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Testing the International Standards Organization Verification and Validation protocol for evacuation simulations - An application to the FDS+Evac model

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Abstract

Nowadays, many evacuation models exist in the market, and new models are continuously released with new features. How to assess the usability and reliability of model results becomes an issue for both developers and users. Therefore, verification and validation (V&V) protocols were introduced in the assessment process of evacuation models. To conduct V&V of a model, a widely accepted test procedure should be defined and followed by the tester. However, there are no comprehensive and globally accepted V&V test procedures available to conduct V&V of evacuation models. Therefore, the International Standard Organization Verification and Validation Standard (ISO V&V Standard) (ISO, 2019) was proposed as a new benchmark of V&V for building evacuation models. This ISO document (ISO, 2019) includes carefully designed V&V tests based on accepted knowledge of human behaviour in fire and building features. Notably, a most comprehensive validation test procedure is provided with a list of recommended experimental data for the first time, along with methods to conduct the mode results evaluation. This thesis goes through the whole ISO V&V test procedure including a global validation test by applying it to a simulator named FDS+Evac (Korhonen, T., & Hostikka, 2009). The benefits of the application of the ISO test procedure in V&V were identified and discussed in comparison with existing test procedures. Based on the simulated results except test 26, the issues and challenges of FDS+Evac and current evacuation models were analysed and summarised. It should be noted that the ISO document referred in this thesis is undergoing modifications and is routinely updated by ISO; therefore, the thesis work can be used to provide possible suggestions for improvements to refine the ISO V&V Standard protocol.

摘要

如今，很多的人员疏散（撤离）模拟模型（软件）可供选择和使用。新的模型也在不断地进行研发并且具备新的功能。但是，如何对这些模型和软件就行实用性和可靠性的验证，是一个对开发者和测试者都具有的难题。因此，验证及确认（**verification and validation**）被提出并且用于对撤离模型的评估中。在进行验证及确认的过程中，一个被广泛接受的验证及确认流程应该被规定下来，测试者也应该遵循此流程。但是，现如今没有一个可被广泛接受和认可的测试流程能用于对撤离模型的验证及确认中。这是因为现有的验证及确认流程或多或少在实际应用中存在一些问题。因此，新的国际标准化组织起草的验证及确认标准（**International Standard Organization Verification and Validation Standard**）（**ISO, 2019**）被提出，并且作为新的对撤离模型的验证及确认流程的标准。在新的验证及确认标准中，包含有精心设计的验证及确认的测试实验。这些实验都是结合最新的人类行为学和建筑发展精心设计的。尤其是对确认部分（**validation**）的测试流程和建议的实验数据来源的详细陈述，尚属首次。本文将用 **FDS+Evac**（**Korhonen, T., & Hostikka, 2009**） 软件对整个 **ISO** 验证及确认流程中的各个测试实验进行模拟。经过与现有的验证及确认流程的对比，使用 **ISO** 验证及确认流程的优势将被详细陈述。基于各个测试实验的结果，在模拟过程中发现的问题和将来面对的挑战将会分析和总结。由于本文使用的 **ISO** 文件尚处于最后的完善阶段，尚未发布，因此本文的一些结论可被用于对 **ISO** 测试流程的改进和完善。

Table of Contents

1 List of abbreviations

ISO	International Standard Organization
V&V	Verification and Validation
IMO	International Maritime Origination
RiMEA	Richtlinie für Mikroskopische EntfluchtungsAnalysen (Guideline for Microscopic Escape Analysis)
NIST	National Institute of Standards and Technology
PBD	Performance-Based Design
TET	Total Evacuation Time
ASET	Available Safe Evacuation Time
RSET	Required Safe Evacuation Time
MFR	Maximum Flow Rate
AFR	Averaged Flow Rate
p	Person(s)
FED	Fractional Effective Does
SD	Standard Deviation
ERD	Euclidean Relative Difference
EPC	Euclidean Projection Coefficient
SC	Secant Cosine

2 List of used namelist and commands from the FDS+Evac User Guide

&PERS	a namelist group used to define different agent types and properties such as walking speed, pre-evacuation time, etc.
&CORR	a namelist group used to define stairs and horizontal corridors
&EXIT	a namelist group used to defines an exit, which removes agents from the calculation for good
&EVSS	a namelist group used to define an incline such as stairs, a spectator stand or an escalator
&STRS	a namelist group used to define an entire staircase
&INIT	a namelist group used to set initial condition of a simulation began at time=0 such as temperature, pressure, components and concentration of the gases/soot, etc.
KNOWN_DOOR _PROBS	a parameter of &PERS. It defines the probabilities that the exit doors are known
PRE_EVAC_DIST	the type index of the reaction time distribution
DET_EVAC_DIST	the type index of the detection time distribution
TIME_CLOSE	a parameter of &Exit. It defines the time (s) when this exit becomes unusable
DENS_INIT	the initial density of agents (p/m2). Normally, the value should be less than 4
AGENT_TYPE	a parameter used to define the type of agents from four types: conservative, active, herding and following. This parameter cannot be found in FDS+Evac User Guide since the associated model is currently under development
HUMAN_SMOKE _HEIGHT	a parameter pacifying the level above the floor, where the smoke and FED information is taken
Adult	one of the default agents in FDS+Evac. There are five default agent types defined, and they are 'Adult', 'Male', 'Female', 'Child', and 'Elderly'
WAIT_AT_XYZ	a parameter used to point a place where agents wait for elevators. LOCKED_WHEN_CLOSED: a parameter used to control the agents stop at the door line if the door/exit is closed
TARGET_WHEN _CLOSED	a parameter used to control the door/exit is included in the door selection algorithm even if it is closed
ELEVATOR	if it is set TRUE, a &CORR is defined as an elevator
TRAVEL _TIME	a parameter used to define the travel time of an elevator from floor to floor
ESC_SPEED	a parameter used to define the upward/downward speed of an escalator defined by &EVSS
FCONST_A, FCONST_B, L_NON_SP	three controlling parameters for the social force model

3 Table of tables and figures

4 Introduction

Different inconsistent methods and procedures are applied today for the verification and validation (V&V) of evacuation simulation results. IMO (International Marine Organization) test procedure, namely MSC/Circ.1238 (*Guidelines for evacuation analysis for new and existing passenger ships*) (IMO, 2007), is widely used by evacuation model testers, especially in the maritime context. Test procedures like the NIST testing procedure (Ronchi, Kuligowski, Reneke, Peacock, & Nilsson, 2013b) and the RiMEA testing procedure (Rimea, 2016) are also used in the field of evacuation simulation in buildings. However, those procedures for the V&V of evacuation simulation models present a set of issues. For instance, IMO test procedure was initially designed for maritime evacuation applications. Therefore, structural components widely equipped in modern buildings were not in the testing list such as escalators, lift, etc. RiMEA test procedure came out to address this issue and tried to optimize the test procedure to fit building evacuations. However, the RiMEA test procedure does not include any validation test. Improvement has been made in NIST Technical Note 1822: *The Procedure of Verification and Validation of Building Fire Evacuation Models* (Ronchi et al., 2013b) to broaden and optimise the test procedure to modern buildings with seventeen verification tests and to provide suggested validation tests. However, from the view of the author, the NIST test procedure still has space of improvement in validation section by specifying validation teats in more detail. Therefore, an ongoing effort has been started by the International Standard Organization to develop a Validation and Verification standard for building fire evacuation simulation (ISO V&V standard (ISO, 2019) is used in the thesis, and it is referred here either with the term standard or protocol). The scope is to develop a comprehensively acceptable V&V test procedure for evacuation results and software. The ISO V&V standard is deemed to play an essential role as a benchmark document to evaluate whether evacuation software meets the requirements and specifications for their intended purposes. At the time this thesis was conducted, the first edition of the ISO V&V standard is at the latest stage of development. This means that only a draft version is available. Therefore, this thesis evaluated the draft version of the ISO V&V Standard with a set of V&V tests currently available and try to find the benefits of the application of the ISO V&V standard. Meanwhile, the thesis work is also useful to inform refinement of the tests.

The current draft of the ISO V&V standard introduces twenty-one verification tests for component testing and nine validation tests with suggested experimental data. Seventeen tests of verification are directly designed based on the IMO document and NIST document, but four tests are brand new. In the verification section, a list of tests (see Section 2.2 for detail) is designed to verify essential components in evacuation models reacting to building fires (evacuations). Main functionalities analysed in the verification section contain pre-evacuation time, movement of agents (byname of evacuees in evacuation simulations, an agent has its personal properties and escape strategies), navigation/route selection and flow condition in the ISO V&V Standard document. All verification tests mostly focus on these functionalities. In the validation section, tests (see Section 2.3 for detail) are designed to evaluate the ability of evacuation model to represent the scenarios where field experiments were conducted. Both component validation and global validation in The IOS V&V Standard document should be analysed in order to ensure that an evacuation model is able to simulate individual aspects of an evacuation scenario as well as ensuring that the combination of all sub-models, algorithms and modelling methods implemented lead to accurate results for a complete evacuation scenario in buildings. The necessary procedure in the validation is to compare the simulation results with experimental data. Therefore, sources of experimental field data are recommended in each test. The validation tests could be conducted based on these field experiments in geometry or methodology.

Open calculation or blind calculation (Lord, Meacham, Associates, & Fahy, 2005) can be used in the design of the test in verification and validation depending on the availability of data. Blind validation is a type of test that the tester only knows the basic description of the scenario to be modelled (Lord et al., 2005). This test method will ignore the existence of variables. There is no necessary to compare the results with the benchmark data-sets as well. Therefore, the tester is more critical for defining the scenario and calibrating the models. In the open validation, the tester is provided with the most complete information about the scenario including the inputs provided with a specified calculation along with actual evacuation data or benchmark model runs completed using the blind calculation or specified calculation with the same model or results from a validated egress model for the same scenario to be modelled (Lord et al., 2005). Therefore, the comparison with results and benchmark data-sets is possible. The benchmark data-sets are mainly from experimental data. Blind testing should be performed only when the model has been first validated against open testing. In the thesis, these two validation tests are going to be used depending on the request of each test from the ISO V&V Standard.

Multi-simulations (multiple simulations) are encouraged in data analysis collaborating with a set of convergent criteria to address the impact of human uncertainty. The term *multi-simulation* means conducting many runs of the same scenario under the same settings and collecting data from all of runs. However, there is a question: how many runs should be conducted. This part will be detailed in the methodology section.

4.1 Purpose and objectives

The purpose of this thesis is to study the usability of the draft ISO V&V standard (ISO, 2019) and apply the methodology to the FDS+Evac simulator (Korhonen & Hostikka, 2008) which is the agent-based evacuation calculation module of the Fire Dynamics Simulator(Korhonen, T., & Hostikka, 2009). It should be noted that the ISO V&V protocol was also tested against simulated results from another evacuation simulator named SimTread (Kimura, T., Sano, T., Hayashida, K., Takeichi, N., Minegishi, Y., Yoshida, Y., & Watanabe, 2009). The benefits of the usage of ISO V&V standard were summarised by conducting all thirty-one tests from both validation and verification section. Meanwhile, limitations were also pointed out for further improvement.

The objective of the thesis is to conduct verification and validation based on the tests in the ISO document (ISO, 2019). The focus was on the new ISO tests (ISO, 2019) and comparison with existing procedures such as IMO procedure. Verification tests were verified into four sections: basic component, behaviour component, fire-people component and building-specific component (IMO 2016). All validation tests were conducted as well except test 26 since no suitable experimental data-sets were identified for those tests.

4.2 Method

The ISO document referred in this thesis is currently under developing as a draft version. Therefore, this thesis will serve as the pilot of those tests and provide possible improvement to these tests and the ISO document. In this thesis, FDS+Evac simulator (Korhonen & Hostikka, 2008) was used to conduct tests of validation and verification. It is an open-source evacuation simulation model developed and maintained by VTT, Finland. FDS+Evac allows performing performance-based design in fire safety engineering about measuring ASET (available safe egress time) and RSET (required safe egress time). The inputs for the tests conducted in this thesis were developed by hand coding. The output of the simulator was collected and analysed by hand and by a tool developed by Erik Smedberg in Lund University (Smedberg, 2019). Each test would be documented in a specific template (as provided in the draft ISO standard (ISO, 2019)) with all details such as the defined properties of agents, the scenarios and the results etc. The appendix 1 contained the full version of the filled test templates; only the results were shown in the thesis.

The tool developed by Smedberg (Smedberg, 2019) was mainly used for the calculation of the convergence criteria and flow rate in this thesis. Acceptance criteria, referred from the description in the ISO document, form the basis for assessing the acceptability of the safety of the design of a building It should be mentioned that the tool was initially designed for another evacuation simulator named Pathfinder (Smedberg, 2019) and it was modified in the context of this thesis to be usable also for FDS+Evac.

4.3 Limitations

The first limitation is that evacuation modelling is a relatively new field of science and the capabilities of evacuation models are rapidly developing (Kuligowski et al., 2010). Therefore, there is a difficulty in developing a comprehensive list of tests which can evaluate their evolving capabilities (Ronchi et al., 2013). Meanwhile, since the IOS V&V Standard document is currently under development, the tests might be modified in later versions.

V&V tests were conducted by applying the sub-models included in FDS+Evac. There usually is not only one sub-model available to achieve the test scenario. For instance, sub-models like &STRS and &EVSS are both available to build a staircase. However, only one sub-model was chosen in each test. Differences may exist in the results when different sub-models are applied. Further studies are needed to address this issue, mainly when new software is about to be tested by following the test procedure in the ISO V&V Standard document.

Meshes are used for building the geometry and the route choice algorithm but not for movement modelling in FDS+Evac. Limited by choice of the mesh size, the geometry in each scenario is typically optimised to match the mesh size. The geometrical length could be slightly stretched or compressed. Therefore, differences could be introduced in the results relative to the layout of the buildings and the route choice. A compromise had been made between the performance and accuracy of the simulation.

The acceptance criteria, as the basis for assessing the acceptability of the safety of the design of a building, were used in the data processing. However, the acceptable thresholds for convergent criteria are still in debate. The values of the acceptable thresholds used in this thesis were directly referred from the examples provided in Ronchi et al. (2013). Details of the thresholds can be found in section 2.4.

A comprehensive uncertainty analysis was not conducted in this thesis due to the lack of time. Quantification of uncertainty is a crucial topic in evacuation simulation. In this thesis, only behavioural uncertainty was included in data analysis.

