the Default settings scenario. Figure 45 shows the arrival time in Scenario B where Specified settings were used. It can be seen that there is a less variance in the total arrival time in this scenario. Moreover, Figure 46 shows that the behavioural uncertainty in this scenario is quite high. SD Convergence criterion crossed the 5% criterion many times. In addition, TETj criterion crossed the 0.5% criterion many times as well. Also, EPCj crossed the 1% criterion in the beginning before it converged. Other criteria converged smoothly under the 1% criterion.

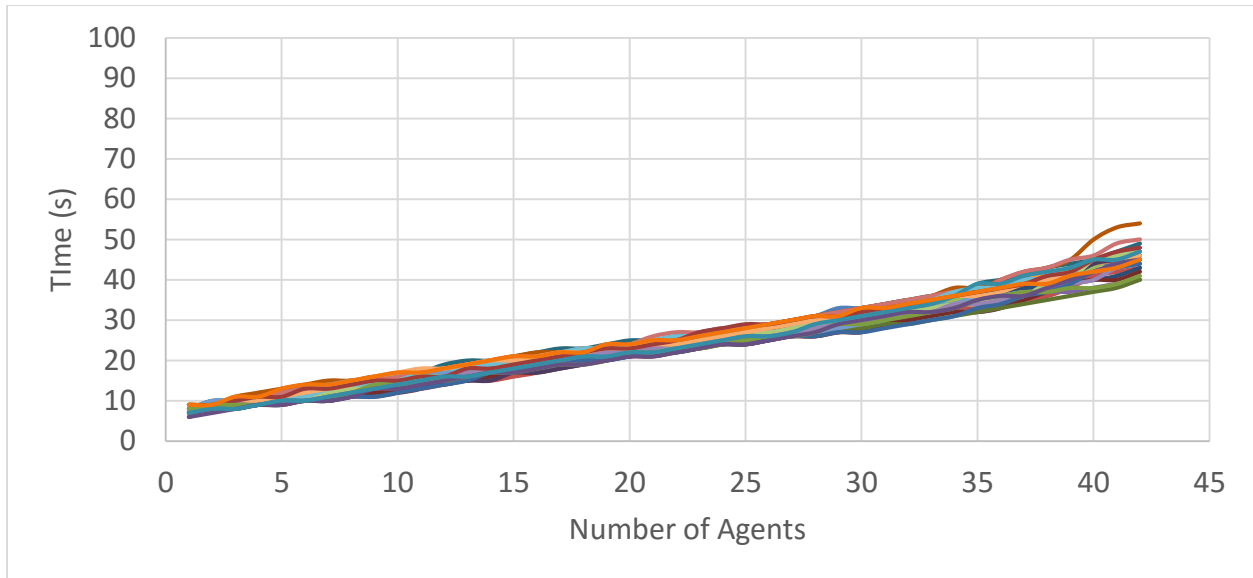


Figure 45 Total Arrival Times for Scenario B with specified settings for Validation Test 1

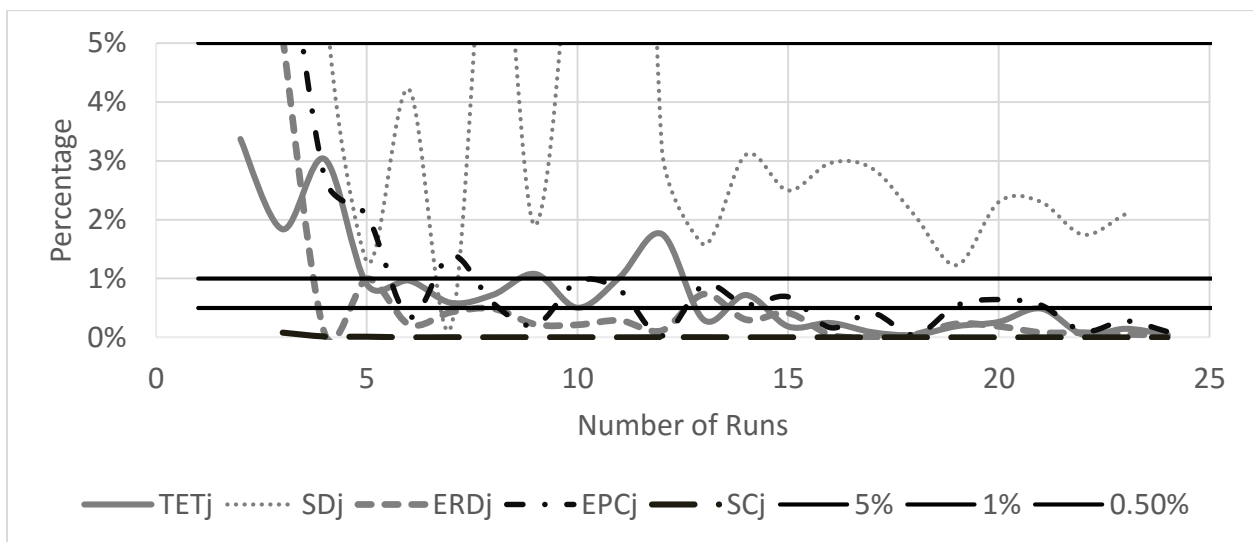


Figure 46 Functional Analysis Method for Corridor Test of Scenario B Specified Settings

4.4.4.1.2 Scenario C

4.4.4.1.2.1 Default Settings

Scenario C with Default settings took 32 runs to converge applying the method based on functional analysis. Figure 48 shows the arrival time in Scenario C where default settings were used. It can be seen that there is a large variation in the total arrival time in this scenario among different repeated runs. Moreover, Figure 47 shows that the behavioural uncertainty in this scenario is quite high. SD Convergence criterion crossed the 5% criterion many times. In addition, TETj criterion crossed the 0.5% criterion many times as well before it converges at the end of the test runs. EPCj also crossed the 1% criterion many times as well.

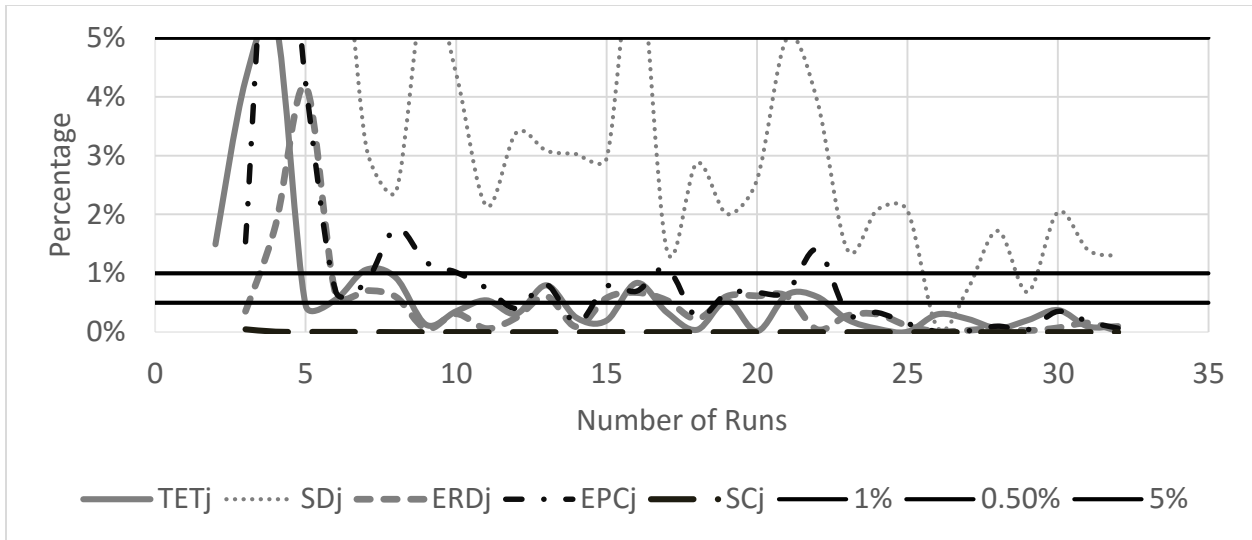


Figure 47 Functional Analysis Method for Corridor Test of Scenario C Default Settings

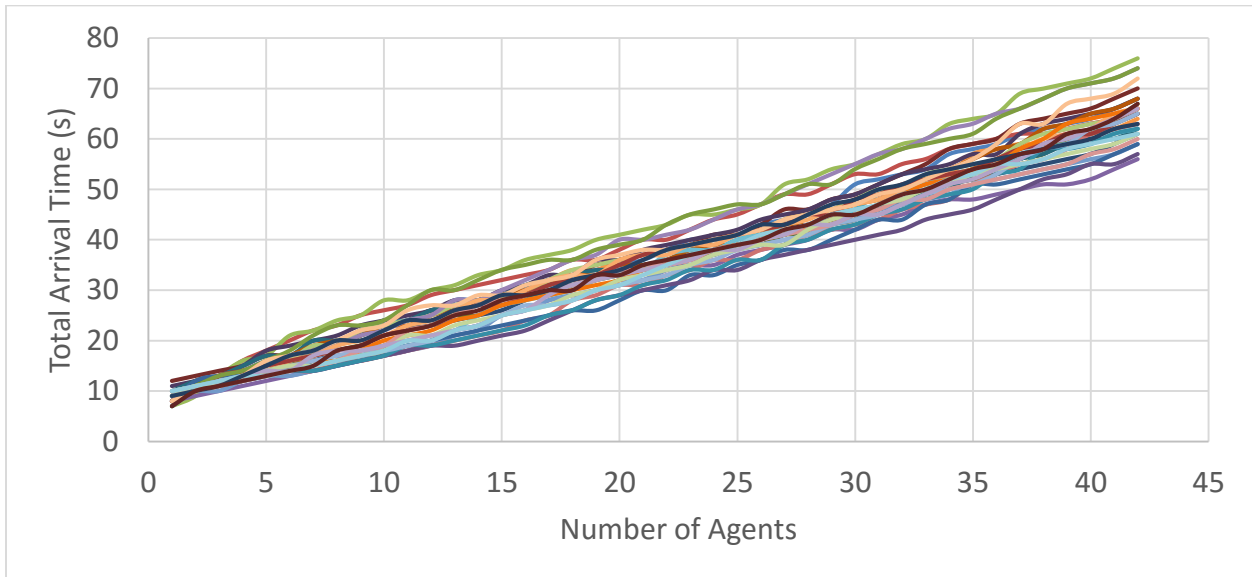


Figure 48 Total Arrival Times for Scenario C with default settings for Validation Test 1

4.4.4.1.2.2 Specified Settings

Scenario C with Specified settings took 33 runs to converge applying the method based on functional analysis. Figure 50 shows the arrival time in Scenario C where specified settings were used. It can be seen that the variance in the total arrival time is greater than the default settings. Moreover, Figure 49 confirms that the behavioural uncertainty in this scenario is significantly high. SD convergence criterion crossed the 5% criterion. In addition, TETj criterion crossed the 0.5% criterion many times. Also, EPCj crossed the 1% criterion in the beginning before it converged. Furthermore, ERDj crossed the 1% criterion in the beginning before it converged.