Although the tool made by Smedberg (Smedberg, 2019) was successfully adapted to run multiple simulations, it should be tested by applying more data from FDS+Evac simulator to identify possible issues. Results in this thesis were calculated by the tool in Version 3.2.

5 Verification and Validation of Evacuation Models

Verification is defined as '*the process of determining that a calculation method implementation accurately represents the developer's conceptual description of the calculation method and the solution to the calculation method'* (International Standards Organization, 2008).

Validation is defended as *'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'* (ISO, 2008). Validation, also named as quantitative validation or quantitative verification (terms used in the IMO test procedure and RiMEA test procedure respectively), is used for the assessment of the capability of a model to represent and predict the behaviours of agents based on current theoretical and experimental knowledge in evacuation simulation.

5.1 Evacuation simulation and simulators

The primary purpose of using evacuation models and simulators in fire safety engineering is to calculate the evacuation time for engineering analysis in performance-based design (PBD). Two types of time are the most important in PBD: ASET (available safe egress time) and RSET (required safe egress time). ASET is the time between fire detection and the onset of conditions which are hazardous to continue human occupancy (Cooper, 1983). REST is the time needed for occupants to leave the hazardous environment and reach a safe place. REST should be less than ASET since life safety is the priority in PBD. Therefore, ASET is generally calculated by fire models/simulators which contain the estimation of the factors such as temperature, fire spread, toxicity, etc. In the past decades, the capabilities of the prediction of fire models have had significant progress due to the flourishing growth of the computational power and knowledge of fire safety. Therefore, the accuracy of the prediction of these factors relative to fire is improving.

However, calculation and analysis of RSET have stagnated (Averill, Reneke, & Peacock, 2007). The reason for the stagnation is not the lack of efforts and studies but the limitation of the natural property of RSET itself. Unlike the ASET, REST is often not treated as a deterministic value as it is associated to behavioural uncertainties (Averill et al., 2007). This means that enough data are required to verify the model/simulator and validate the simulated results. However, there is a shortage of data generated by researchers' study REST due to the complexity and high expense in data collection.

5.2 Evacuation model testing

It is a fact that today it is impossible to precisely predict the individual behaviour of an evacuee in a fire scenario. However, we can understand the trends in their behaviours in an emergency fire situation based on the current knowledge/theories of human behaviour. Evacuation models are often used to establish a REST time in the performance-based design. Meanwhile, models are designed to have the ability to evaluate the evacuation dynamics in different scenarios such as flow rates, density, etc. Because of the development of computational technology, evacuation models and simulations are developed continuously. The importance of the evacuation models is increasing in the field of fire safety engineering. Therefore, the performance and reliability of evacuation models are vital and should be proved before their application in real projects.

Verification and validation (V&V) are introduced into this objective to assess whether the test model could generate useful, appropriate and credible results about the application under consideration. Frequently, the tester will change and modify the default assumptions in the model to fit different scenarios. In this case, the tester must confirm that the performance and the results of the model are still reliable. Therefore, V&V is an essential part of the evacuation model testing. In this thesis, the author conducted the new ISO V&V test procedure (ISO, 2019) and reviewed various existing test procedures in details. Here, a more general review of evacuation model testing will be conducted in this section.

Four aspects should be considered in evacuation model testing based on the description from SFPE Human Behaviour Guide in Fire (2017). They are:

1. *The selection of an appropriate evacuation model.*
2. *The configuration of the selected evacuation model for the scenarios of interest.*
3. *The testing of the configured evacuation model to assess whether it is fit for purpose.*
4. *The reporting of test results.*

Based on the SFPE Human Behaviour Guide in Fire (2017), the testing process can be classified into two categories: pre-model execution which includes the model selection and model configuration, and post-model execution which includes the model verification and model validation/calibration. The first two aspects are in the category of the pre-model execution. The post-model execution is an extension of the third aspect. *The reporting of test results* will not be discussed in this section since it is not the critical point of this thesis.

PRE-MODEL EXECUTION

Model selection

There are many evacuation models in the market, but the ability to simulate the same scenario varies from model to model even if the model user effect is not taken into consideration(Ronchi, 2013). Selecting a suitable model for a scenario simulation is critical so that the tester needs to justify the use of the selected model.

A proper model selected for a particular scenario should fulfil these requests. First, a formal document to describe the model's assumptions and functionality should be provided to the tester so that the tester can have better understandings of the model itself and the limitations of the usage. Previous model testing should also be documented to avoid waste of effort in the testing. Then, the tester should have a clear sense about how the model responses to the tester's action since the model may be predicted fully controlling of the movement of the agents in the simulation rather than user-driven. If this is a user-driven model, the expertise of the tester can be essential to the reliability of results. The technical document or user guide should be available to give a thorough description of the application field including the scale of the project that the model could cope with and target scenarios that the model could present. The document should also contain the details of sub-models and means to represent core components such as human behaviours, simulated agents, decision-making procedures, etc. The last aspect is whether the output that the model provide can meet the demands of the expected data analysis. Combined with all requests mentioned above, the tester should have an essential judgement about the appropriateness of the selected model for the scenario.

Model configuration

After a model selection, the tester must configure the model to fit the scenario. A set of initial conditions are decided by the tester based on the real scenario and properties of occupants. These initial conditions can make the simulated scenario try to restore the real scenario. Therefore, the quality of the initial conditions is vital to reflect the scenario. The first thing to determine the initial conditions is to identify scenario factors such as the population property, the application of the way-finding system, etc. The expected impact of these factors should be identified on aspects of walking speed, pre-evacuation time, flow rate, exit/route choice, etc. Once the impacts are found, the tester should check whether the default settings of the model are plausible to represent the scenario. If it is not, the tester must modify the settings based on the available information provided by the model and make the proper changes to enhance the presentation of the expected scenario.

POST-MODEL EXECUTION

Verification and model validation/calibration

Post model execution includes verification and validation/calibration of results. The details of V&V will not be introduced here since this thesis has already had a thorough description in section 2. Calibration mentioned in this section is a process that minor modification of settings can be made to improve the model's results in the validation stage.

Benchmark data and comparison techniques are critical in the validation section. Typically, experimental data are selected as the benchmark data for a particular scenario to reflect the real-world conditions, or results simulated form other models, ideally those that have been rigorously subjected to the validation process (SFPE Human Behaviour in Fire Task Group, 2017). Other sources of benchmark data also can be adopted such as evacuation exercises, a real incident, etc. The tester has to be aware of the limitations of the selected data in their completeness, consistency, refinement and description (SFPE Human Behaviour in Fire Task Group, 2017). It is recommended to use multiple data-sets for a single validation case, but it usually is impossible due to the lack of data-sets. Some comparison techniques are necessary for the comparison between benchmark data-sets and simulated results. These techniques can be classified into two categories: qualitative assessment means and quantitative assessment means. It is possible to apply multiple assessments means at the same time in one case. Sensitivity analysis was not emphasised in this thesis but important in the assessment of the impact of the input on the output. It ensures the model's predictions reflecting the real world expectation (SFPE Human Behaviour in Fire Task Group, 2017).

5.3 IMO test procedure

The IMO test procedure is initially designed for the verification and validation of maritime evacuation models/simulators. The IMO test procedure is described in detail in Annex 3, MSC.1/Circ.1553(IMO, 2016). It includes at least four forms of verification that evacuation models should be tested: component testing, functional verification, qualitative verification and quantitative verification (validation). The details of the test list with brief descriptions can be found in Appendix 1 in this thesis. The comparison with other test procedures can be found in section 3.

From the test list, the initial intent of the testing design mainly forces on verifying the basic components embedded in evacuation models/simulators. There are no designed tests or recommended experimental data for validation since there are few sufficient experimental data available at this stage. Overall, the IMO test procedure fulfils the fundamental requirement of component verification.

5.4 RiMEA test procedure

After a review of the IMO test procedure, the RiMEA test procedure was developed for more general building applications. The RiMEA test procedure is described in detail in Annex 1, *Guideline for Microscopic Evacuation* Analysis (Rimea, 2016). It has the same forms of verification as IMO test procedure. The main improvement is that tests are adapted and added according to new knowledge and research of evacuation simulation of buildings. The details of the test list with brief descriptions can be found in Appendix 1 in this thesis. The comparison with other test procedures can be found in section 3.

The RiMEA test procedure presents more details such as testing scenarios, expected results if compared to the IMO test procedure(IMO, 2016), etc. More importantly, the RiMEA test procedure is designed for modern buildings, hence except basic components, other components such as behaviour component are firstly taken into consideration. However, tests relative to fire-people interaction are missing. Other functional components installed in modern buildings like escalators are not included in the testing list as well. There are no tests designed for validation. Overall, the RiMEA test procedure contains an improved list of tests for the analysis of evacuation simulators in buildings, but issues still exist.

5.5 NIST test procedure

Since none of the test procedure mentioned above can be thought of as a comprehensive and acceptable testing procedure, National Institute of Standards and Technology (NIST) provided their own guidance on test procedure, in the document *The Process of Verification and Validation of Building Fire Evacuation Models* (Ronchi et al., 2013), to set a standard for the V&V of evacuation simulators/models. This is a further improved test procedure of V&V of evacuation simulation which considers existing test procedures, the knowledge of human behaviour in fire and some newest features of modern buildings. The NIST test procedure includes seventeen verification tests and a list of validation tests with suggested experimental data-sets. Tests are designed by using five core components of evacuation models (Gwynne et al., 2012a): pre-evacuation time, movement and navigation, exit usage, route availability and flow condition, which will be concentrated into four core components in the new ISO document (ISO, 2019). It should be noted that the new ISO test procedure (ISO, 2019) is mainly designed on the foundation of the NIST test procedure. The details of the test list with brief descriptions can be found in Appendix 1 in this thesis. The comparison with other test procedures can be found in section 3.

In the NIST test procedure, tests for verification are classified by newly-defined core components into five categories: pre-evacuation time, movement and navigation, exit usage, route availability and flow condition. It provides a more explicit classification of key features embedded into simulators/models used for evaluation simulation of buildings which the tester should look at. Meanwhile, quantitative evaluation and qualitative evaluation of model results are suggested as test methods employed for verification. The validation section lists seven tests with different suggested variables, such as evacuation time, exit choice, flow, etc., and recommended experimental data. Methods of analysis of human uncertainty are also offered.

6 The ISO V&V Standard

In this section, the ISO test procedure is introduced in detail with a comparison of designed tests between the ISO test procedure and other three existing test procedures. Meanwhile, methods for uncertainty analysis are briefly described, and a tool designed for data analysis is introduced.

6.1 Verification and verification tests in ISO Standards

According to the ISO standard, four categories of components should be verified in an evacuation model: basic components, behavioural components, fire-people interaction components and building-specific components. The methods for verification include two parts: quantitative evaluation and quantitative evaluation. In this thesis, the choice of whether quantitative verification or quantitative evaluation should be conducted was given by the request of each test in the ISO document. The expected results were also provided with the tests.

The term *Sub-model(s)* is used in this thesis to express the models embedded in an evacuation model/simulator such as FDS+Evac simulator. The author classified sub-models into two categories: primary sub-models and secondary sub-models. The primary sub-models include four main models: agent movement model, counter-flow collision avoidance model, fire and human interaction model and exit selection model. The primary sub-models are the theoretical basis of the evacuation model in FDS+Evac so that few options can be controlled in the primary sub-models. The secondary sub-models consider the simulation more into detail. For instance, a staircase can be represented by using the secondary sub-model &STRS including the very details of the geometry of the staircase. These secondary sub-models have plenty of user-defined parameters available to control and modify each evacuation scenario. In verification, both primary and secondary sub-models are verified by tests designed in the ISO document.

It should be mentioned that the tests listed below are suggested but not limited by the ISO V&V standard since the new components (sub-models) could be purposed and added in the future. The term *New test* means that the test is entirely newly-designed compared with tests available in the NIST test procedure (Enrico, Kuligowski, Reneke, Peacock, & Nilsson, 2013). Tests modified from the NIST test procedure, and the RiMEA tests procedure are listed and explained. More details of the comparison of these three test procedures can be found in section 3.

The first category is the ***basic components*** which are used to represent basic evacuation scenarios. These components represent the fundamental ability of an evacuation simulator. Tests of the basic components currently include thirteen tests in the ISO V&V Standard (ISO, 2019):

Test 1. Pre-evacuation time assignment
Test 2. Walking speed in a corridor
Test 3. Walking speed on stairs (modified from NIST test 2.2)
Test 4. Movement around a corner (modified form NIST test 2.3)

Test 5. Assigned demographics
Test 6. Horizontal counter-flows
Test 7. People with movement disabilities
Test 8. Exit route allocation
Test 9. Dynamic availability of exit
Test 10. Congestion in front of a flight of stairs (modified form NIST test 5.1 and RiMEA test 13)
Test 11. Maximum exit/door flow rates
Test 12. Stair flow rates (new test)
Test 13. Relationship between walking speed, unidirectional flow and density (modified from RiMEA Test 4)

The second category is the ***behavioural components***. These components are used to achieve the theories of human behaviour such as affiliation, social influence, etc. Tests of the behavioural components currently include four tests in the ISO V&V Standard (ISO, 2019):

Test 14. Group Behaviour
Test 15. Social influence on exit choice
Test 16. Affiliation to familiar exits (slightly modified form NIST test 3.3)
Test 17. Route choice (modified from RiMEA Test 14)

The third category is the ***fire-people interaction components***. This category is to represent the interaction between occupants and the effect of fire. This category gives an interface between fire models (ASET) and evacuation models (RSET) by representing the impact of smoke and toxic gases generated by a fire on the behaviours of occupants in the evacuation simulation. Tests of the firer-people interaction components currently include two tests in the ISO V&V Standard (ISO, 2019):

Test 18. Reduced visibility vs walking speed
Test 19. Occupant incapacitation

The fourth category is the ***building-specific components***. This category is for components that a model may be included for special applications such as escalator, lift, etc. It should be mentioned that the components are not limited by the tests in the ISO V&V Standard. Every available unique component in an evacuation model/simulator should be listed and verified in this section when the IOS test procedure is applied even if the component was not listed. New tests of verification could be added based on the demand for new components. Tests of the building-specific components currently include two tests in the ISO V&V Standard (ISO, 2019):

Test 20. Lift usage (slightly modified form NIST test 2.7)
Test 21. Escalator usage (new test)

It should be mentioned that the list should not be considered as an exhaustive list of verification tests since new components could be available at any time.

6.2 Validation and validation tests in ISO Standards

Validation is highly dependent on the availability of the experimental data for the analysis of the ability of a model representing the real-world evacuation scenario and the real human behaviour in a fire. Suggested experimental data were provided with each test in the ISO document. Meanwhile, only quantitative validation was conducted since the comparison with the real data should be processed in mathematics.

Two main aspects should be highlighted in the application of validation. The first aspect is the field of the application of the model (Galea et al., 1997). The performance of a model can only be ensured in the field where the model is initially designed for. For instance, a model fully designed for the maritime evacuation simulation could not be possible to provide credible results in a high-rise building evacuation simulation without any modification. If the model is attempted to be applied in other fields, the results should be untrustworthy unless a comprehensive validation and exclusive modification are conducted before the application. However, this request is often challenging to be achieved since the compatibility is negative and the available data may be insufficient for the modification and validation. The second aspect is the duration of validity (Galea et al., 1997), which requires that validation should be conducted after every update of the models or every change of the real-world condition.

In the ISO V&V Standard, two categories of validation, namely component validation and global validation, are purposed. Tests for component validation currently include nine tests in the ISO V&V Standard (ISO, 2019). They are all new-designed tests.

Test 22. Pre-evacuation
Test 23. Relationship between walking speed, uni-directional flows and densities
Test 24. Stairwell evacuation
Test 25. Flight of steps
Test 26. Movement around a corner
Test 27. Counter-flows
Test 28. Route/Exit choice
Test 29. Bottlenecks at openings
Test 30. Reduced visibility vs walking speed

The global validation should be conducted with full-scale data-sets from full evacuation scenarios. In this thesis, only one global validation test was conducted in a scenario of a 10-storey building. The data-sets recommended in the ISO V&V draft document (ISO, 2019) for global validation are listed below.

Building type	**Example of suitable experimental data-sets**
A nightclub	(Grosshandler et al., 2005)
A residential building	(Kuligowski et al., 2014)
	(Averill et al., 2005)

	(Kuligowski et al., 2014)
An office building	(Hostikka et al., 2007)
	(Sano et al., 2016)
A hotel	(Kobes et al., 2010)
	(Bryan, 1983)
A hospital/elderly home	(Hunt et al., 2015)
	(Purser, 2015)
An arena/stadium	(Hoskin and Spearpoint, 2004)
A theatre	(Bayer and Rejnö, 1999)
	(Galea et al., 2017)
An exhibition hall	(Zhang et al., 2012)
A library	(Hostikka et al., 2007)
A store	(Shields and Boyce, 2000)
	(Samochine et al., 2005)
A sports hall	(Paloposki, T., Myllymäki, J., Weckman, H., 2002)
A school	(Cuesta and Gwynne, 2016)
	(Najmanová and Ronchi, 2017)
	(Kholshchevnikov et al., 2012)
A train station	(Yeo and He, 2009)
A tunnel	(Fridolf et al., 2013)
	(Nilsson et al., 2009)
	(Seike et al., 2016)
	(Boer and Veldhuijzen van Zanten, 2007)
	(Fridolf et al., 2015)

It should be mentioned that the list should not be considered as an exhaustive list of validation tests since new and suitable experimental data could be available at any time.

A list of methods for analysing the results was suggested in the new ISO document. These methods were divided into two categories: *basic methods* and *advanced methods*. Referred from the ISO document (ISO, 2019), basic methods are designed for the evaluation of high-level results concerning an evacuation scenario while the advanced analysis methods look more in detail into the model predictions by quantitatively analysing the outcome of the simulations. In each validation test, methods were recommended at two levels: primary recommended tests and secondary recommended tests. Primary recommended tests should be considered as the main objectives in comparison with the experimental data while secondary recommended tests could be conducted if the data are provided in the data-sets. In this thesis, only suggested primary recommended tests in each validation test were conducted since the lack of time. However, a few primary recommended tests were not possible to conduct since the lack of available experimental data from the selected data-set/experiment for comparison.

Basic methods include four methods named from letter A to D including pre-evacuation time, arrival time comparison, exit choice comparison and comparison of flows through exit/doors.
All these methods consider multiple simulations and representative runs. More detail can be found

in the ISO document.

Advanced methods contain nine methods named from letter E to M. These methods contain more items for comparison, such as arrive time curve, arrive time in different section of scenario, route choice comparison, density comparison, queening time comparison, movement paths and travelled distance comparisons, relationship between flows, walking speeds and densities and Visual inspection of occupant behaviour of representative runs. More detail can be found in the ISO document.

6.3 Overview of four V&V test procedures

Table 1 below gives an overview of all verification tests from the IMO test procedure, the RiMEA test procedure, the NIST test procedure and the developing ISO test procedure. The tests from the new ISO test procedure was set as a standard in the comparison. All tests were divided into four categories: pre-movement(P), movement(M), navigation/route selection (N&R) and flow condition/constraints (F), which is a new category method relation to core components in the ISO document (ISO, 2019). Tests can also be classified by different methods, such as by levels (individual/aggregate and scenario level) which are addressed in the components, but not used here.

Tale 2 shows the overview of validation tests mainly from the NIST test procedure and the ISO test procedure in that the IMO and RiMEA test procedure did not provide any tests or suggested experimental data for validation. It is listed by the same category method mentioned above, but with an additional category of Route/Exit choice (E, R) which appeared in the list of components for validation testing from the ISO document (ISO, 2019). Since the validation tests in the NIST test procedure did not have test numbers so that tests are represented by the sub-element's name which the test focuses on.

From table 1, test 12 and test 21 in the ISO test procedure are brand new. Test 13 and test 17 are improved versions based on tests form the RiMEA test procedure rather than the NIST test procedure. A test which is about verifying the movement of a large crowd of people leaving a room was removed in the NIST and ISO test procedure but existed in both IMO and RiMEA test procedure. Some tests were slightly improved to be adopted in the ISO test procedure. A detailed comparison can be found in the discus section. From table 2, more data-sets are listed for the validation tests in the ISO test procedure.

Categories	Verification tests in ISO document	NIST	RiMEA	IMO
Pre-movement (P)	*Test 1:* **Pre-evacuation time assignment**	**Yes. Test.1.1**	**Yes. Test 5**	**Yes. Test 5**
Movement (M)	*Test 2:* **Walking speed in a corridor**	**Yes. Test 2.1**	**Yes. Test 1**	**Yes. Test 1**
	Test 3: **Walking speed on stairs**	**Yes. Test 2.2**	**Yes. Test 2 & 3**	**Yes. Test 2 &3**
	Test 4: **Movement around a corner**	**Yes. Test 2.3**	**Yes. Test 6**	**Yes. Test 6**
	Test 5: **Assigned demographics**	**Yes. Test 2.4**	**Yes. Test 7 & 8**	**Yes. Test 7**
	Test 6: **Horizontal counter-flows**	**Yes. Test 2.8**	*No*	**Yes. Test 8**
	Test 7: **People with movement disabilities**	**Yes. Test 2.10**	*No*	*No*
	Test 14: **Group behaviour**	**Yes. Test 2.9**	*No*	*No*
	Test 18: **Reduced visibility vs walking speed**	**Yes. Test 2.5**	*No*	*No*
	Test 19: **Occupant incapacitation**	**Yes. Test 2.6**	*No*	*No*
M - N&R	*Test 20:* **Lift usage**	**Yes. Test 2.7**	*No*	*No*
M - N&R	*Test 21:* **Escalator usage**	*No*	*No*	*No*
Navigation/ Route selection (N&R)	*Test 8:* **Exit route allocation**	**Yes. Test 3.1**	**Yes. Test 10**	**Yes. Test 10**
	Test 9: **Dynamic availability of exit**	**Yes. Test 4.1**	*No*	*No*
	Test 15: **Social Influence on exit choice**	**Yes. Test 3.2**	*No*	*No*
	Test 16: **Affiliation to familiar exits**	**Yes. Test 3.3**	*No*	*No*
	Test 17: **Route choice**	*No*	**Yes. Test 14**	*No*
Flow condition/ Constraints (F)	*Test 10:* **Congestion in front of a flight of stairs**	**Yes. Test 5.1**	**Yes. Test 13**	**Yes. Test 11**
	Test 11: **Maximum exit/door flow rates**	**Yes. Test 5.2**	**Yes. Test 12**	**Yes. Test 4**
	Test 12: **Stair flow rates**	*No*	*No*	*No*

	Test 13: **Relationship between walking speed, uni-directional flows and densities**	*No*	**Yes. Test 4**	*No*

Table 1 Comparison of verification tests from four test procedures

Categories	Validation tests in ISO document	NIST	RiMEA	IMO
Pre-movement (P)	*Test 22:* **Pre-evacuation** **(5 experimental data-sets available)**	**Yes.** **Pre-evacuation time distribution** **(only 1 data-sets available)**	*No*	*No*
Movement (M)	*Test 26:* **Movement around a corner** **(4 experimental data-sets available)**	*No*	*No*	*No*
Route/Exit choice (E, R)	*Test 28:* **Route/Exit choice** **(5 experimental data-sets available)**	**Yes.** **Impact of way-finding installations** **(only 1 data-sets available)**	*No*	*No*
Movement and Navigation/ Route selection (M,N&R)	*Test 23:* **Relationship between walking speed, uni-directional flows and densities** **(6 experimental data-sets available)**	**Yes.** **Stairwell evacuation** **(only 1 data-sets available)**	*No*	*No*
	Test 24: **Stairwell evacuation** **(9 experimental data-sets available)**			
	Test 25: **Flight of steps** **(2 experimental data-sets available)**			
	Test 27: **Counter-flows** **(3 experimental data-sets available)**			
	Test 29: **Bottlenecks at openings** **(5 experimental data-sets available)**			
	Test 30: **Reduced visibility vs walking speed** **(3 experimental data-sets available)**			
Flow condition/ Constraints (F)	*Contained in M, N&R.*	**Yes.** **Three small scale experiments** **(only 1 data-sets available for each)**	*No*	*No*
Global validation	**15 different types of buildings are listed with recommended experimental data. Full list can be found in section 2.3.**	**Yes.** **Full building evacuation** **(only 1 data-sets available)**	*No*	*No*

Table 2 Comparison of validation tests from four test procedures

6.4 Mathematical methods for assessing behavioural uncertainty

Behaviour uncertainty reflects the stochastic nature of human behaviour in action. Therefore, single data-sets could not fully represent the behaviour uncertainties of the occupants in an evacuation scenario. More data-sets will represent uncertainties into a specific range so that a full display of behaviours is possible. Hence, multiple simulations of one evacuation scenario are generally conducted in the simulation process. *'Behavioural uncertainty needs to be analysed in both experimental and modelling studies'* (Ronchi, Reneke, & Peacock, 2014). Therefore, a list of mathematical methods is adopted in the analysis of behaviour uncertainty. In this section, four methods are going to be briefly introduced.

Brute force

A simple mathematical method to use enough simulated runs to cover all possible results of the input variables in a case. The method can also be called as proof by exhaustion. The number of runs has no upper limit. Therefore, the runs could be only several times or thousands of millions of times dependent on the complexity of the case.

Fixed number

IMO guideline (IMO, 2016) gave an arbitrary minimum number of 500 runs for a simulated scenario and 95th percentile total evacuation time as the representative TET. It leads to a problem whether this fixed number of runs can capture all behaviour uncertainties, or it is too much that leads to a waste of computational power.

Qualitative visual assessment

This method requires the simulator having the function of visualising the results into 2D or 3D display. This function is installed in many current evacuation simulators such as FDS+Evac, Pathfinder, etc. This function gives the tester a better way to analyse the results by observing the simulation. However, it is just a qualitative method so that an accurate comparison of results could be tough. It also requests the tester having the knowledge about what should be observed, which makes the method highly user-dependent.

Dynamic assessment of variance in an output variable/series

This method is a mathematical analysis method for the uncertainty assessment of simulated results by using a set of convergence criteria to determine the optimised number of runs to minimise the computational burden.

A representative agent-evacuation time curve can be plotted by a convergent curve from multi-simulations of the same scenario as a representative of the evacuation simulation. Meanwhile, the number of runs of the same scenario needs to be determined to represent the 'average behaviour' of agents and provide a quantitative and computationally inexpensive benchmark for the behaviour uncertainty analysis (Ronchi et al., 2013).

Five convergence criteria for analysing the representative agent-evacuation time curve are proposed by Ronchi et al. (2014): Total Evacuation Time (TET), Standard Deviation of TET (SD), Euclidean Relative Difference (ERD), Euclidean Projection Coefficient (EPC) and Secant Cosine (SC). The acceptance thresholds for each convergent criterion used in this thesis are directly referred from Ronchi et al. (2014). These acceptance thresholds are arbitrarily defined and still in the debate so that values may change depending on different testers. The number of runs of the same scenario can be determined based on the satisfaction of all thresholds of convergent criteria. The acceptance thresholds used in this thesis are listed below:

$TR_{TET} = 0.5\%$
$TR_{SD} = 5.0\%$
$TR_{ERD} = 1.0\%$
$TR_{EPC} = 1.0\%$
$TR_{SC} = 1.0\%$

The data processing relative to convergent criteria is conducted by applying the tool made by Erik Smedberg at Lund University (Smedberg, 2019). Hence the mathematical principle will not be stated in this thesis. The detail can be found in '*A Method for the Analysis of Behavioural Uncertainty in Evacuation Modelling'* (Ronchi et al., 2014).

6.5 Description of the tool used in the data analysis

The tool used in this thesis was developed by Smedberg in his master thesis of '*The Analysis of Results of Stochastic Evacuation Models'* (Smedberg, 2019). The tool was designed by using VBA in Excel and initially compatible with Pathfinder version 2018.3.0730 (Smedberg, 2019). However, it was modified to be capable of applying in the convergence analysis of multiple-simulated data generated by FDS+Evac. It should be noted that thought the newest version (Ver.3.2) of the tool modified for FDS+Evac has been tested and continuously improved during the whole period of simulation.