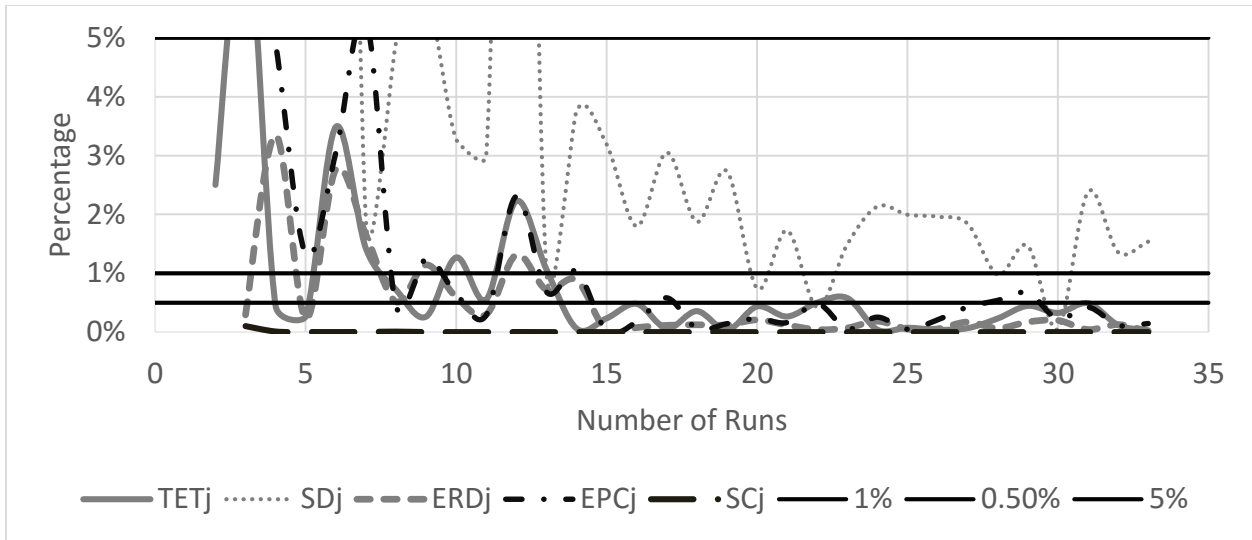


Figure 49 Functional Analysis Method for Corridor Test of Scenario C Specified Settings

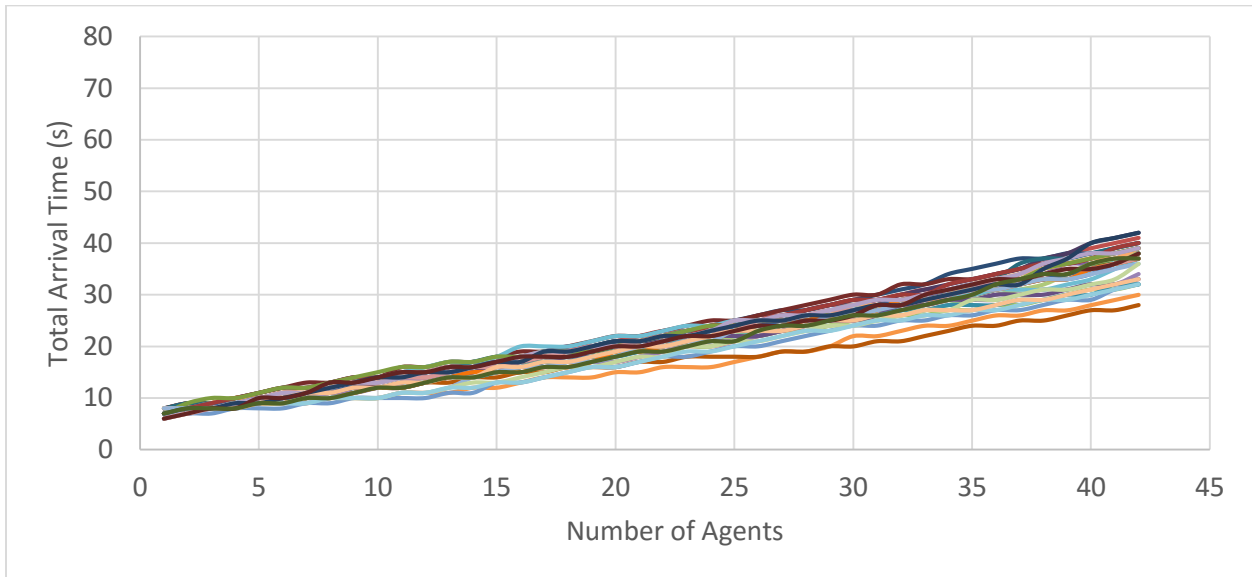


Figure 50 Total Arrival Times for Scenario C with specified settings for Validation Test 1

4.4.4.1.3 Scenario D

4.4.4.1.3.1 Default Settings

Scenario D with Default settings took 21 runs to converge applying the method based on functional analysis. Figure 52 shows the arrival time in Scenario D where default settings were used. It can be seen that there are a variance in the total arrival time in this scenario. Moreover, Figure 51 shows that the behavioural uncertainty in this scenario is quite high. SD Convergence criterion crossed the 5% criterion in the beginning. In addition, TETj criterion crossed the 0.5% criterion many times as well before it converges at the end of the test runs.

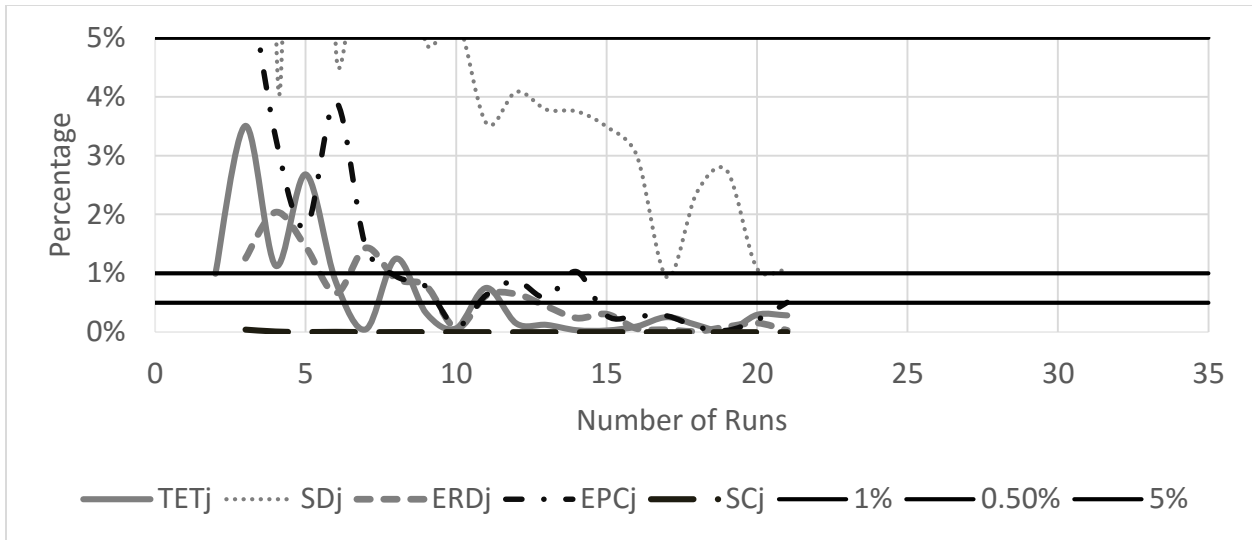


Figure 51 Functional Analysis Method for Corridor Test of Scenario D Default Settings

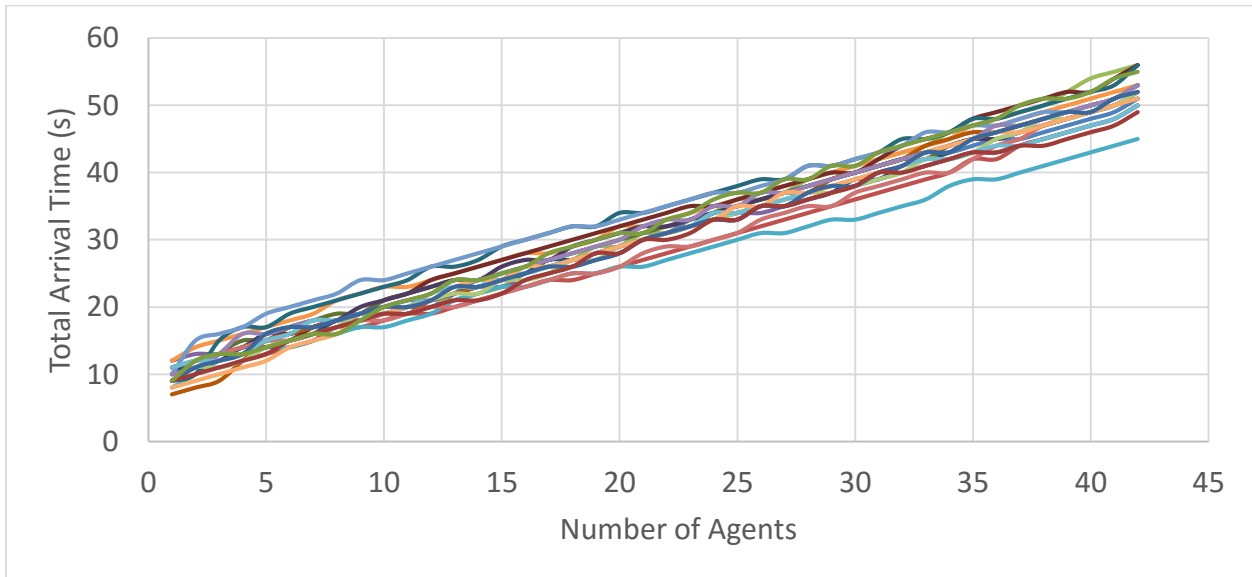


Figure 52 Total Arrival Times for Scenario D with default settings for Validation Test 1

4.4.4.1.3.2 Specified Settings

Scenario D with Specified settings took 34 runs to converge applying the method based on functional analysis. Figure 54 shows the total arrival time in Scenario C. It can be seen that the variance in the total arrival time is greater than the default settings. Moreover, Figure 53 confirms that the behavioural uncertainty in this scenario is significantly high. SD convergence criterion crossed the 5% criterion. In addition, TETj criterion crossed the 0.5% criterion many times. Also, EPCj crossed the 1% criterion many times. Furthermore, ERDj crossed the 1% criterion in the beginning before it converged.

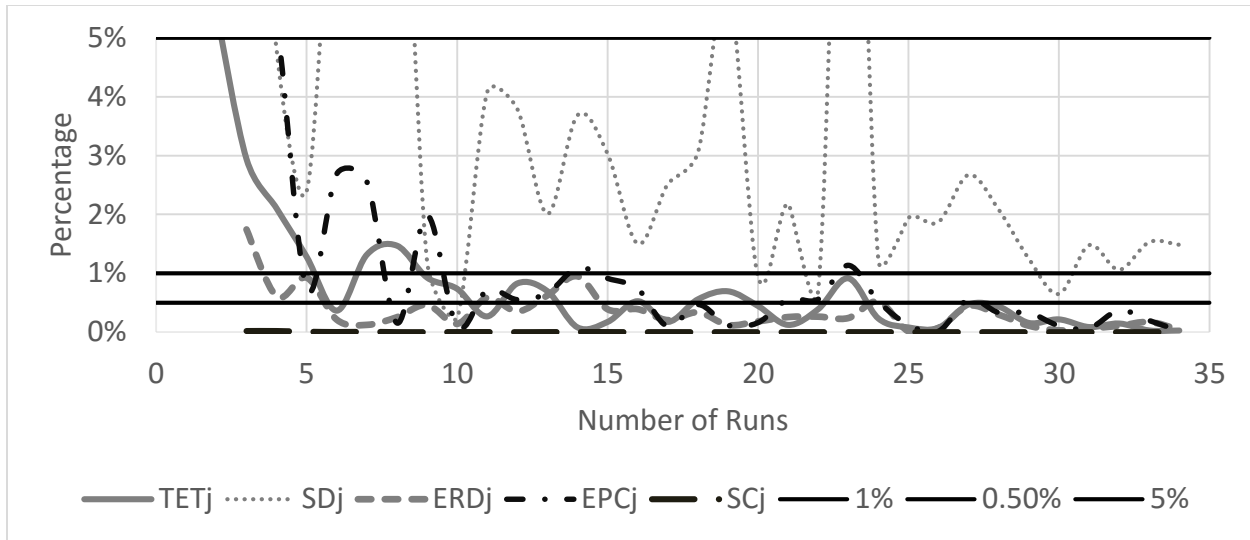


Figure 53 Functional Analysis Method for Corridor Test of Scenario D specified Settings