The request time-step of the tool is 1 second (DT=1 in FDS+Evac) since this is the time step required in the calculation. Other time-steps used such as 0.5 will cause less accurate results calculated by the tool. The input data sheet is the *_evac.csv* data sheet generated in the result folder of FDS+Evac without any modification. The convergence criteria are blank for the tester to set. Each parameter can be explicitly determined as showed in figure 1. In multiple simulation cases, calculated results from the tool vary based on the tester-defined convergence criteria. The tool currently has six output items including evacuation time, queuing time, density, flow rate, spatial location and used exit. In this thesis, only evacuation, flow rate and used exit were used for data analysis. Other output items are not currently available since the lack of time for a modification.

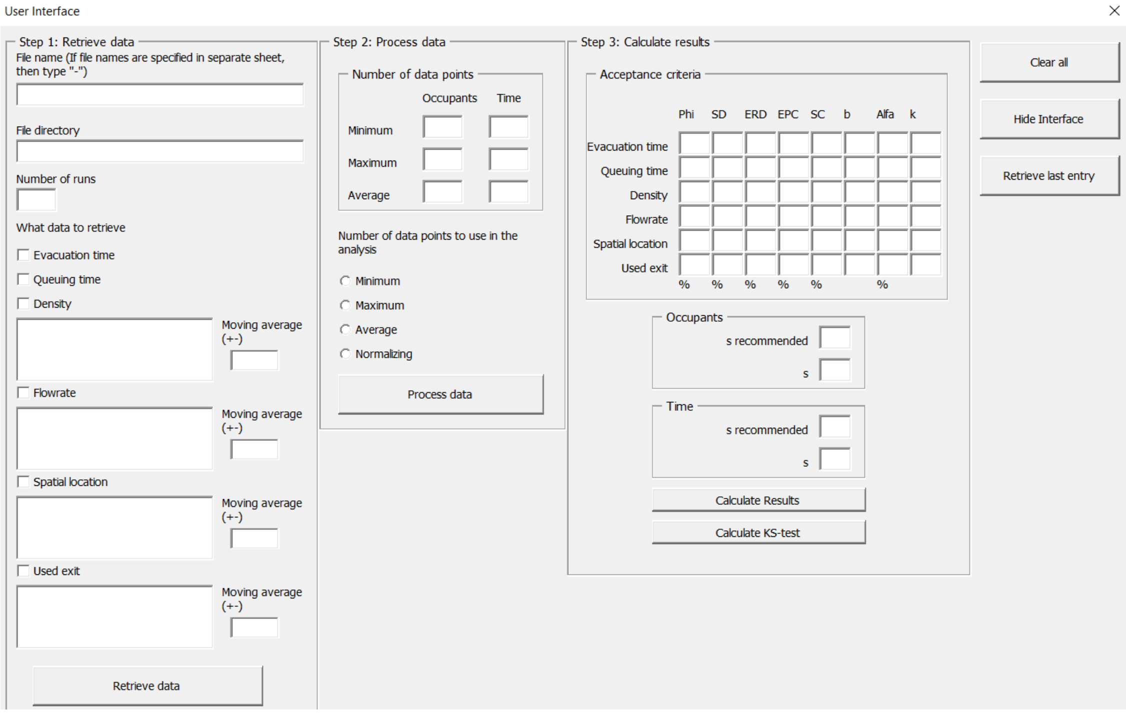

Figure 1 Screenshot of the tool's interface.

For the total evacuation time, the averaged value can be calculated based on the multiple simulations with a standard deviation. Meanwhile, a graph of the representative agent-evacuation time curve can be drawn with curves from all runs. The flow rate in the output is the averaged maximum flow rate which is the averaged value of maximum flow rates picked up from each time interval. It is different from the averaged flow rate which is a value from the division of the total number of agents and total passing time. Generally, averaged flow rate is generally used in the data analysis or as a threshold in the comparison, but the tool can only provide averaged flow rate in each defined time interval in the process of calculating maximum averaged flow rate. Therefore, both flow rates are taken into consideration as collected data in the thesis, but the averaged flow rate is more important in the comparison with other data or expected results. The used exit can represent the usage of each exit so that it is perfect to be used in tests relative to exit/route choice. Another significant output is to define the number of runs (multiple simulations) for one scenario. It corresponds to the pre-set thresholds of convergence criteria. Once every convergence criterion are fulfilled, the corresponded number of runs can be determined by the tool. Further modification or analysis of data will lay on the number of runs.

7 Simulation and results

7.1 Simulated tests

There are thirty tests in total in the section of verification and component validation in the ISO V&V test procedure (ISO, 2019). It includes twenty-one verification tests and nine component validation tests. All verification tests and eight component validation tests were conducted by using the FDS+Evac simulator except test 26 since the current lack of suitable experimental data. One additional full-scale global validation was conducted, namely, test 31. The results of test 31 were compared against experimental data. In this section, only simulated results of each test will be represented with the analysis of data and comparison with selected experimental data. The full test report can be found in Appendix 2 with more details.

7.2 Multiple simulation

Multiple simulations are often required in models which consider a probabilistic approach (e.g. pseudo-random sampling from distributions (Tavares & Ronchi, 2015)) to reflect human variability in simulation scenarios. In each test report, a question of '*how many simulations (runs) of the same scenario were conducted'* was reported, e.g. 50 runs. The initial number of runs determined by the tester was chosen based on the judgement of the tester since the real number of runs leading to convergence is hard to be pre-decided. As mentioned before, the calculation of five convergent thresholds is conducted by using the tool made by Smedberg (Smedberg, 2019). After the first calculation, the results will show whether the initial number of runs is enough to meet the acceptance thresholds. If one or more thresholds are not met, additional runs should be added until all criteria are met. In the test report, the number of runs listed is the initial number of runs for each scenario decided by the tester. Meanwhile, at which run the acceptance thresholds are all met is also listed in the test reporting form.

7.3 Test structure and reporting form

Each test in the ISO V&V standard has a prescribed structure. The tests contain five parts: *geometry, scenarios, expected results, test method and user's action.* The ISO V&V Standard (ISO, 2019) suggested a test reporting form for documenting the details of each verification and validation test in Annex C Reporting Template. The reporting form currently contains eight main questions for the tester to answer. Conducted tests in this thesis were documented by following the test reporting form. The full test report can be found in Appendix 2.

7.4 Results of tests

Twenty-one tests for verification and ten tests for validation were conducted in this thesis. The full version of the test report can be found in Appendix 2. Only the results of each test were represented in this section. The source of selected experimental data was introduced at the beginning of each validation test.

Verification tests

Test 1: Pre-evacuation time assignment

Brief description:

Uniform distribution and normal distribution of pre-evacuation time were conducted and analysed.

Result:

Case 1: uniform distribution:

Figure 2 showed the distribution of pre-evacuation time (including both reaction time and detection time). The X-axis was agents evenly spreading the data so that the linear trend can be observed. Y-axis was the pre-evacuation time. From visual observation, the distribution of the pre-evacuation time was almost linear, which means that the assigned time was evenly distributed in the period from 5 seconds to 15 seconds. No value exceeded the range.

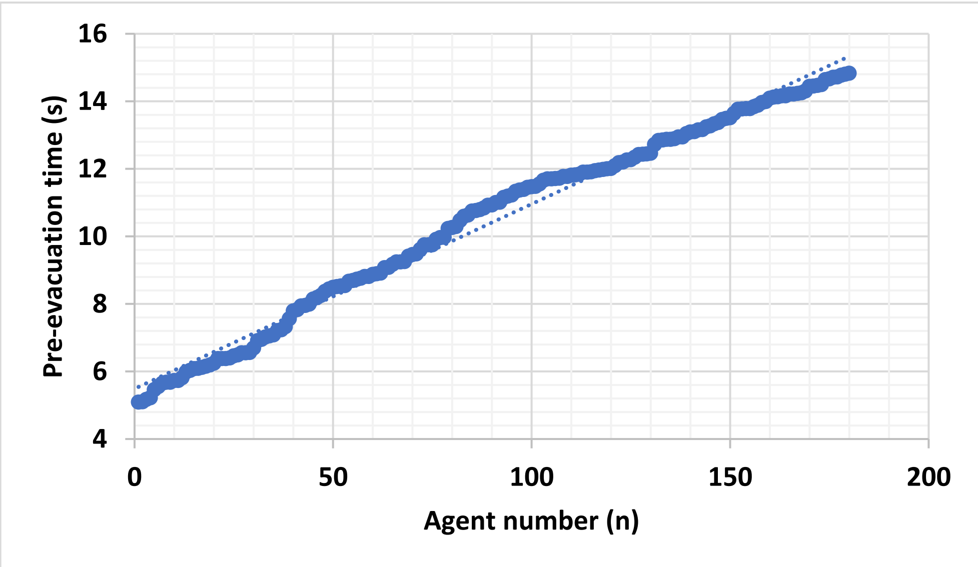

Figure 2 Uniform distribution of pre-evacuation time of 10 runs

Kolmogorov-Smirnov test was conducted to compare results and theoretical values by using MATLABTM™ quantitatively. Value p, which is the probability of observing a test statistic as extreme as, or more extreme than, the observed value under the null hypothesis (Mathworks, 1984), was used as the standard for analysing whether the distribution of data obeyed the pre-defined distribution. Small values of p cast doubt on the validity of the null hypothesis (Mathworks, 1984). The statement being tested in a test of statistical significance is called the null hypothesis. The outcome is considered unlikely concerning an assumed distribution if their probability is lower than a significance threshold of 0.05 which was decided by Fisher (1926). Therefore, the assigned pre-evacuation time reflects a uniform distribution since p=0.40>0.05.

Case 2: normal distribution

Figure 3 showed the normal distribution of pre-evacuation time picked up from 10 runs. The X axis was the pre-evacuation time (including both reaction time and detection time). Y-axis was the probability. From visual observation, the distribution matched the pattern of normal distribution. Since the pre-defined normal distribution had a sizeable standard deviation of 5, the minimum value can be less than 0 in mathematics. However, the simulator correctly assigned the time without any mistakes such as minus time.

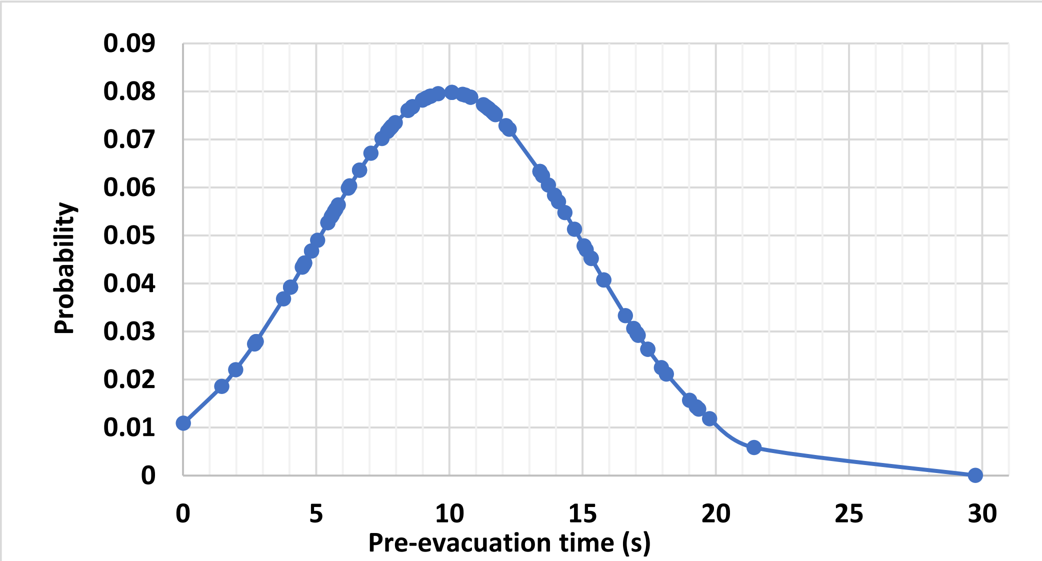

Figure 3 Uniform distribution of pre-evacuation time of 10 runs

Kolmogorov-Smirnov test was conducted to compare results and theoretical values by using MATLABTM^{TM} quantitatively. The assigned pre-evacuation time obeyed pre-defined normal distribution since $p=0.15>0.05$.

Test 2: Walking speed in a corridor

Brief description:

The ability of the assignment of pre-defined impeded walking speed verified here.

Result:

The results are shown in Table 3. The difference between simulated walking speed and the expected walking speed of 1 m/s is reported in the *Difference* column.

	Averaged TET (s)	SD (s)	Speed (m/s)	Difference
Case 1	41.2	0.4	0.97	3%
Case 2	41.6	0.8	0.96	4%
Case 3	41.5	0.6	0.96	4%

Table 3 Simulated results of all three cases

Test 3: Walking speed on stairs

Brief description:

The ability of the assignment of pre-defined walking speed on stairs verified here.

Result:

The total length of the staircase was 10 meters as request. Since the walking speed was defined to 1 m/s, the expected time was 10 seconds.

Upward movement simulation: The averaged total evacuation time of 30 runs was 10.8 seconds with a standard deviation of 0.2 seconds. The difference compared with the expected time was 8%.

Downward movement simulation: The averaged total evacuation time of 30 runs was 10.7 seconds with a standard deviation of 0.2 seconds. The difference compared with the expected time was 7%.

Test 4: Movement around a corner

Brief description:

A corner was built to test the ability of simulated agents to move around the corner.

Result:

The averaged maximum flow-in rate of all 50 runs at the corner was 1.45 p/ms (person per meter per second). The averaged maximum flow-out rate of all 50 runs at the corner was 1.41 p/ms. The averaged flow-in rate was 1.00 p/ms. The averaged flow-out rate was 0.77 p/ms. In general, the flow-out rate was smaller than the flow-in rate.

Figure 4 below shows the flow-in and flow-out rate of the 27th run. It represented the general trend of a difference of the flow-in and flow-out rate. The flow-in rate was higher than the flow-out rate since the slope of the agent-time curve of the flow-in was slightly higher in figure 4.

It should be mentioned that more agents could lead to a more accurate analysis since the flow-in and flow-out rate was very sensitive and fluctuating when the number of agents was few.