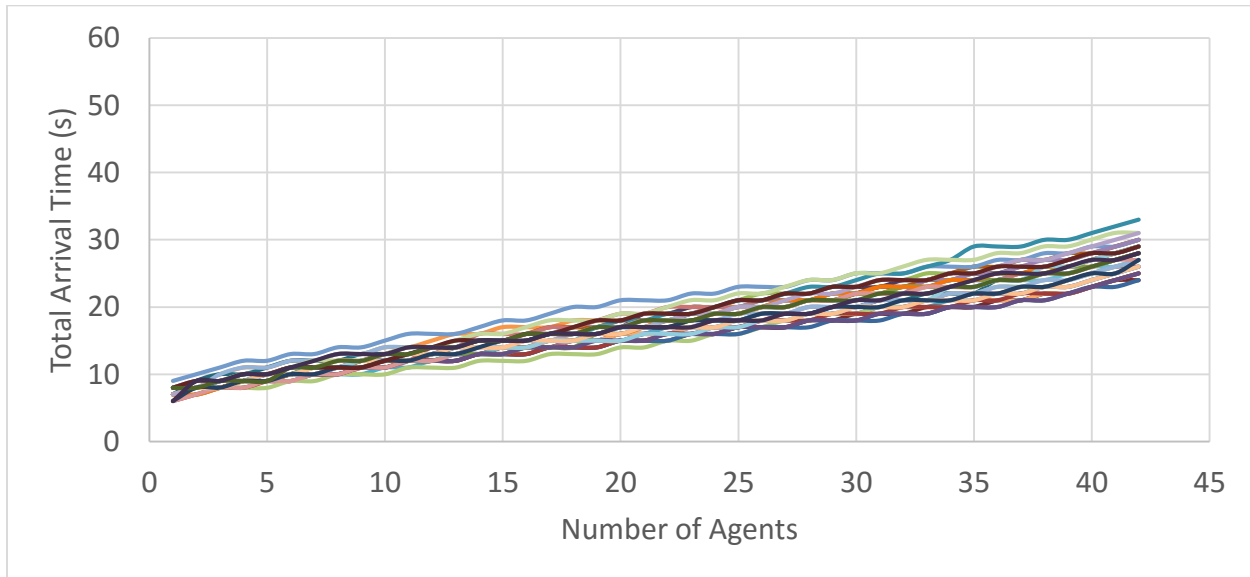


Figure 54 Total Arrival Times for Scenario D with specified settings for Validation Test 1

4.4.4.1.4 Scenario E

4.4.4.1.4.1 Default Settings

Scenario E with Default settings took 34 runs to converge applying the method based on functional analysis. Figure 56 shows the total arrival time in Scenario E where default settings were used. It can be seen that there is a variance in the total arrival time in this scenario. Moreover, Figure 55 shows that the behavioural uncertainty in this scenario is quite high. SD Convergence criterion shows high uncertainty since it crosses the 5% criterion many times. In addition, TETj criterion crossed the 0.5% criterion two times. Other criteria converge rapidly below the 1% criterion.

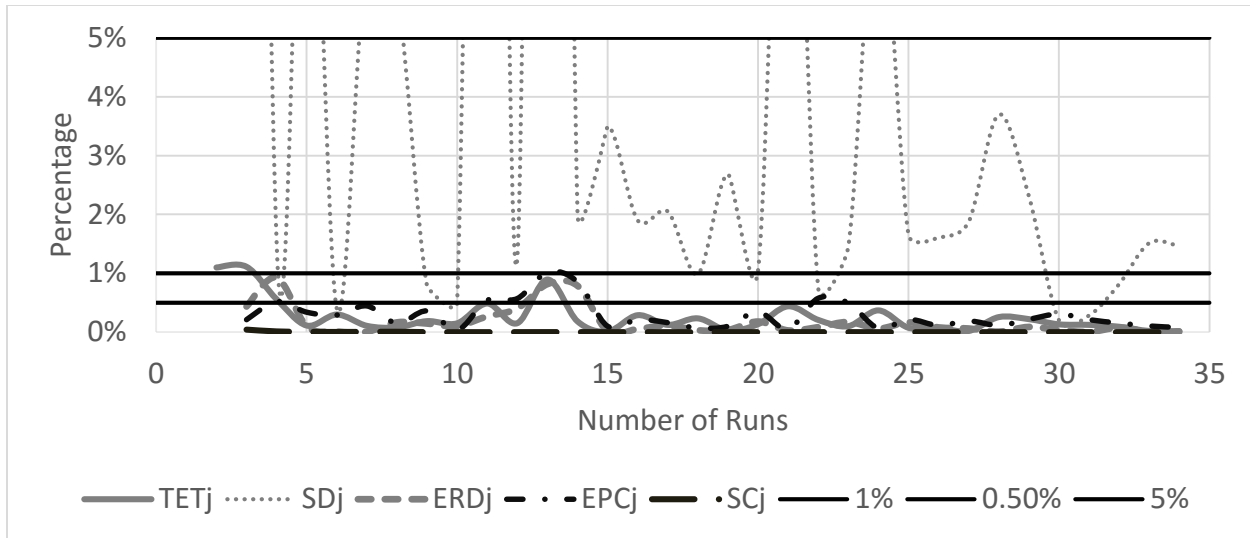


Figure 55 Functional Analysis Method for Corridor Test of Scenario E Default Settings

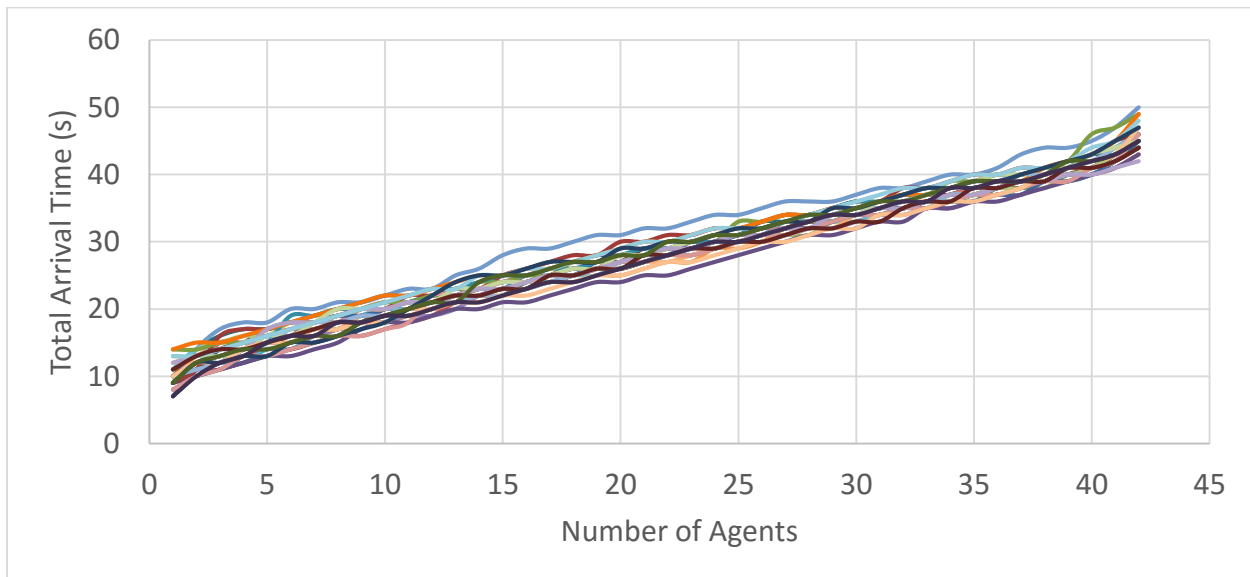


Figure 56 Total Arrival Times for Scenario E with default settings for Validation Test 1

4.4.4.1.4.2 Specified Settings

Scenario E with Specified settings took 22 runs to converge applying the method based on functional analysis. Figure 58 shows the arrival time in Scenario D where Specified settings were used. It can be seen that the variance in the total arrival time is smaller than the default settings. Moreover, Figure 57 confirms that the behavioural uncertainty in this scenario is lower than the Default Scenario. SD convergence criterion crossed the 5% criterion. In addition, TETj criterion crossed the 0.5% criterion two times. Also, EPCj crossed the 1% criterion in the beginning before it converged.

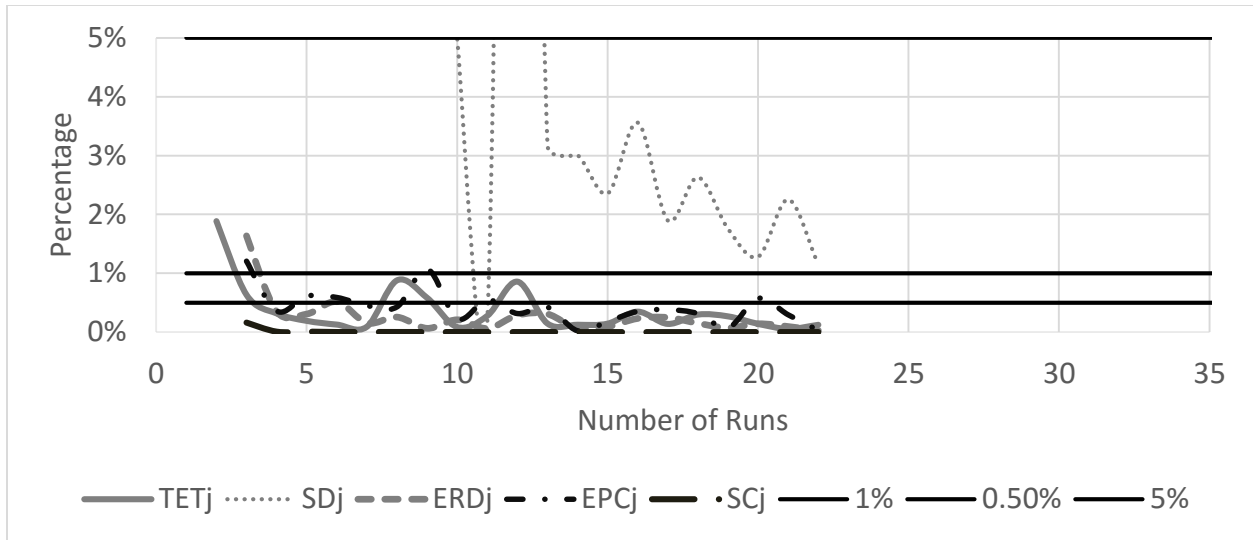


Figure 57 Functional Analysis Method for Corridor Test of Scenario E Specified Settings

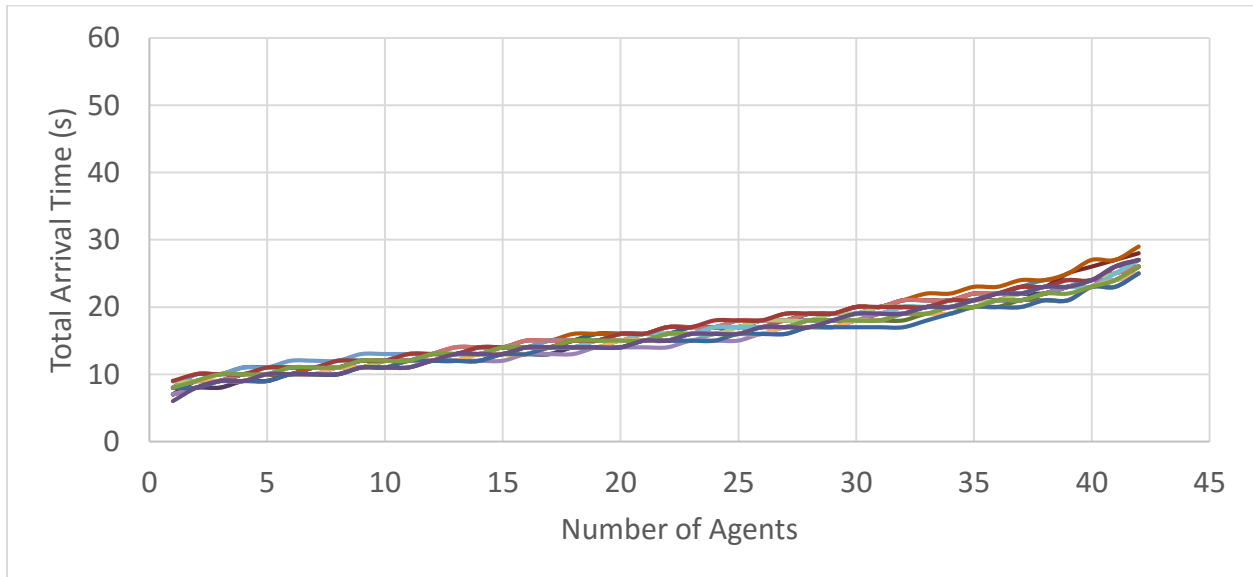


Figure 58 Total Arrival Times for Scenario E with specified settings for Validation Test 1

4.4.4.2 Stair Merging Test

Total evacuation time was also analyzed for scenario 3 and scenario 9, where these two scenarios can be a representative of a Default settings scenario and a Specified settings scenario. Functional analysis method was used in this analysis to check the behavioural uncertainty regarding the movement on the stairs.

4.4.4.2.1 Scenario 3

Scenario 3 needed only 13 runs to comply with the criteria of the functional analysis method. Figure 59 shows the variability of evacuation times of the runs that were simulated. The figure

shows that all runs converge to about the same results. Figure 60 shows the functional analysis criteria, which shows that the results converge quickly and the behavioural uncertainty at this scenario is low. Also the SD convergence was expected to be higher than the other criteria, however, it converges under the 5% criterion that has been set. Furthermore, the average total evacuation time was 167 seconds and the average standard deviation was 2.32 seconds.

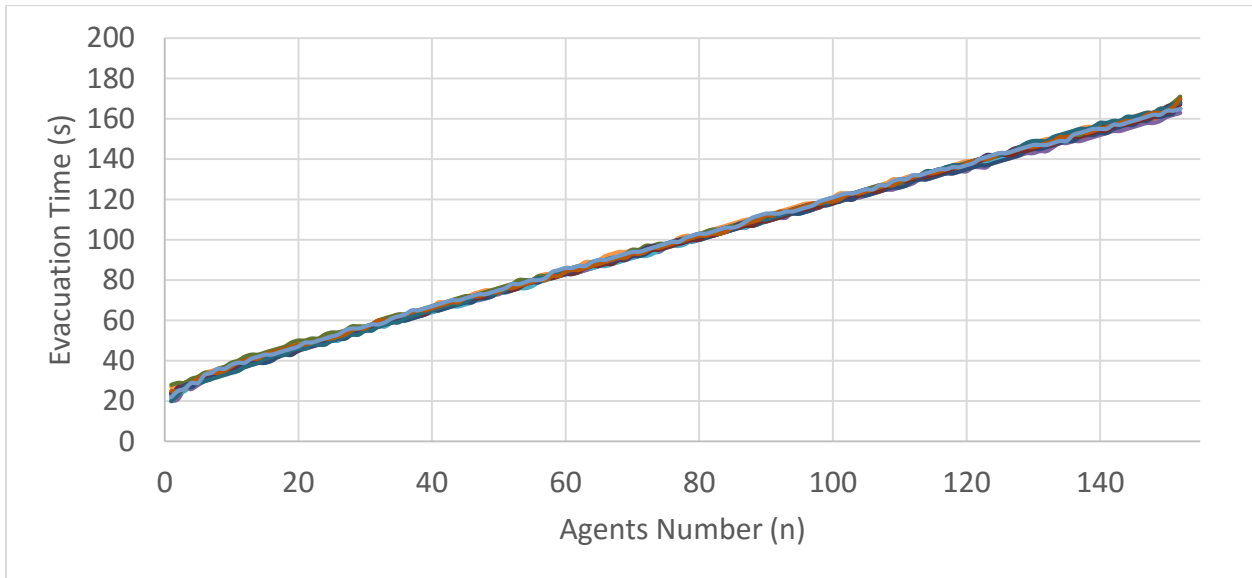


Figure 59 Total Evacuation times for Stair Merging test Scenario 3

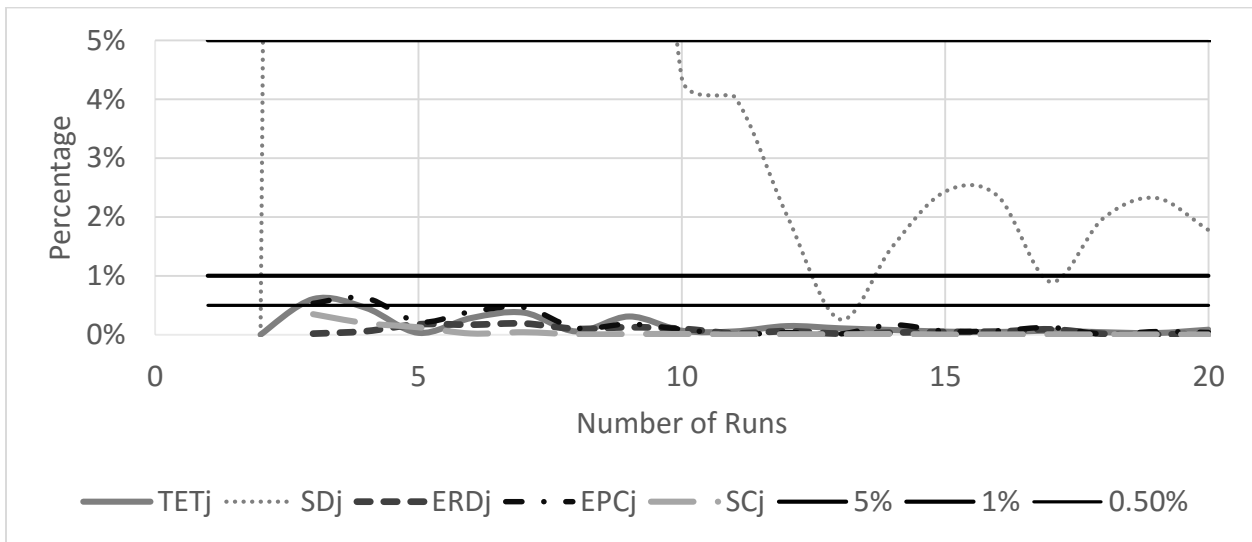


Figure 60 Functional Analysis Criteria Compliance for Stair Merging Test Scenario 3

4.4.4.2.2 Scenario 9

In Scenario 9, the speed of agents increased due to deactivation of Fruin’s LOS, behavioural uncertainty increased and more runs were compulsory in Scenario 9. A total of 28 runs were

made. The results show that at the beginning of the simulation test, agents had less behavioural uncertainty than the agents who were at the end of the simulation since the results vary on the end (See Figure 61). Figure 62 shows the functional analysis criteria compliance, where it converges quickly as Scenario 3. Also the SD convergence was expected to be higher than other criteria, however, it converges under the 5% criterion that has been set. In addition, the average total evacuation time was 111 seconds and the average standard deviation was 2.98 seconds.

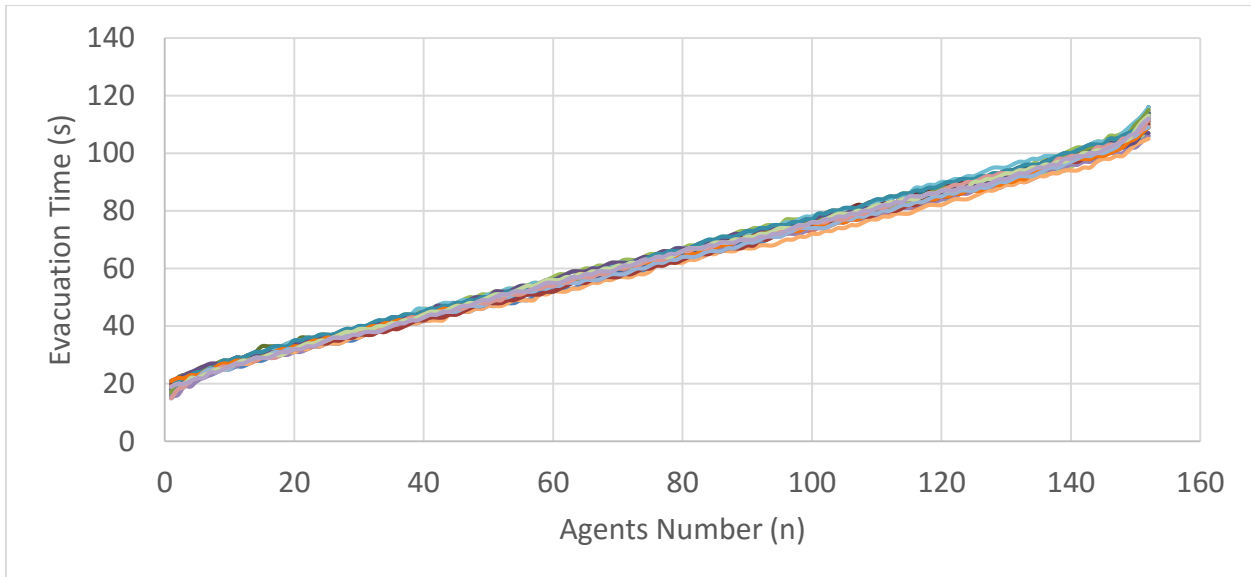


Figure 61 Total Arrival Times for Scenario 9 for Validation Test 3

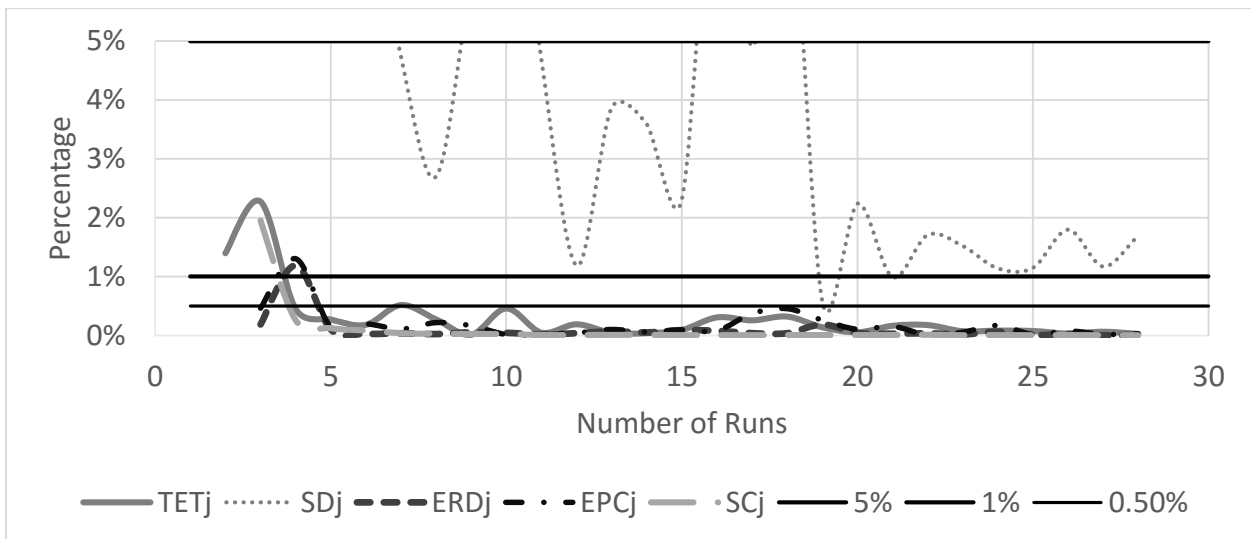


Figure 62 Functional Analysis Criteria Compliance for Stair Merging Test Scenario 9

5 Discussion

This chapter contains a discussion about the work that has been performed in this thesis. Results of validation and uncertainty analysis are discussed in this chapter.

5.1 Validation

As expected, at a general level, all validation tests gave results with higher differences when using the default settings than the specified settings when compared to the experimental results. This is related to the walking speeds assigned to the agents by MassMotion and the density correlation. The walking speeds assigned for specified scenarios were higher than the default scenarios. In addition, Fruin's LOS was deactivated and this might not reduce the walking speeds drastically. This happened in all tests, with the exception of validation test 2 (cinema theatre test) in which the interest was only on pre-evacuation times.

Examining the representation of total arrival times and comparing it to the experimental results is possible to evaluate the test. The only validation test that provided walking speeds was validation test 1 which is the corridor test. Default settings provided results that are 45%-60% longer than the experimental results. Afterwards, when specified settings were taken from the experimental parameters and applied to the test, results were varying between approximately 2% longer than the experimental results and from approximately 1% to approximately 13% shorter than the experimental values.