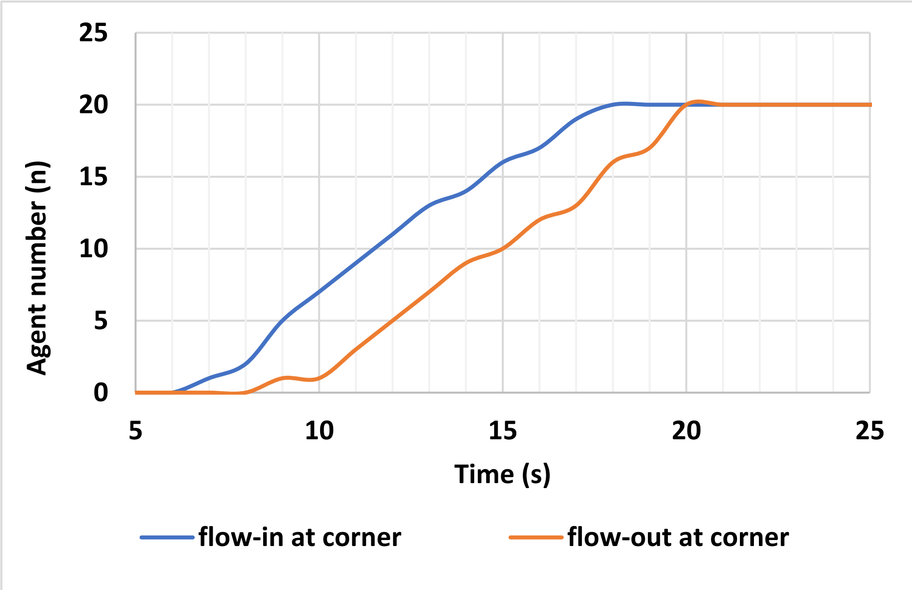

Figure 4 Flow-in rate vs flow-out rate at the corner

Test 5: Assigned occupant demographics

Brief description:

The ability of the assignment of pre-defined occupant demographics verified here.

Result:

Figure 5 was a representation of the distribution of walking speed of 5 runs. The probability where the value was bigger than 1 means that the value of walking had a very high probability of being assigned to agents. The peak was at the point where the speed is 0.86 m/s. Since it was a truncated normal distribution, the distribution of walking speed can be observed separating in a range from 0.25 m/s to 1.5 m/s. No data point was out of the range.

Compared with the distribution figure from the experiment, the simulated distribution did not wholly follow the experimental distribution given the way input has been implemented. It is understandable that the experimental distribution was more realistic while the simulated distribution was matching the mathematical distribution.

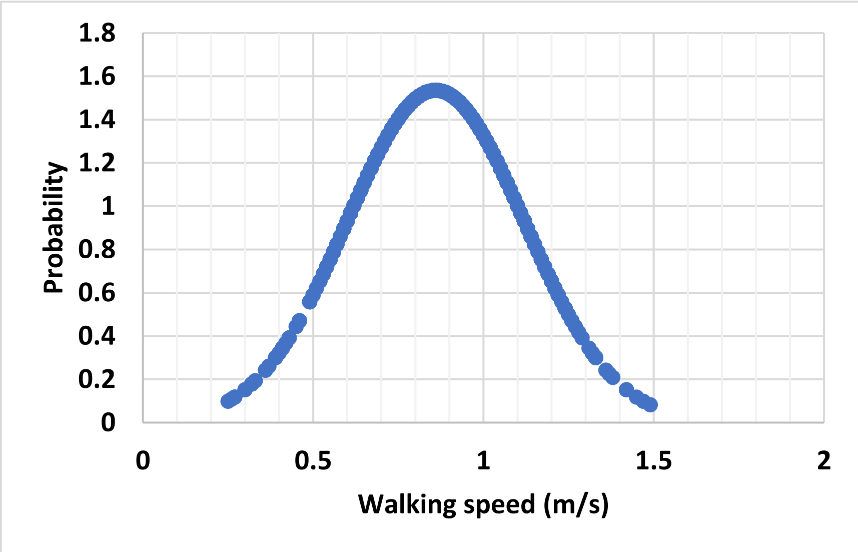

Figure 5 The distribution of the walking speed of 5 runs

Test 6: Horizontal counter-flow

Brief description:

Counterflow was simulated and analysed here. A different number of agents in the counterflow was simulated (0 agent, 10 agents, 50 agents and 100 agents). The impact of the number of agents in the counterflow was identified.

Result:

From table 4, the total evacuation time increased when the number of agents increased in the counterflow. More agents in the counterflow prolonged the congestion time; therefore, the total evacuation time was prolonged as well. The trend was also clearly demonstrated in figure 6. However, no long-term blocking was observed in all simulations.

	TET (s)	SD (s)
Case 1	85	10.9
Case 2	114	10.5
Case 3	154	18.2
Case 4	200	11.1

Table 4 Results of averaged total evacuation time and standard deviation from case 1-4

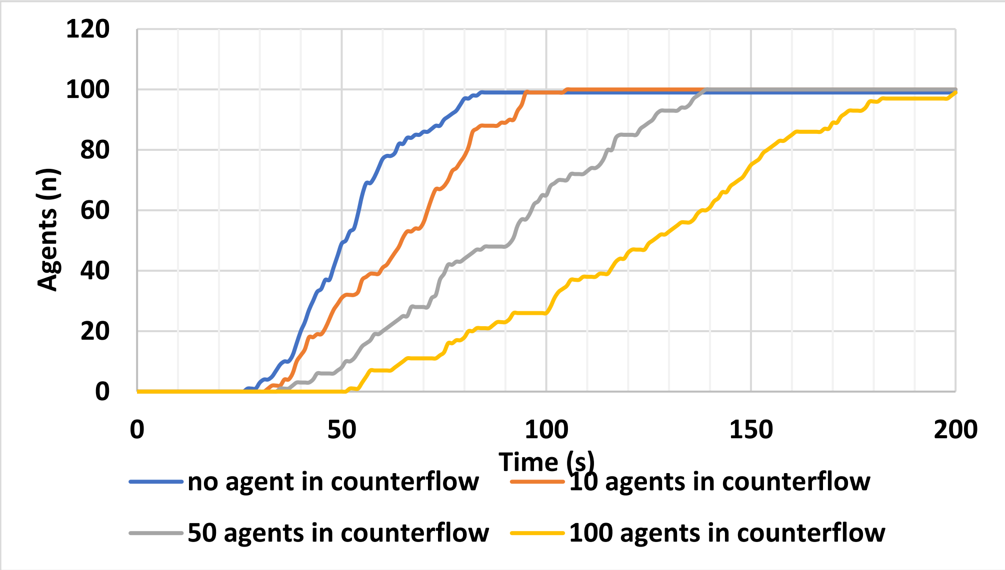

Figure 6 Total evacuation time vs different number of agents in counterflow

Test 7: People with movement disabilities

Brief description:

A disabled agent was simulated in the scenario. The impact of the disabled agent was identified.

Result:

Scenario 1: agents with one disabled agent

The averaged total evacuation time of 50 runs was 43 seconds with a standard deviation of 1.5 seconds. The convergent curve of agent-time was shown in figure 7 in the red line.

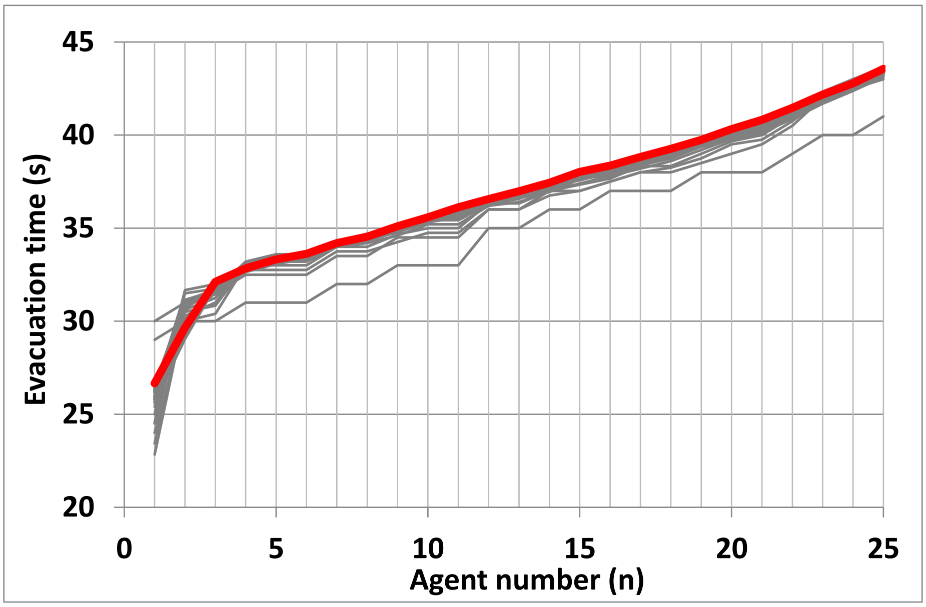

Figure 7 Convergent agent-time curve of scenario 1in the red line. Each black line represents each run

Scenario 2: agents with no disable agents

The averaged total evacuation time of 50 runs was 37 seconds with a standard deviation of 1.5 seconds. The convergent curve of agent-time was shown in figure 8 in the red line.

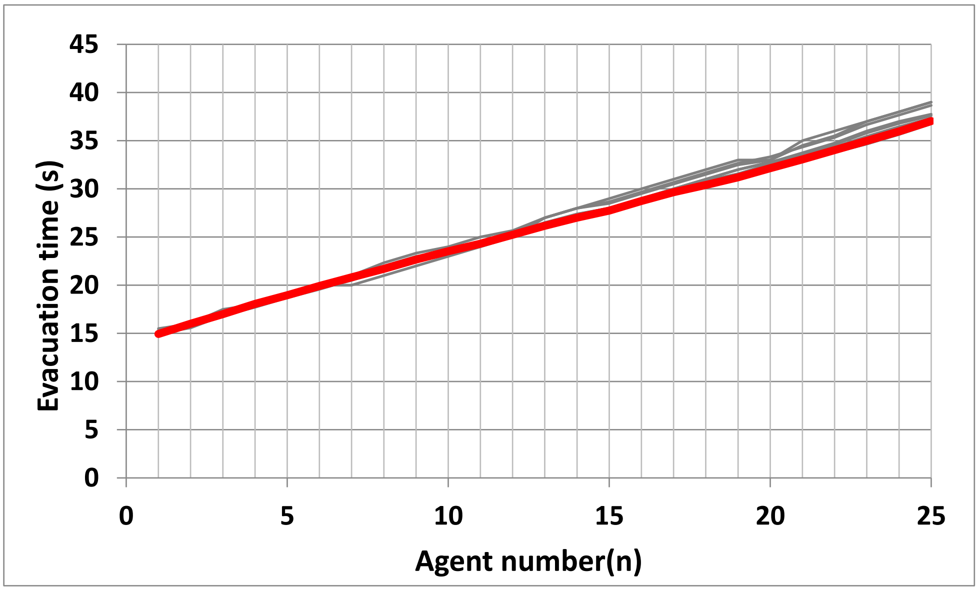

Figure 8 Convergent agent-time curve of scenario 2 in the red line. Each black line represents each run

Comparison:

The convergent curves in scenario 2 showed that the flow was smoother and faster than scenario 1 since the slope was straight and higher. The averaged total evacuation time of 50 runs demonstrated that the disabled agent slowed down the whole evacuation process.

Test 8: Exit route allocation

Brief description:

This test was conducted to check whether the assigned route choice to agents can work properly.

Result:

The agents in room 1, 2, 3, 4, 7, 8, 9 and 10 were assigned to the main exit with the probability of 1. In all simulations, the agents correctly moved to the main exit. The rest were assigned to the secondary exit with a probability of 1. The agents correctly moved to the secondary exit. Overall, the simulated route choice was identical to the expected route choice.

Test 9: Dynamic availability of exit

Brief description:

A door could be out of function after several minutes in a real fire scenario. This test was conducted to verify whether a door can properly be closed after a defined period.

Result:

The probability of usage of the exit 2 after exit 1 was closed was 100% in 50 runs. The agent re-directed to exit 2 without any hesitation.

Test 10: Congestion in front of a flight of stairs

Brief description:

Congestion condition was simulated and analysed with the impact of the bottleneck and stairs.

Result:

Figure 9 was plotted from a randomly-chosen run. The figure showed the relationship between the passing time and the number of passed agents. The passing time was longer at the door to the stair than the time at the exit, which means that the flow rate should be slower than the flow rate of the exit of the room. The same relationship can be observed in other runs.

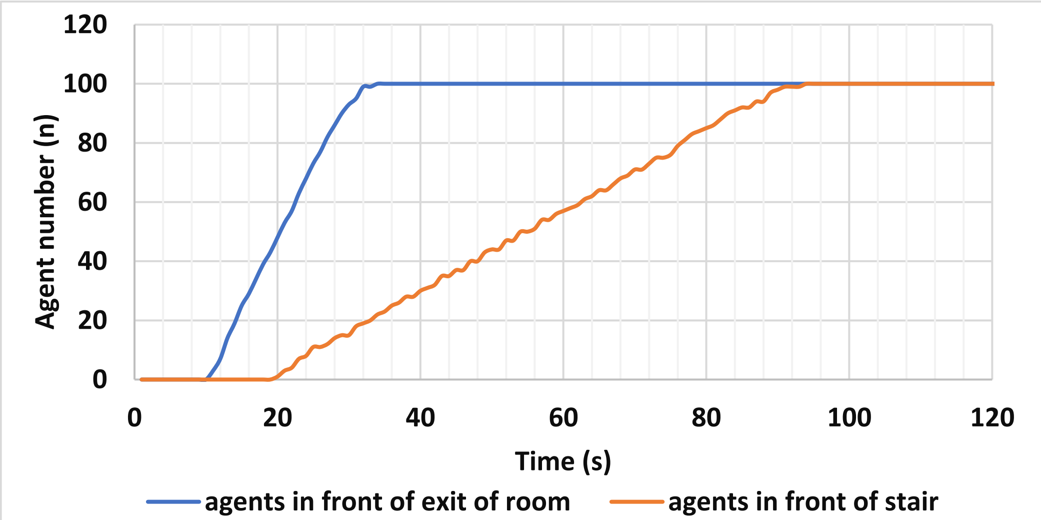

Figure 9 Passing time vs the number of passed agents at the exit of the room and the door to the stair

The flow rate was measured based on all 50 runs. The averaged maximum flow rate of the exit of the room was 1.25 p/ms with a standard deviation of 0.63 p/ms. The averaged maximum flow rate of the door to the stair was 0.53 p/ms with a standard deviation of 0.22 p/ms. The time interval for calculating the flow rate was set to 6 seconds. The averaged flow rate of the exit was around 1.12 p/ms. The averaged flow rate of the door to the stair was around 0.38 p/ms.