The second parameter to examine is the representation of flow rates in MassMotion. Validation test 1 and Validation test 3 have examined flow rates represented by MassMotion and compared with the experimental results. In validation test 1, default settings gave a flow rate difference which was approximately 30% to 60% shorter than the experimental results. Specified settings in validation test 1 showed a flow rate difference which was approximately 4% to 30% greater than the experimental results. In addition, validation test 3 had also flow values of the corridor agents and the upper floor agents who used the staircase and merged together. It should be noted that the settings which were used in the first scenario were the default settings from MassMotion, and the last scenario that was used in this test deactivated Fruin's LOS functionality. The first flow rate that was examined was for the agents who came from the corridor, and it showed a difference of approximately 20% to 36% less than the experimental results and this is only in the stable flow of agents. The last scenario which is scenario 9 showed a flow rate in the corridor which was approximately 1.5% longer than the experimental results. For the agents who came from the upper floor, the flow rate difference was varying from 30% to 90% less than the experimental results. Scenario 9 showed a flow rate difference of approximately 23% longer than the experimental results.

Another parameter that was under scrutiny is density at specific areas. Validation test 1 and validation test 3 examined the density and compared it with the experimental results. In validation test 1 both default and specified settings were compared. In default settings scenarios, the results varied than the experimental results by approximately 53% less to 27% longer in the two zones before the opening. Specified settings scenarios were varying from approximately 16% less to 32% longer than the experiment results in the same two zones. In validation test 3, the instantaneous densities at the merging area were compared with each other and in general all the scenarios had a density that varied between 3 and 5 in the stable stage. The instantaneous densities that were in the experiment at the same merging area varied between 5 and 7. Since the interest of this particular test was to examine the stair merging ratios for different scenarios, the density results from the simulation were not compared quantitatively with the experimental results.

Validation test 2 examined the representation of pre-evacuation times of MassMotion. Two set of data were provided and simulated. The difference between the average pre-evacuation times of the two tests was between approximately 0.8% and 2% longer than the experiment results. The difference between the maximum and minimum results was between approximately 0.6% and 4% longer than the experimental results. In addition, there was a comparison between results in each row for average, max, min, and standard deviation results. Both scenarios had about the same results for each row, and especially in the second scenario. In Addition, a qualitative assessment of the congestion levels of agents showed a close representation to reality, this might be because the one passage was bigger than the other passage which is more realistic to have more agents on that side of the cinema theatre. It should be noted that the bigger passage was the route to the same exit area that people used to enter the cinema theatre in real life.

Validation test 3 examined the merging ratio in a staircase where two flow of agents merged at one point. The merging ratios for MassMotion for all the scenarios that were performed varied between 52% and 66%. The difference between the experimental results and the simulation results varied between 8.5% less and 39% more. Scenario 4 and 5 had about the same merging ratio as the experiment results. While scenario 1 had approximately 39% more than the experiment result. Scenario 9 had approximately 8.5% less than the experiment merging ratio. These results are expected since walking speeds in Scenario 9 were higher than the other scenarios since Fruin's LOS was deactivated. In addition, a percentage of 52% to 66% is approximately close to the theoretical stair merging ratio which is 1:1.

A phenomenon was noticed in validation test 1 where agents at the opening used to switch their direction to face the other side. This phenomenon is caused by the social force model when the agent get close to an obstacle and other agents are close to that agent.

Another phenomenon was noticed in validation test 2 where agents stuck in narrow places. This is also caused by the social force model that is implemented in the continuous approach model, where the sum of the forces of each agent makes the agent shuffle in his current location of space.

5.2 Uncertainty Analysis

A convergence method based on functional analysis was used to examine the behavioural uncertainty in total arrival times. Additionally, while examining the other uncertainties, the functional analysis method was also used to investigate the behavioural uncertainty related to it.

The first uncertainty analysis was related to model input uncertainties which had two tests: walking speed reduction test and body size reduction test.

The purpose of the walking speed reduction test was to examine the impact of changing the walking speed on the uncertainty related to MassMotion. Walking speeds had been reduced to 25% for stair merging test scenario 3. The difference in the total arrival time was approximately 10% higher than the original walking speeds, and this is in line with expectations. Also, functional analysis method showed that the behavioural uncertainty related to changing walking speeds is minimal to the results which is expected since the stair merging test configuration had less disturbance on the agents and decreasing walking speeds for everyone does not affect the results.

Another test related to the model input uncertainty was changing the body size of agents. Body size of agents was reduced by 20%, and corridor test scenario B was used to examine the impact on the total arrival time. The total arrival time for the reduced body size scenario was approximately 12% lower than the original body size scenario. Also, flow rates and density were examined, and flow rate was approximately 16% higher than the original scenario. The density for zone 1 was approximately 15% higher and zone 2 was approximately 31% higher than the original scenario. Examining the functional analysis method for this experiment showed that changing the body size of agents can increase the behavioural uncertainty and variance in results can occur. This result was expected since changing the body size at the corridor test means more agents going through the opening. Yet, when decreasing the size to 20% which is 20 cm and the opening width of scenario B was 60 cm, theoretically three agents can go through the opening at the same time. But this cannot happen due the social forces that is generated by the obstacles at the opening and the forces of other agents nearby and this might increase the behaviour uncertainty for this scenario.

Measurement uncertainty was also examined by a time interval test. The test mainly was to examine the impact of changing the time interval for the stable stage of flow of agents on the

results of flow rates. The time intervals were increased and decreased by 10 seconds of the original time interval. Increasing the time interval gave approximately 13% lower flow rate than the original scenario. While decreasing the time interval raised the flow rate by approximately 7%. This is expected because of the distribution of the flow rates, in the beginning and at the end it is a low flow rate and while decreasing the time interval, the high flow rates are calculated only leading to a higher flow rate.

Afterward, behavioural uncertainty was examined for corridor test and stair merging test. Basically, total arrival times were examined by the functional analysis method. All scenarios of the corridor test were examined, while only scenario 3 and scenario 9 of the stair merging test were examined.

Generally, corridor tests had a high behavioural uncertainty. This might happen because of the stuck agent's phenomenon at the opening, while in the stairs test there were less obstacles to block the route of agents. The highest behavioural uncertainty in corridor test was scenario C with default settings since four of the convergence criteria were crossing the threshold criteria. This can be due to the width of the opening which is 75 cm, which means theoretically the opening fits three agents of 25 cm body size at a time. However, there are many forces affecting the agents such as the obstacles and the agents nearby, and that might increase the phenomenon of stuck agents at the opening. Another scenario which had a relatively high behavioural uncertainty was scenario B with default settings where it took 52 runs to converge because TET_j and SD_j were crossing the threshold criteria. On the other hand, scenario D with default settings showed the lowest behavioural uncertainty where only 21 runs were needed and it converged relatively quickly than the other scenarios. This can be reasoned by the opening width at scenario D where less forces acting upon the agents from the obstacles. The width of the opening at scenario D was 90 cm where only three agents with 25 cm body size can be there at the same time and enough space is available for agents to go through without much disturbance.

In contrast, stair merging tests had lower behavioural uncertainty than the corridor tests. Scenario 3 needed only 20 runs to converge under the functional analysis method. Scenario 9 had a higher behavioural uncertainty than scenario 3, where it needed 28 runs to converge.

5.3 Future Recommendations

There are some recommendations for future research and functionalities that MassMotion can be useful with:

- MassMotion does not have a library for occupants' demographics; where agents can be divided into males and females, age of agents, or their usage of the structure such as

commuters, school users, etc. This addition to the model makes it possible to have different profiles of agents.

- Pre-evacuation timetable functionality: where it is more practical to export the pre-evacuation times of agents directly in an evacuation scenario.
- Deactivation of density correlation from the GUI interface instead of deactivating it through the command line prompt.
- Groups of Agents: it would be also beneficial to make agents in MassMotion capable of forming groups where it is more realistic in some scenarios.
- Additional Verification and Validation scenarios where more functionalities of MassMotion can be tested. Also, the study of behavioural uncertainties in those V&V tests can be performed in order to examine the impact of behavioural uncertainties on the results.

6 Conclusions

The validation tests show that MassMotion is able to represent reasonably pedestrian movement if the input configuration is carefully calibrated. In simulations where specified settings were used, the total arrival times deviate from 0% to 13% and flow rates deviate from 5% to 30%. Whereas, in the default settings, the total arrival times deviate from 47% to 60% and the flow rates deviate from 31% to 90% in all validation tests that are related.

Furthermore, the model is able to reproduce pre-evacuation time distributions and levels of congestion with difference in the order of 0% to 2% for pre-evacuation times. A qualitative assessment of the congestion levels showed that MassMotion is able to represent approximately the same congestion levels.

In addition, the percentage of stair merging ratio in MassMotion differences from 52% to 66% in the stable flow stage using the default walking speeds. The flow rates deviated from 22% to 90%. When deactivating Fruin's LOS density correlation, the model can produce flow rates that deviate from 2% to 23%.

The uncertainty analysis showed that when decreasing the walking speeds of agents, the total arrival time can increase by 10%. Also, when decreasing the body size of agents, the total arrival time decreases by 12%. The flow rates of the reduced body size scenario increased by 16%. In addition, increasing the time interval of calculating the flow rate can decrease the flow rate by 13%. While decreasing the time interval of calculating the flow rate can increase the flow rate by 8%.

The behavioural uncertainty showed that it is dependent on the experiment under scrutiny. Some validation tests showed higher behavioural uncertainty while other validation tests showed a less behavioural uncertainty where the results converged relatively quickly.

Moreover, the movement behaviour of agents in MassMotion could sometimes deviate from the real life experiments in a specific situation. Sometimes agents get stuck between walking in narrow places. Another observation was when agents be susceptible to idle beside openings.

Finally, the results of the model are as good as the user. If the user has the capability of calibrating the model carefully, more reliable results can be obtained.

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8 Appendices

8.1 Appendix A: Validation Test 1

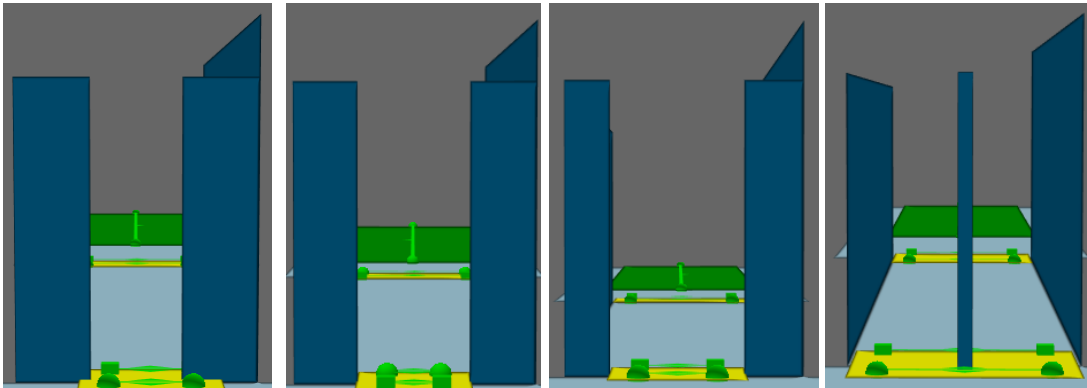


Figure A 1 Opening of Scenario B, C, D, E in order

Table A 1 Comparison between Experiment A and Simulation A

Groups	Experimental	Groups	Simulation
		0.7-0.8	5
		0.8-0.9	8
<1.0	0	0.9-1.0	15
1.0-1.1	1	1.0-1.1	26
1.1-1.2	0	1.1-1.2	50
1.2-1.3	0	1.2-1.3	62
1.3-1.4	7	1.3-1.4	56
1.4-1.5	6	1.4-1.5	67
1.5-1.6	18	1.5-1.6	65
1.6-1.7	19	1.6-1.7	34
1.7-1.8	19	1.7-1.8	18
1.8-1.9	10	1.8-1.9	8
1.9-2.0	2	1.9-2.0	4
2.0-2.1	1	2.0-2.1	2
>2.1	0		
Count Total	83 Observation	Count Total	420 Observation

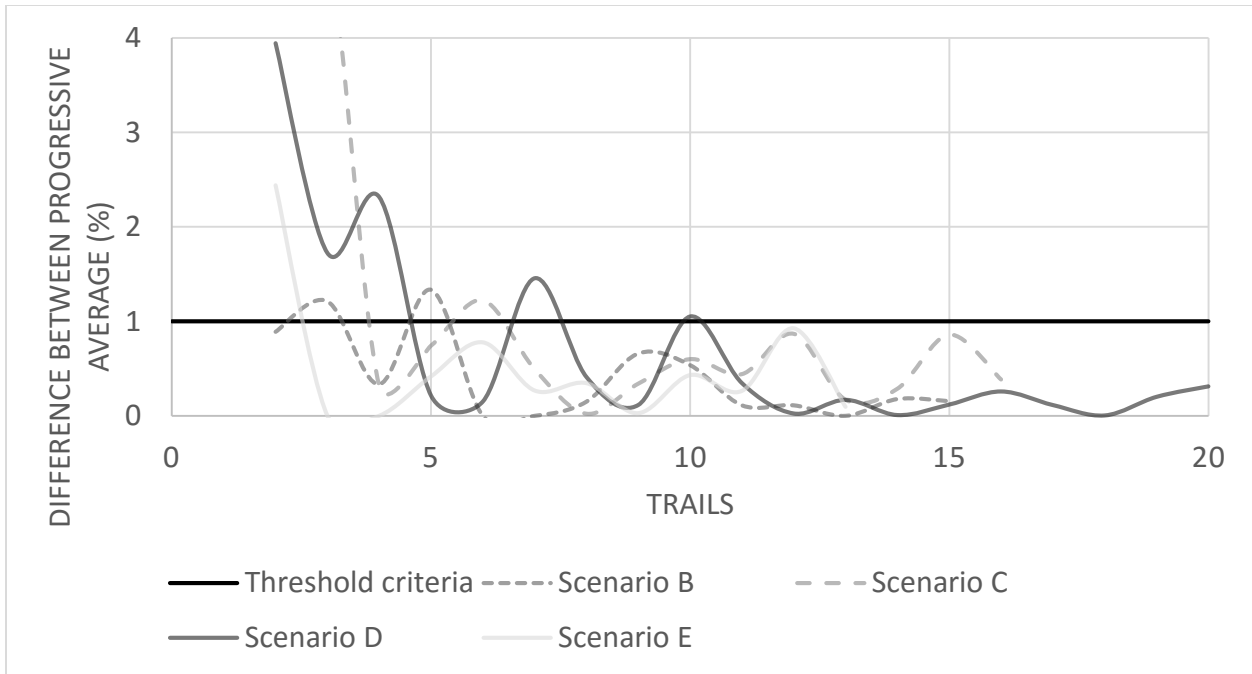


Figure A 2 Difference between progressive averages for walking speeds of default settings scenarios

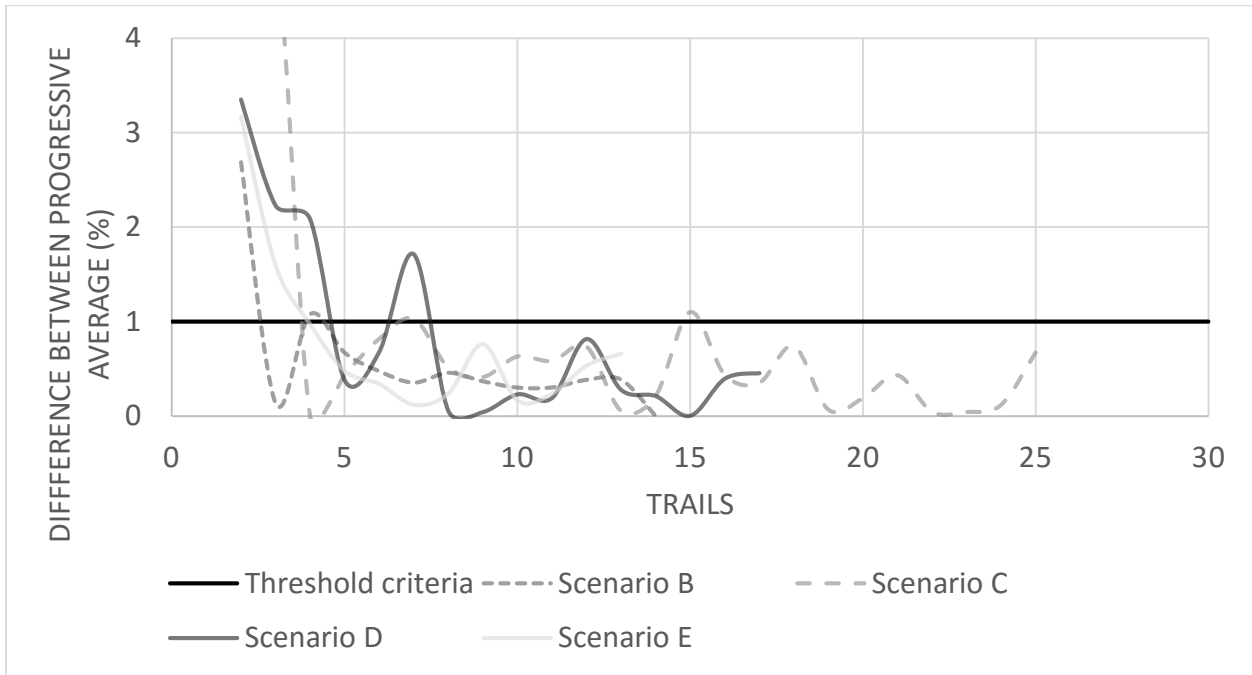


Figure A 3 Difference between progressive averages for flow rates of default settings scenarios

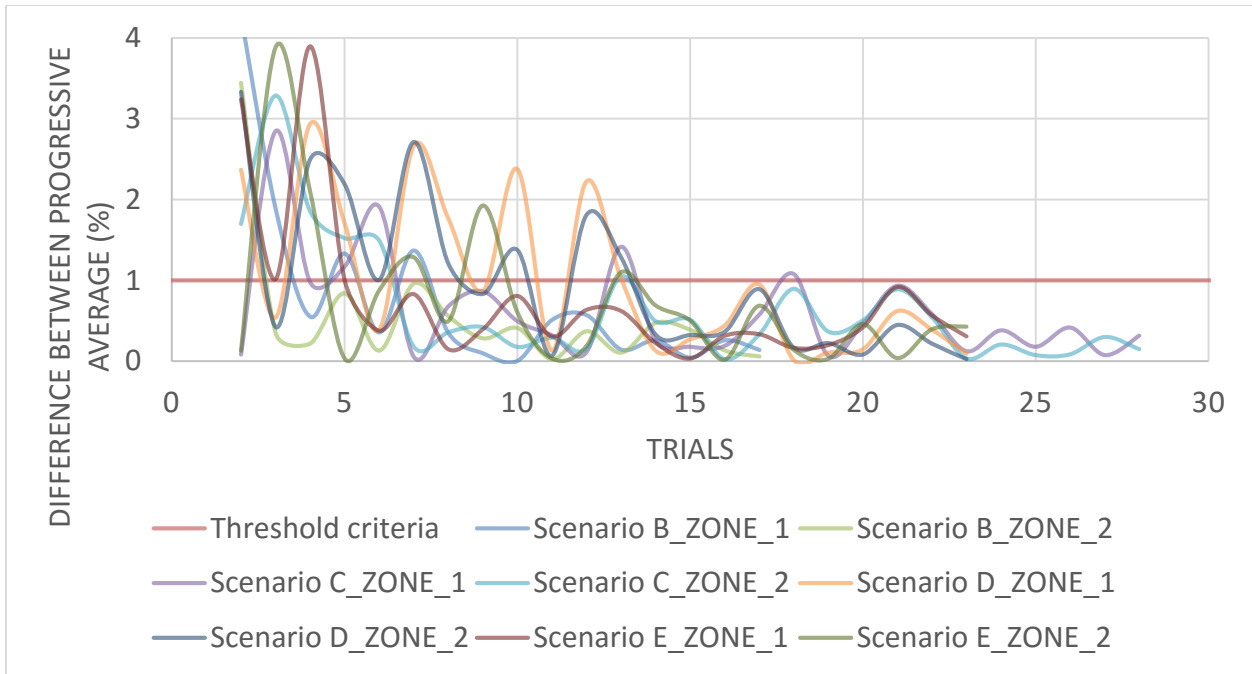


Figure A 4 Difference between progressive averages for density zones of default settings scenarios

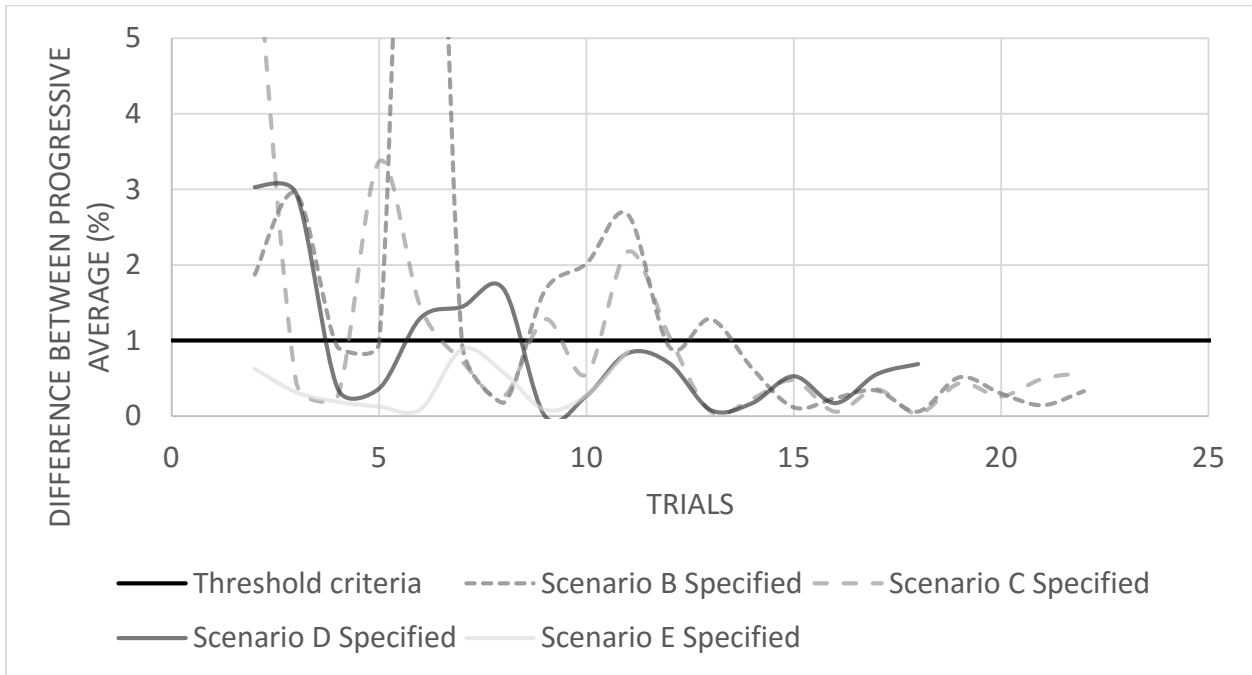


Figure A 5 Difference between progressive averages for walking speeds of specified settings scenarios