	At the exit	At the door
Averaged maximum flow rate (p/ms)	1.25	0.53
SD (p/ms)	0.53	0.22
Averaged flow rate (p/ms)	1.13	0.38

Table 5 Results of flow rate at the exit of the room and the door to the stair

It is clearly observed from Smokeview that congestion was generated at the exit of the room. A steady flow rate of 1.13 p/ms was generated by the width of the exit to the corridor in the corridor. Since the walking speed on the stair was slower than the speed on the corridor, another congestion was generated in front of the stair under a flow rate of 0.38 p/ms. It was also observed in the Smokeview that agents were queueing in the corridor for walking on the stair.

Test 11: Maximum exit/door flow rates

Brief description:

Flow rate is vital in evacuation simulation. Therefore, this test was conducted to find the rationality of measured flow rates.

Result:

Table 6 showed the results of the flow rate. The averaged maximum flow rate was calculated from all 30 runs. The time interval for calculating the flow rate was set to 10 seconds for flow rate calculation.

	Averaged maximum flow rate (p/ms)	Standard deviation	Averaged flow rate (p/ms)
Case 1	1.56	0.09	1.30

Table 6 Results of flow rate from case 1

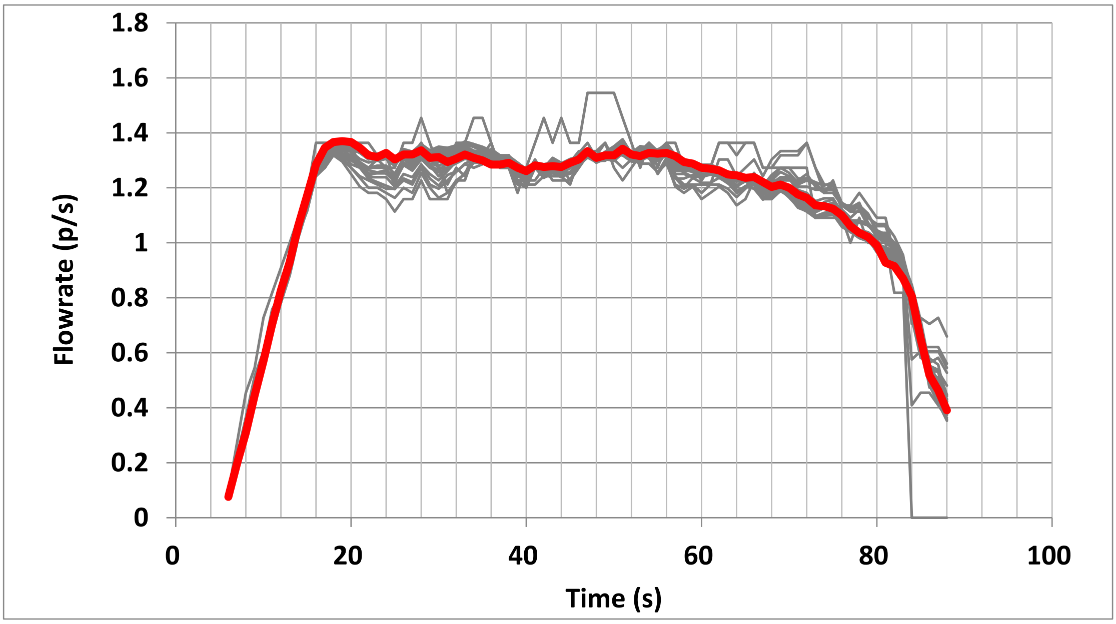

Figure 10 The convergent curve of the flow rate of case 1 in the red line. The flow rate at each time point was calculated in a time interval of 10 seconds. Some data points have exceeded the threshold of 1.33 p/ms

Comparison:

The averaged flow rate in case 1 was lower than the threshold of 1.33 p/ms, but the maximum flow

rate was exceeded by 17%. It should be mentioned that the maximum flow rate varies when the different time interval is applied.
The curves of flow rate changing with time were should in figure 10. Each curve represented the change of the flow rate of one run. It can be observed that the averaged flow rate was near 1.30 p/ms, but some curves showed a higher flow rate almost reaching 1.40 p/ms at some time points.

It should be mentioned that the default values of social force were used in all simulations. To study the impact of the social force on the flow rate, three parameters of the social force model embedded in FDS+Evac shall be studied, but it will not be discussed in this thesis.

Test 12: Stair flow rates

Brief description:

The flow rate in relation to the impact of stairs was simulated and analysed.

Result:

Table 7 showed the calculated flow rate of all 10 cases in two scenarios. The averaged flow rate was used to represent the relationship between width and flow rate. The averaged maximum flow rate was also calculated. The time interval of calculating the flow rate was set to 10 seconds for all cases.

		Upward				
Width of stair	m	1	1.2	1.4	1.6	1.8
Averaged maximum flow rate	p/s	0.85	0.98	1.04	1.19	1.40
	p/ms	0.85	0.82	0.74	0.74	0.78
Averaged flow rate	p/s	0.64	0.75	0.89	1.03	1.15
	p/ms	0.64	0.63	0.64	0.64	0.64
		Downward				
Width of stair	m	1	1.2	1.4	1.6	1.8
Averaged maximum flow rate	p/s	0.87	0.97	1.05	1.20	1.40
	p/ms	0.87	0.81	0.75	0.75	0.78
Averaged flow rate	p/s	0.64	0.77	0.90	1.01	1.14
	p/ms	0.64	0.64	0.64	0.63	0.64

Table 7 Results of flow rate for upward case (above) and downward case (below)

The flow rate increased while the width of the stair increased. The flow rates for both upward and downward flow were almost the same under the same width since there was no limit for the walking speed on the stairs. If the unit of person per meter per second was used, it could be found that all averaged flow rates were around 0.64 p/ms. There was some fluctuation in the averaged maximum flow rate, but the trend was identical to the averaged flow rate.

The walking speed was observed in the Smokeview, and it was around 0.75 m/s on the stair for both scenarios. If there is a speed limit set by users on the stair, the flow rate will change since congestion may cause longer queening time.

Comparative test: (upward movement with a walking speed of 0.75m/s. The width of the stair was 1.2 meters.)
The averaged maximum flow rate of 30 runs was calculated as 0.72 p/ms with an SD of 0.06. The averaged flow rate was 0.58 p/ms. Compared with the test (1.2 meters width, upward, no speed limit on the stair), both flow rates were smaller.

Averaged total evacuation time was 164.2 seconds with SD of 3.26. It is longer than the time of 149.43 seconds from the previous test. From the Smokeview, the speed observed on the stair was around 0.55 m/s. The reason is that the speed limit on stair caused more serious stagnation in front of the stair and on the stair. Agents on the stair were closer to each other as showed in figure 11.

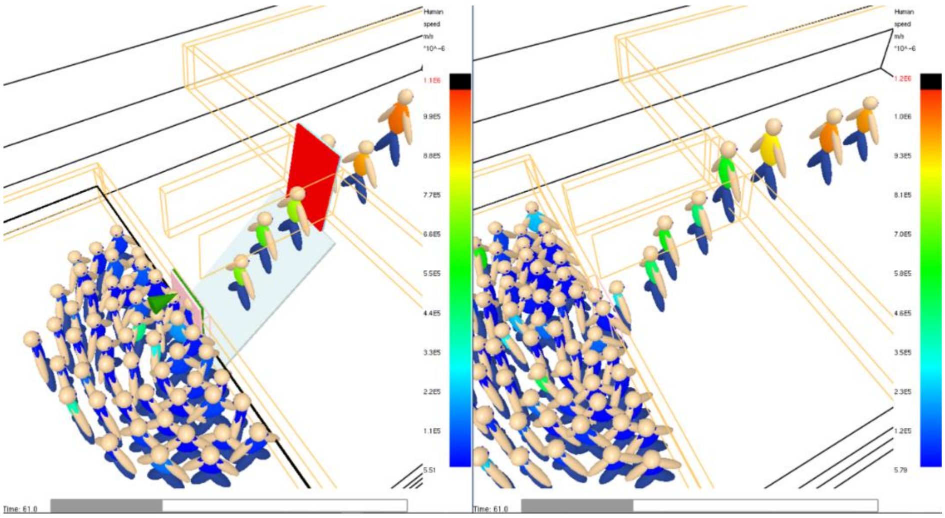

Figure 11 Comparison of the case (left) without speed limit and case (right) with a speed limit of 0.75 m/s on the stair

Test 13: Relationship between walking speed, uni-directional flow and density

Brief description:

The Relationship between walking speed, flow and density were analysed by analysing the movement of agents under different densities in a tunnel structural geometry.

Result:

Passing time from line 1 to line 2 was measured in the simulation. Table 8 showed the results of the passing time and the corresponding walking speed.

Case:	1	2	3	4
Passing time (s)	22	22	35	--

Speed (m/s)	0.9	0.9	0.6	--

Table 8 Results of the passing time and calculated walking speed

Results of case 1-3 were calculated from all 30 runs. The simulation with the high initial density was very unstable. The simulation was very often automatically suspended after several seconds running in case 4. Therefore, no data was collected for case 4.

The averaged maximum flow rate and averaged flow rate were calculated in table 9. The time interval was set to 10 seconds for calculating the flow rate.

Case:		1	2	3	4
Averaged maximum flow rate	p/s	1.44	1.94	2.80	--
	p/ms	0.72	0.97	1.40	--
Averaged flow rate	p/s	1.19	1.81	2.48	--
	p/ms	0.60	0.91	1.24	--

Table 9 Results of flow rate

The flow rate of Case 1-3 was calculated in table 9 based on 30 runs. For case 4, the initial density of agents cannot be set more than four agents per square meter since FDS+EVAC puts agents randomly in their initial positions. In this simulation, the initial density was set to four agents per square meter. However, the simulation became very unstable when the density was four agents per square meter since agents cannot be easily generated in the geometry. The default method to place agents in FDS+Evac is random, but a certain distance between agents are required. Therefore, in the high-density situation, agents are too close to be placed by the simulator. The problem can be solved by manually placing agents in the geometry. However, if the number of agents is enormous, the solution can be time-wasted. In this case, no data was collected for case 4.

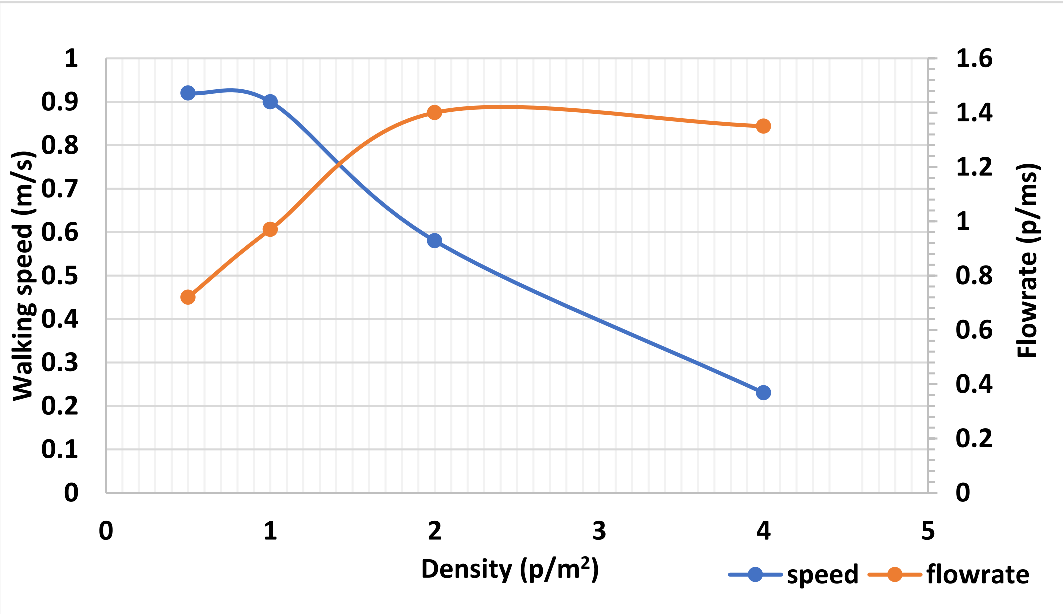

Figure 12 Relationship between walking speed, averaged flow rate and density

Comparison:

From figure 12, the walking speed reduced while the density increased, but the magnitude of the drop was small when the density was not very high. The flow rate showed an increase while the density increased.

Test 14: Group behaviour

Brief description:

Theory of group behaviour was tested here. In the results, 5 agents in the target group were analysed. The herding agent(s) shifted within the 4 agents and the remained 1 agent in scenario 1 and 2. An additional test in scenario 3 was conducted without the influence of group behaviour to make a comprehensive comparison.

Result:

Table 10 showed the results of the evacuation time collected for all three scenarios.

Scenario	Time of first leave of 4 agents in group 1 (s)	Time of last leave of 4 agents in group 1 (s)	Time of the remained 1 agent in group 1 leave (s)
1	16	18	54
2	16	18	49
3	16	18	57

Table 10 Comparison of evacuation times for agents in Group 1

Comparison:

Scenario 2 was the required scenario in the ISO document. The total evacuation time for the remained 1 agent (see in the table 10) was 49 seconds which is 14% shorter than the time measured in scenario 3 without the use of the herding algorithm in FDS+Evac (Korhonen & Hostikka, 2008). It means that the rest agent fastened its speed to match the other four agents' speed. However, the required time difference for agents of group 1 to reach the exit was more than 10 seconds. Considering that the choice of 10 seconds is arbitrary driven by the need for a quantitative standard, the time difference should be more carefully decided based on the defined walking speed of agents. Scenario 1 should that although the 4 agents were defined as herding agents, their speed was not dragged by the agent with a speed of 0.5 m/s. On the contrary, the agent with slower speed was slightly speeded up about 3 seconds to reach the exit compared with scenario 3.

Test 15: Social influence on exit choice

Brief description:

Theory of social influence was tested here by using one agent influencing the route choice made by other agents.