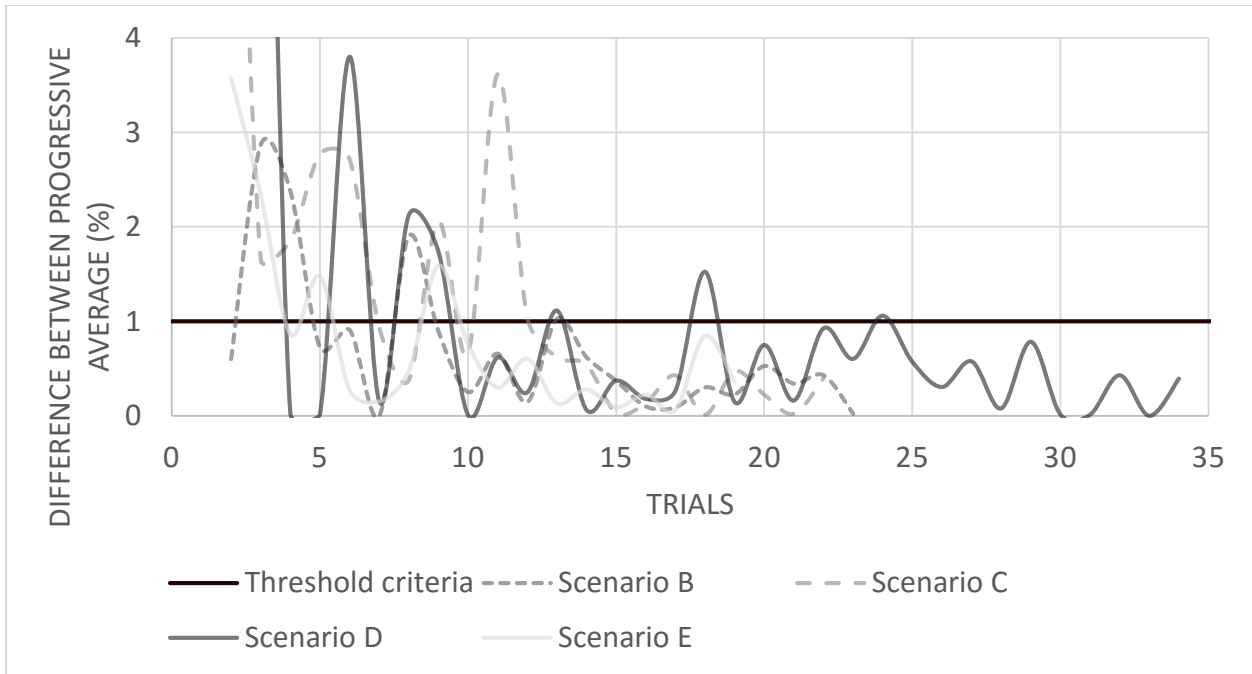


Figure A 6 Difference between progressive averages for flow rates of specified settings scenarios

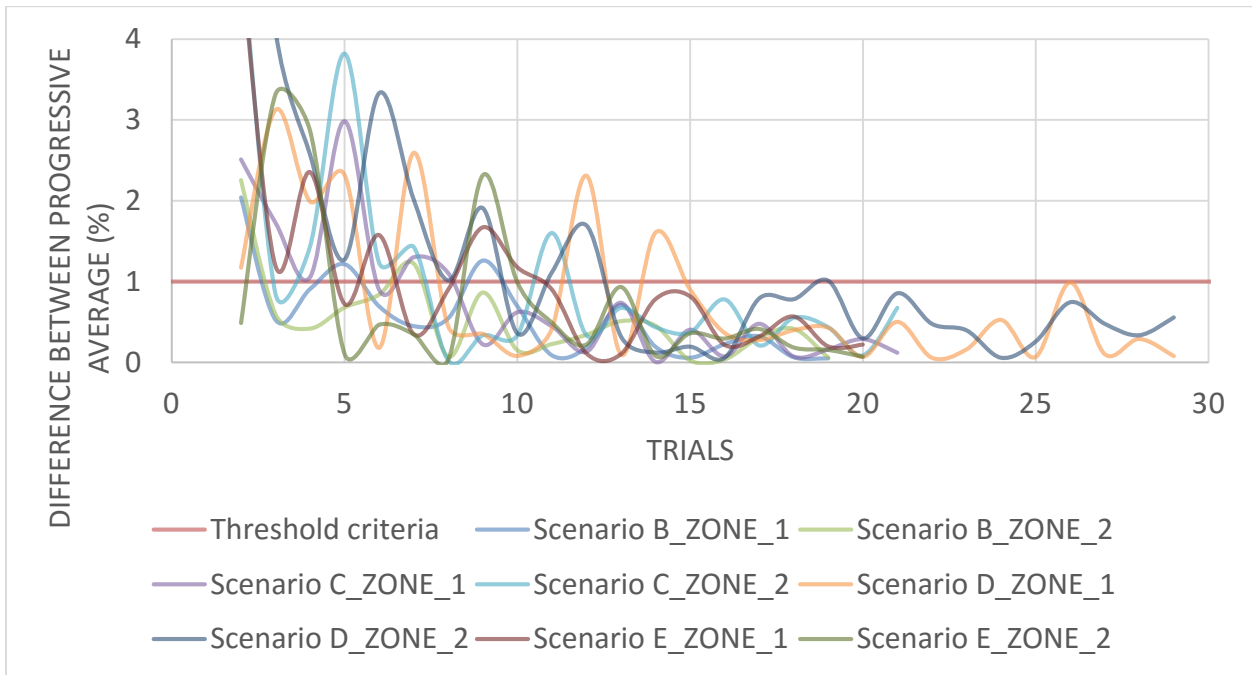


Figure A 7 Difference between progressive averages for density zones of specified settings scenarios

8.2 Appendix B: Validation Test 2

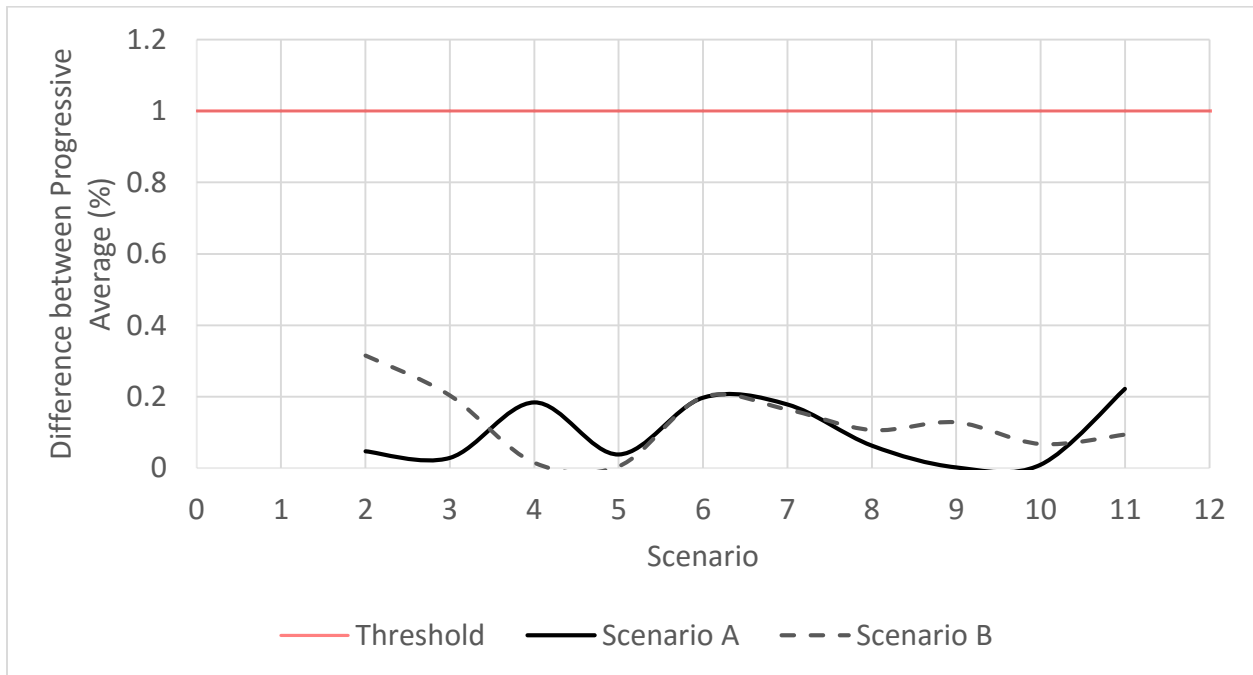


Figure B 1 Convergence Criteria for Pre-Evacuation Times in Cinema Theatre Test

Table B 1 Results of Pre-Evacuation Time and Comparison with Benchmark test for Scenario A

	Row 1	Row 2	Row 3	Row 4	Row 5	Row 6	Row 7	Row 8	Row 9	Difference (%)
Average	34	34	32	33	33	42	33	31	32	2%
MIN	24	25	25	23	25	23	25	25	20	3%
MAX	42	44	41	54	45	60	48	41	51	4%
STD	4	4	3	5	4	9	5	3	6	27%

Table B 2 Results of Pre-Evacuation Time and Comparison with Benchmark test for Scenario B

	Row 1	Row 2	Row 3	Row 4	Row 5	Row 6	Row 7	Row 8	Row 9	Difference (%)
Average	33	32	34	32	28	29	32	31	30	0.89%
MIN	26	27	25	24	25	21	20	26	22	1.11%
MAX	41	38	48	41	30	36	42	36	37	0.64%
STD	4	3	6	4	1	3	5	3	4	0.76%

8.3 Appendix C: Validation Test 3

Table C 1 Benchmark experiment data

Stage	N	Corridor Flow		Stairs Flow		Sum Flow		Merging Ratio	
		Flow (p/s)	Specific Flow (p/s/m)	Flow (p/s)	Specific Flow (p/s/m)	Flow (p/s)	Specific Flow (p/s/m)	Flow (%)	Specific Flow (%)
First Stage	1	1.50	1.15	1.50	1.25	3.00	2.40	50.00	47.90
	2	2.00	1.54	1.20	1.00	3.20	2.54	62.50	60.60
	3	1.67	1.28	0.83	0.69	2.50	1.97	66.80	65.00
	4	1.54	1.54	1.00	0.83	2.54	2.37	60.60	65.00
	5	1.62	1.62	1.00	0.83	2.62	2.45	61.80	66.10
	9*	1.67	1.28	0.83	0.69	2.50	1.97	66.80	65.00
Stable Stage	1	1.03	0.79	1.05	0.88	2.08	1.67	49.50	47.30
	2	1.06	0.82	0.94	0.78	2.00	1.60	53.00	51.30
	3	1.21	0.93	0.75	0.63	1.96	1.56	61.70	59.60
	4	1.04	1.04	0.75	0.63	1.79	1.67	58.10	62.30
	5	0.91	0.91	0.74	0.61	1.65	1.52	55.20	59.90
	6	0.79	0.79	1.65	1.18	-	-	-	48.00
	7	0.76	0.76	1.66	1.19	-	-	-	45.80
	8	0.65	0.65	1.68	1.20	-	-	-	38.60
	9*	1.21	0.93	0.75	0.63	1.96	1.56	61.70	59.60
Final Stage	1	0.88	0.67	0.63	0.52	1.51	1.19	58.30	56.30
	2	0.50	0.38	0.50	0.42	1.00	0.80	50.00	47.50
	3	0.54	0.41	0.77	0.64	1.31	1.05	41.20	9.00
	4	0.65	0.65	0.59	0.49	1.24	1.14	52.40	57.00
	5	0.50	0.50	0.69	0.57	1.19	1.07	42.00	46.70
	9*	0.54	0.41	0.77	0.64	1.31	1.05	41.20	9.00

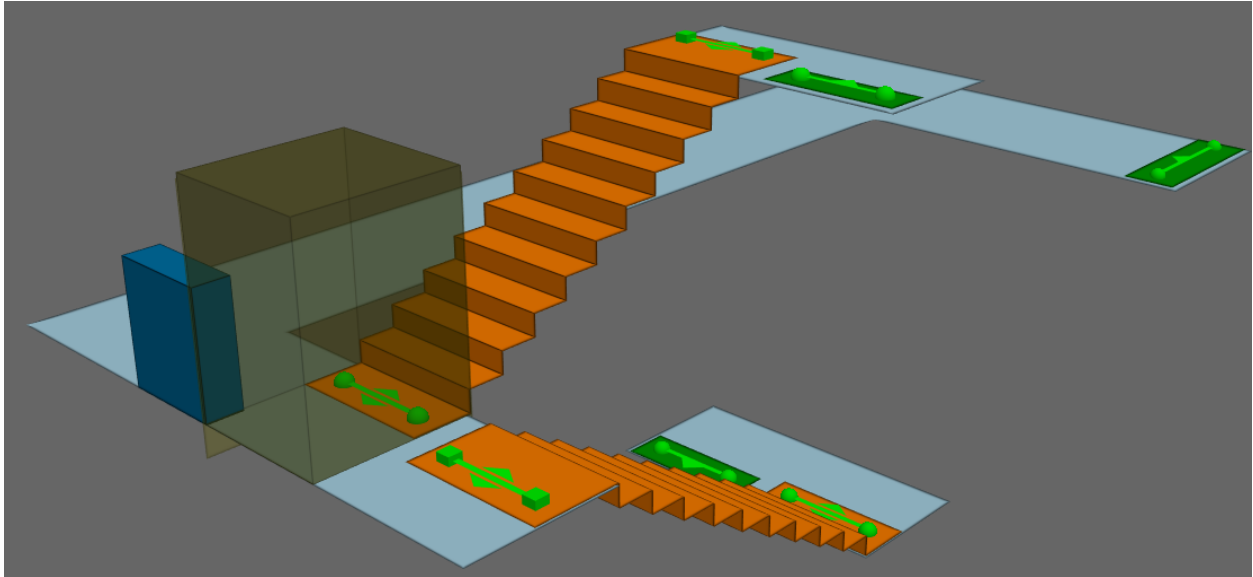


Figure C 1 Layout of Scenario 4 in Validation Test 3

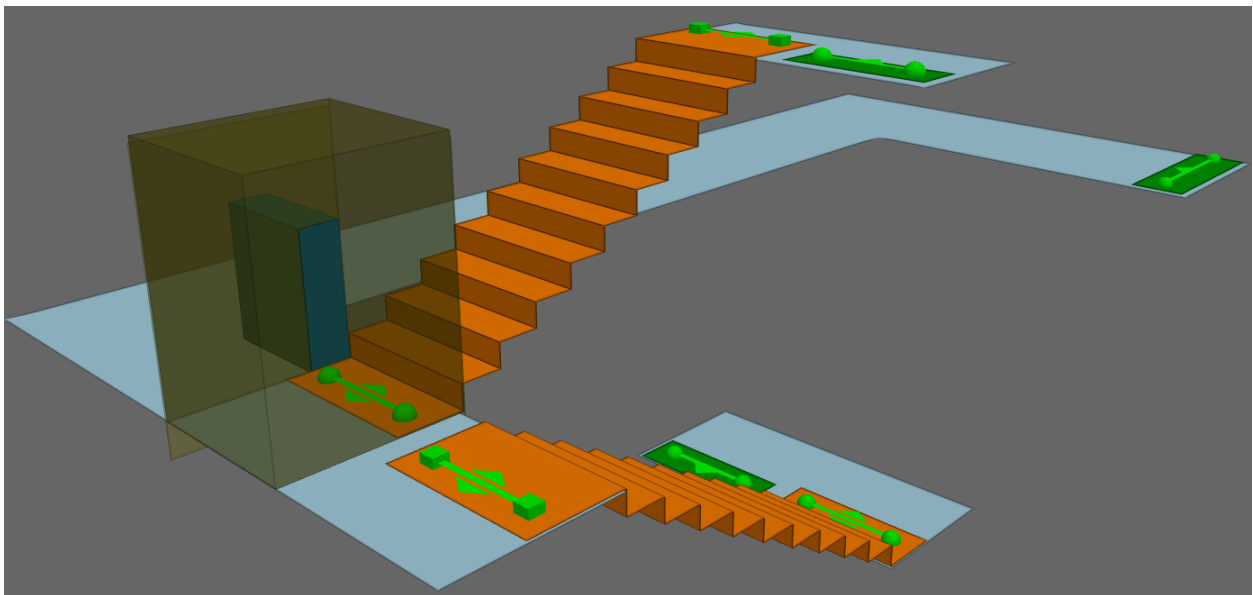


Figure C 2 Layout of Scenario 5 in Validation Test 3

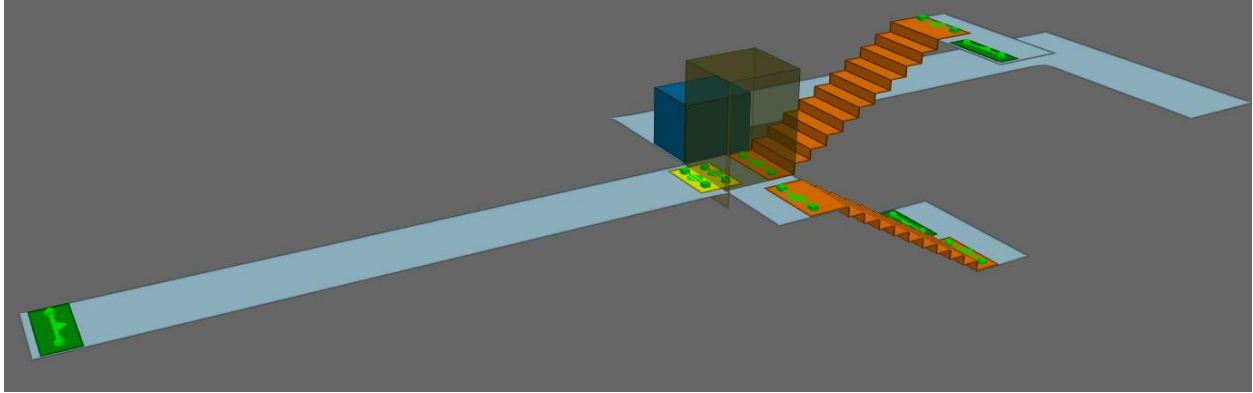


Figure C 3 Layout of Scenario 6 in Validation Test 3

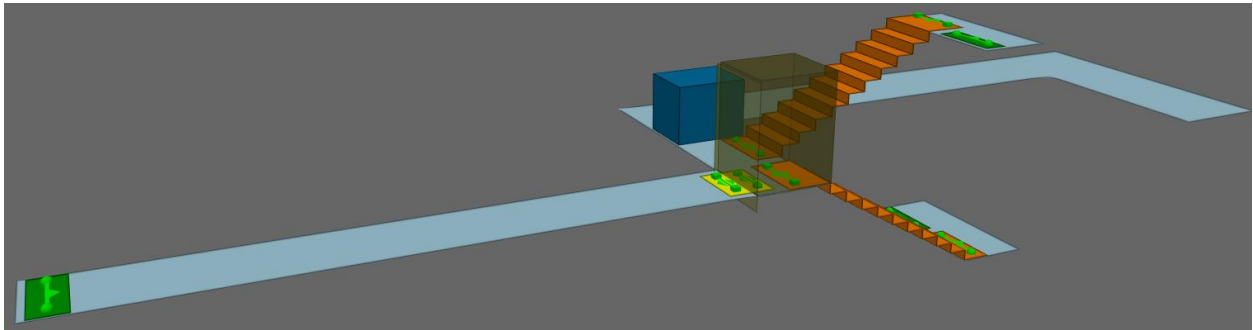


Figure C 4 Layout of Scenario 7 in Validation Test 3

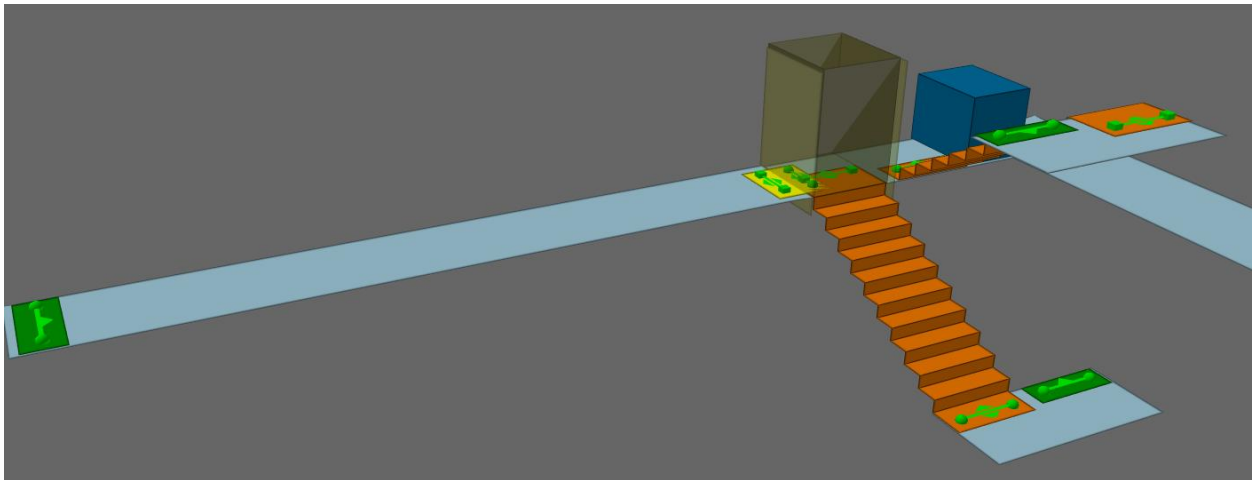


Figure C 5 Layout of Scenario 8 in Validation Test 3

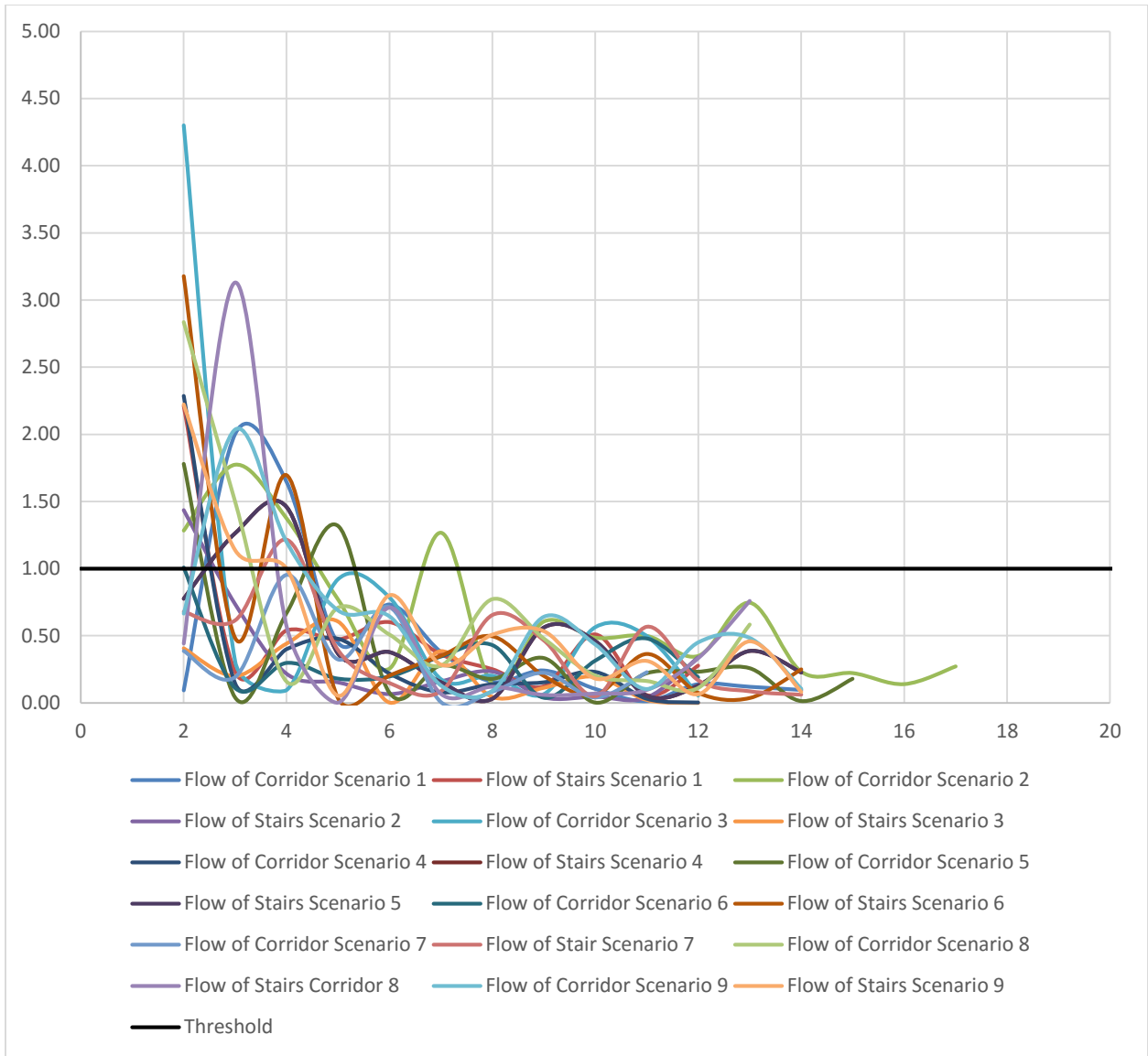


Figure C 6 Difference between Progressive Averages for Scenario 1-9 in Validation Test 3