Result:
Case 1: (which has been simulated 100 times)
The probability of the usage of exit 1: average 48%
The probability of the usage of exit 2: average 52%

Case 2: (which has been simulated 100 times)
The probability of the usage of exit 1: average 13%
The probability of the usage of exit 2: average 87%

Case 3: (which has been simulated 100 times)
The probability of the usage of exit 1: average 86%
The probability of the usage of exit 2: average 14%

Comparison:
There was a social influence in case 2 on the exit choice when the agent had no familiarity (0% probability of knowing exits) to any exit. The probability of the usage of exit 2 of the agent 2 dramatically increased to from 52% to 86%.

However, if the agent had the same familiarity (e.g. 100% probability of knowing exists in case 3), but no preference to any exit, other factors such as collision avoidance could be taken into consideration. Therefore, the agent 2 preferred to choose another exit rather than use the same exit which the agent 1 chose to have faster evacuation.

Test 16: Affiliation to familiar exits
Brief description:
Theory of affiliation was achieved by using user-defined probability to exits.

Result:
Case 1: (which has been simulated 100 times)
Averaged probability of the usage of exit 1: 51%, SD=0.5.
Averaged probability of the usage of exit 2: 49%, SD=0.5.
Case 2: (which has been simulated 100 times)
Averaged probability of the usage of exit 1: 30%, SD=0.46.
Averaged probability of the usage of exit 2: 70%, SD=0.46.

Comparison:
Case 1 showed that the probability of exit choice was almost equal to an agent who was not familiar with any exit. Case 2 represented that once the familiarity was defined by a certain number of probabilities, the simulated results were deterministic.

Test 17: Route choice

Brief description:

The test contained three test cases to verify the route choice under different settings in FDS+Evac.

Result:

Case 1:

The agent chose the corridor rather than stairs in all 30 runs. The reason could be that both the agent and the exit were set on the same evacuation mesh.

Case 2:

Once the agent was defined to know both the door connecting to the stair and the final exit, the only route which the agent chose was the stair in all 30 runs.

Case 3:

Four agents were placed at the start point and just knew the exit. After the start of the simulation, some agents (usually one agent) chose the stair to reach the exit. This agent was always from the last two agents in the group. The rest agents used the corridor to reach the final exit. The reason could be that agents tried to avoid congestion in the corridor so that the agent (go to the stair) had to find a new route which was less crowded. The probability of the usage of the stair for all agents was 38% on average from all agents in all 30 runs, which means that sometimes all agents chose the corridor to reach the final exit.

Test 18: Reduced visibility vs walking speed

Brief description:

The extinction coefficient of 1/m and 3/m were used in the simulation. The data of evacuation time was collected and used to calculate the averaged walking speed.

Result:

Results of case 1: (extinction coefficient=1/m)

Averaged TET: 89.81 s, SD=0.34 s.

Averaged walking speed: 1.11 m/s.

Hand-calculated speed: 1.15 m/s.

The difference between the two speeds was 3.4%.

Results of case 2:(extinction coefficient =3/m)

Averaged TET:114.57 s, SD=0.71 s.

Averaged walking speed: 0.87 m/s

Hand-calculated speed: 0.94 m/s.

The difference between the two speeds was 7.4%.

Test 19: Occupant incapacitation
Brief description:
Carbon Monoxide was used in the simulation. FED was measured and analysed.

Result:
In this simulation, the concentration of CO was 7000ppm. FED reached 1 after 217 seconds in the simulation.

Hand-calculated time based on the algorithm equation form FDS+Evac user guide (Korhonen, T., & Hostikka, 2009) was 226 seconds. The difference to the simulated time was 9 seconds (4.1%).

Hand-calculated time was 300 seconds based on the equation from Purser (2003).
The difference to the simulated time was 83seconds (38.2%).

Test 20: Lift usage
Brief description:
A simple lift model embedded in FDS+Evac simulator was used to simulate the required scenario of the test. It is noted that the sub-model was mere a simple model so that all requirements of the test cannot be fulfilled.

Result:
By observing the simulation, the agent can use the simple simulated elevator sub-model to reach the final exit.

Test 21: Escalator usage
Brief description:
An escalator was simulated in both upward and downward movement direction.
Result:
scenario 1: upward movement of the escalator
Averaged time of the agent on the escalator was 18.3 seconds.
Calculated speed on the escalator was 0.23 m/s.
Difference to the expected speed of 0.2 m/s: 15%.

scenario 2: downward movement of the escalator
Averaged time of the agent on the escalator was 17.7 seconds.
Calculated speed on the escalator was 0.24 m/s
Difference to the expected speed of 0.2 m/s: 20%.

Validation tests
Test 22: Pre-evacuation model

The simulation scenario and experimental data were referred from the experiment conducted by Nilsson and Johansson (Nilsson, Johansson, & Frantzich, 2009).

Brief description:

A tunnel scenario was simulated based on the experimental data. The test analysed the exit/route selection of agents placed in the scenario and compared the selection results with experimental data.

Averaged Total evacuation time was 199.6 seconds with an SD of 2.3 seconds. The maximum was 200.0 seconds, and the minimum was 185.00 seconds in all data. The convergent curve of total evacuation time of picked-up 23 runs was plotted in figure 13.

Figure 13 convergent curve of total evacuation time of 23 runs

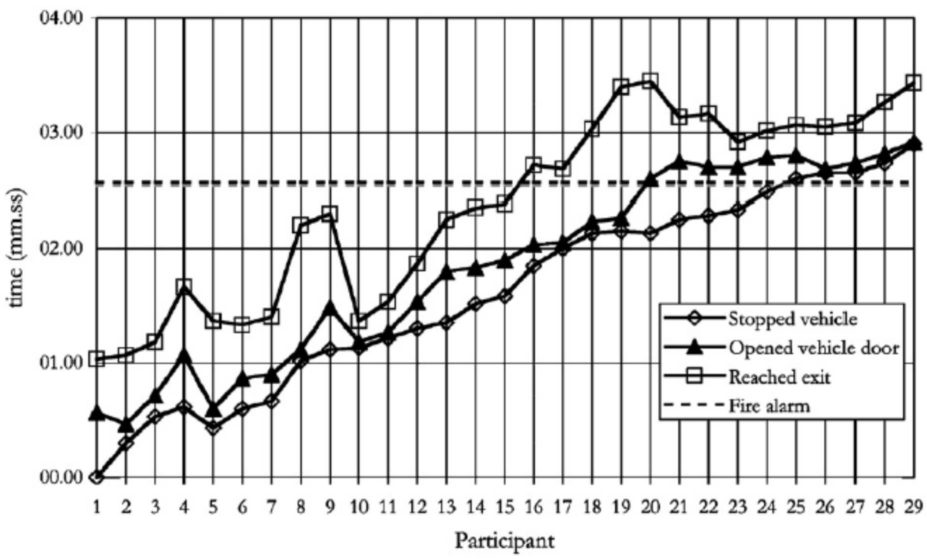

Figure 14 Time curve from the experimental data taken from (Nilsson et al., 2009).

Total evacuation time:

Compared figure 13 with figure 14, the simulated total evacuation time was slightly shorter than experimental data. The main reason could be that the simulation simplified many processes which agents will do, such as observing the environment, collecting personal belongings, etc. Meanwhile, personal differences could be another reason to fluctuate the time curve. Overall, the trend of the Evacuation process was well-represented in this simulation.

It should be noted that the results of the simulation may vary from case to case since the selection of pre-evacuation time and the walking speed can be different.

Exit choice:

There were three exits (exit6, exit7 and exit 8) in the case. All exits were available during the whole Evacuation. No way-finding system was simulated so that the way-finding algorithm was purely based on the user-defined probability.

In the simulation, agent 1-4 evacuated via exit 6. Agent 5-18 evacuated via exit 7. Agent 19-29 evacuated via exit 8. Compared with the experiment, all agents chose the expected exits except agent 4. In the experiment, he/she chose a further exit (exit 7) rather than the closer one (exit 6). This can be considered as human uncertainty of decision making.

Test 23. Relationship between walking speed, uni-directional flows and densities

The simulation scenario and experimental data were referred from the experiment conducted by Armin Seyfried et al. (2007).

Brief description:

The relationship between walking speed, flow and density was simulated and compared based on the experimental data.

Flow condition:

Flow rate at the measured section was calculated. The maximum flow rate was picked up. The right line of the measured section was taken as the measured line of the flow rate. The time interval was set to 10 seconds to calculate the flow rate. From table 11, both flow rates increased with the increase in the number of agents.

	Maximum flowrate (p/s)	Averaged flowrate (p/s)
Case 1 (15p)	1.09	0.69
Case 2 (20p)	1.18	0.88
Case 3 (25p)	1.27	0.97

Table 11 Results of measured flow rate from case 1-3

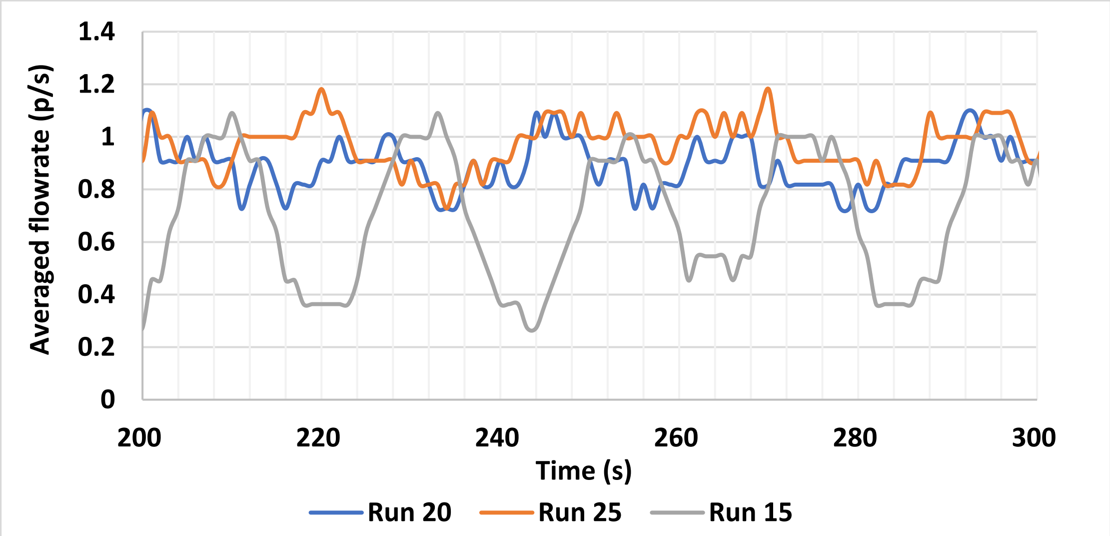

Figure 15 Flow rate changing in 200-300 seconds at the measured section. The time interval for measuring the flow rate was set to 10 seconds

Figure 15 showed that fewer agents led to more fluctuation in the flow rate curve since the data was not continually collected due to gaps between agents. However, more agents (higher density) led to a higher flow rate on average.

Walking speed:

Walking speed was calculated by dividing the distance of the measured section (2 meters) by the passing time (in second). One agent was chosen to measure the walking speed under different densities. The agent passed the measured section several times (passing times N). Walking speed was calculated in every passing time and plotted in figure 16. Table 12 listed the averaged walking speed in a different case.

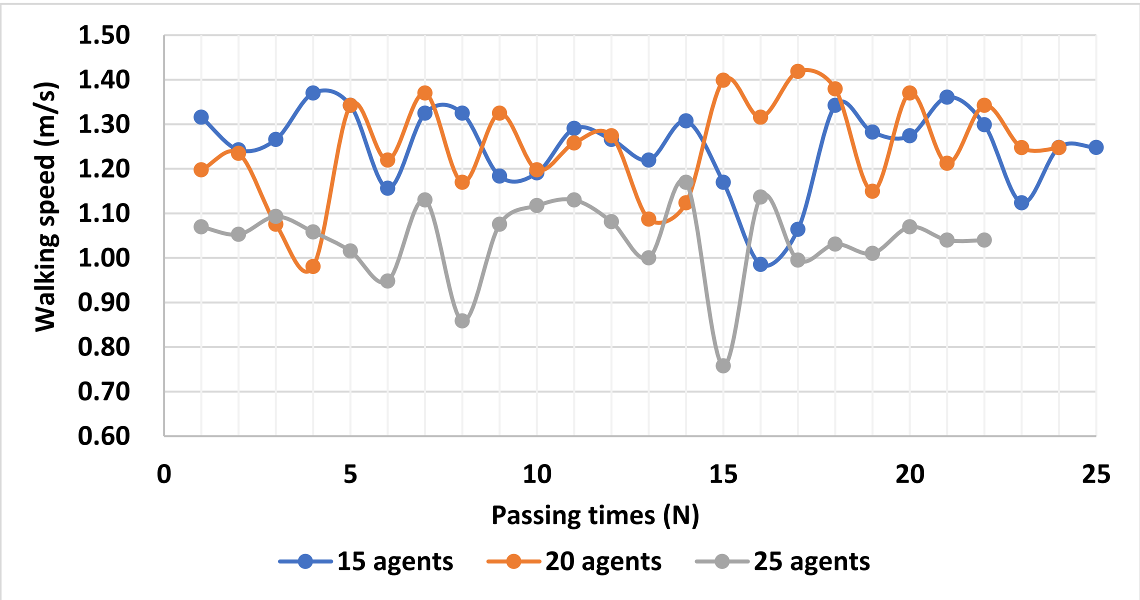

Figure 16 Walking speed at each passing time of all three cases (15 agents, 20 agents and 25 agents)

	Passing times (N)	Averaged speed (m/s)
Case 1 (15 p)	25	1.25
Case 2 (20 p)	24	1.25
Case 3 (25 p)	21	1.04

Table 12 Results of measured walking speed form case 1-3

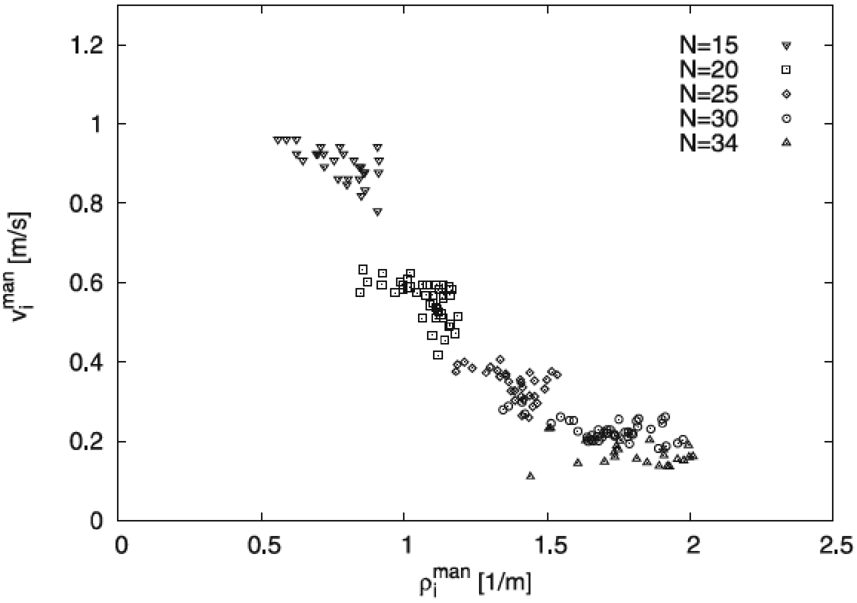

Figure 17 Experimental data of the relationship between density and walking speed (Seyfried et al., 2007).

Comparison:

The averaged walking speed was identical in case 1 and case 2. The speed hugely reduced in case 3. Compared with the experimental data, the simulated results did not match the distribution of the experimental data. Agents were slowed down when the density reached a certain level. In this test, it is twenty-five agents distributed in the geometry. It should be mentioned that the simulated results just formed one agent. The results may vary if another agent or agents are chosen. The relationship between walking speed, uni-directional flows and densities were plotted in figure 18.

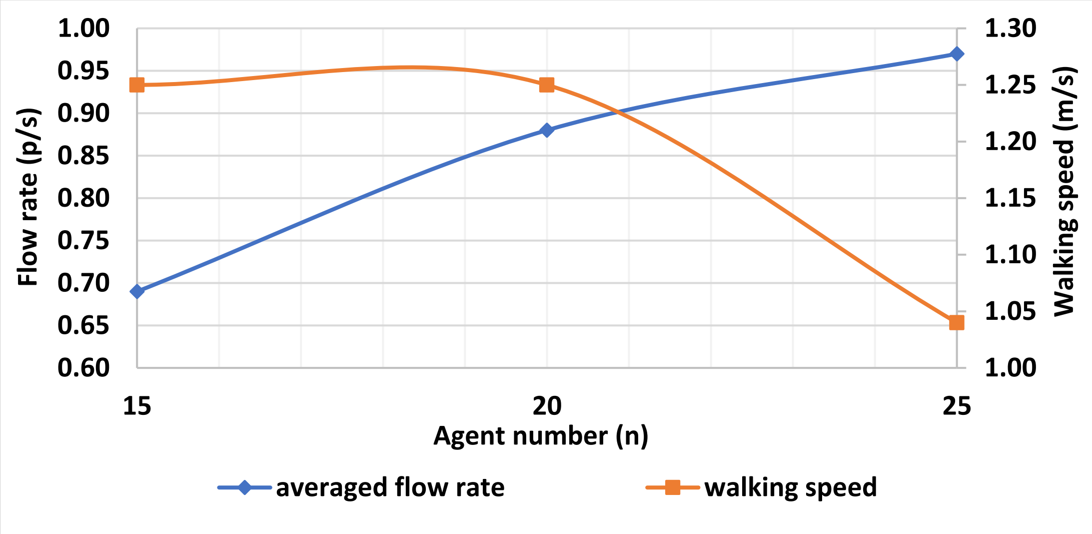

Figure 18 Relationship of the flow rate and walking speed under different densities (15 agents, 20 agents and 25 agents)

Test 24. Stairwell Evacuation

The simulation scenario and experimental data were referred from the experiment (E Ronchi, Norén, Delin, Kuklane, & Halder, 2015).

Brief description:

The movement of an agent on a full staircase was simulated based on the experimental data. It should be noted that the experimental data focuses on the impact of fatigue on the movement of the agents during the whole stair climbing. This test was to find how the sub-model &STRS perform compared with the experiment.

Time:

The averaged total evacuation time of 50 runs was measured as 202.97 seconds with a standard deviation of 3.99 seconds. The maximum time was 212 seconds, and the minimum was 195 seconds.

The vertical height of the stairwell was 48 meters. Therefore, the vertical speed was 0.23 m/s on average. The maximum speed was 0.24 m/s, and the minimum speed was 0.22 m/s. Horizontal speed was hard to be measured in this case since counters cannot be installed inside the geometry simulated by &STRS sub-model.

From the experimental data, the individual vertical speed was shown in figure 19. Data is fluctuating on different floors. The most common median value for the vertical speed is 0.28 m/s after a few floors and the maximum vertical speed is 0.36 m/s (at floor one) and lowest median speed is 0.27 m/s (at floor 9, 10 and 12). The 25th percentile of the vertical speed in the individual Ideon experiment ranges between 0.23–0.33 m/s. The 75th percentile of the vertical speed in the individual Ideon experiment ranges between 0.29 m/s and 0.45 m/s during the ascent. The calculated averaged vertical speed was close to the 25th percentile values of speed. However, compared with median and 75th percentile values of speed, the difference was noticeable. It should be mentioned that the settings of the walking speed were significantly influential on the results.

Table 13 listed the results of speed, time to reach a certain height and calculated vertical speed from the observation of a simulation. Compared the calculated vertical speed with a median value in figure 19, the distribution was very similar that the speed is slightly higher at the low height and then the speed tends to remain the same. However, the calculated speed was always slower than the median value from the experimental data. Since the &STRS sub-model was used in the simulation, it is impossible to precisely measure the time to reach a certain height since it is unable to place measure lines inside of the simulated staircase. Therefore, the variation of the vertical speed is not possible to be presented. It can be fulfilled if the &EVSS sub-model is used in the geometry building.

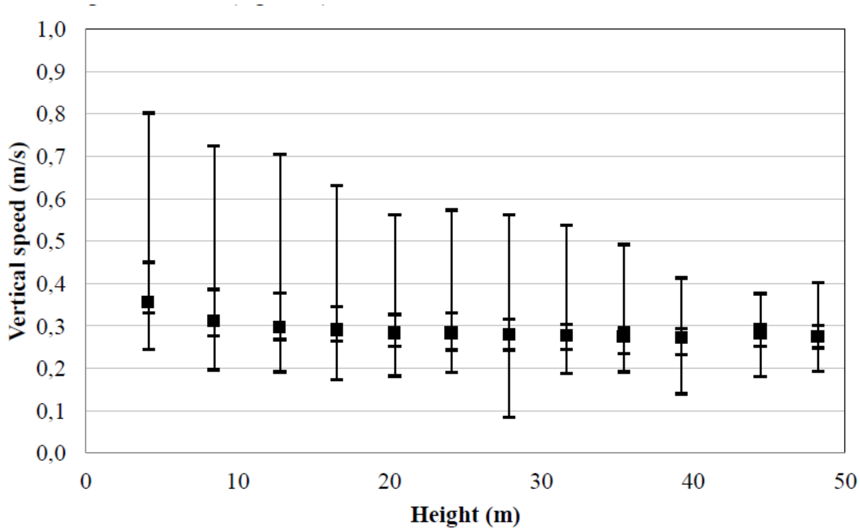

Figure 19 Vertical walking speed during the individual experiment in Ideon building (E Ronchi et al., 2015). The plot shows minimum 25th percentile, median, 75th percentile and the maximum value at a different height

Height (m)	10	20	30	40	48
Speed (m/s)	0.62	0.62	0.60	0.60	0.64
Time (s)	36	79	119	159	191
Vertical speed (m/s)	0.28	0.26	0.25	0.25	0.25
Position	Flight	Flight	Flight	Flight	Flight

Table 13 Results of speed, time to reach a certain height and vertical speed from observation of a simulation

Test 25. Flight of steps

The simulation scenario and experimental data were referred from the experiment (Graat, Midden, & Bockholts, 1999)

Flow condition:

The averaged flow rate was measured for each case and listed in table 14. The time interval was set to 4 seconds which was slightly different from the time interval of 3 seconds in the experiments.

Case	Slope	Motivation	AFR (p/ms)
1.1	steep	normal	0.70
1.2	steep	high	0.87
2.1	normal	normal	0.70
2.2	normal	high	1.01

Table 14 Results of flow rate under different slopes and motivations

Comparison:

Compared with experimental data listed in table 15, the flow rate with high motivation was indeed higher than normal motivation. The difference was 0.17 p/ms (24%) in the steep slope and 0.31 p/ms (44%) in the normal slope. The motivation had more influence on the normal slope rather than the steep slope in the simulation although the fluctuation of flow rate for in both scenarios was close, which can be seen in figure 20. However, from the experiment, increased motivation seems to have more effect on the steep slope than on the normal slope since it could be explained by the fact that people who move carefully on the steep slope under normal circumstances, will let their carefulness go in an emergency while people on the normal slope already move less careful under normal circumstances (Graat et al., 1999). Therefore, the simulated results varied from the experimental data, but the trend showed clear that high motivation caused high flow rate. The effect of the slope with different angles was more identifiable in the situation where the motivation of agents was higher.

It should be mentioned that the properties of agents were not precisely the same as that in the experiment since no available data was provided in the experiment about the walking speed of agents. This may affect the measurement of flow rate in the simulation. Meanwhile, the level of motivation was simply simulated by using default social force parameters and more urgent social force parameters offered in FDS+Evac user guide. This may also affect the flow rate condition.

	Normal slope	Steep slope
Motivation	1.09	1.00
normal	n=36	n=38
Motivation	1.14	1.10
high	n=42	n=36

Table 15 Results of flow rate from the experiment (Graat et al., 1999). n is the number of 3-second intervals observed. The unit of the flow rate is p/ms

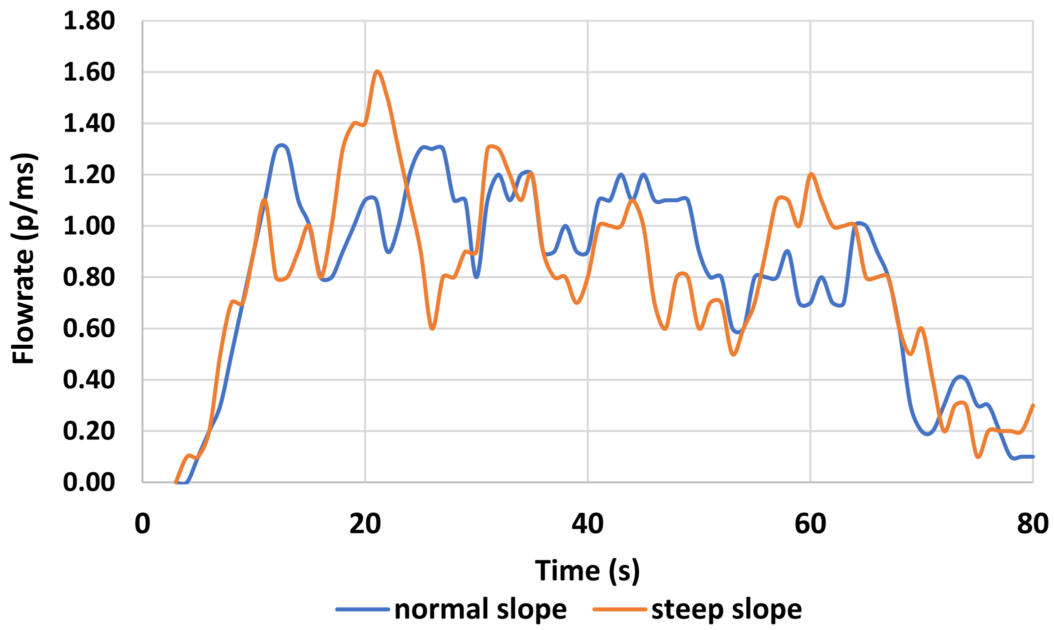

Figure 20 Comparison of the flow rate of steep slope and normal slope with high motivation

Test 26. Movement around a corner

No suitable experimental data was identified for this validation test.

Test 27. Counterflows

The simulation scenario and experimental data were referred from the experiment (Kretz, Grünebohm, Kaufman, Mazur, & Schreckenberg, 2006).

Brief description:

Counterflow condition was simulated based on the experimental data. Case 1.1 and case 1.2 were set to validate the data of no counterflow condition. Case 2 was the counterflow condition with the majority flow of 44 agents and the majority flow of 23 agents. Results were compared and analysed with experiment data.

Time:

Passing time was calculated by counting the agents passing the measured section. Averaged maximum flow rate and avenged flow rate were measured from all 30 runs. The time interval for the measurement of the flow rate was set to 10 seconds. The results of all three cases were listed in table 16 and table 17.

Case 1.1				
		start line	central line	finish line
Passing time (s)		17.7	18.8	20
Averaged maximum flow rate	p/ms	2.01	1.97	2.10
Averaged flow rate	p/ms	1.80	1.76	1.68
Case 1.2				
		start line	central line	finish line
Passing time	s	9.7	10.3	10.5
Averaged maximum flow rate	p/ms	1.93	1.85	1.84
Averaged flow rate	p/ms	1.59	1.59	1.59

Table 16 . Results of measured passing time and flow rate of case 1.1 and case 1.2

Case 2							
		the majority			the counterflow		
Passing time (s)		start line	central line	finish line	start line	central line	finish line
		24.3	29.8	24.5	6.5	23.4	18.7
Averaged maximum flow rate	(p/ms)	1.81	0.93	1.02	1.60	0.73	0.80
Averaged flow rate	(p/ms)	1.76	0.76	0.81	1.43	0.58	0.64

Table 17 Results of measured passing time and flow rate of case 2

In case 1.1 and 1.2, the simulated passing time of the whole group was around 5 seconds less than the experimental data from figure 21. However, the trend was the same since the passing time on all lines increased when the group size increased. The flow rate showed some difference in the simulation. The simulated flow rates were more extensive than flow rates from the experiment (figure 21) through the distribution of data was close to each other.

In case 2, the counterflow of 23 agents was generated against the mainstream consisted of 44 agents. Compared with figure 23, the passing time from simulation matched the experimental data well, but the passing time on the central line was longer. Compared with figure 24, the simulated flow rate showed again that the flow rate was higher than the results from the experiment, and the distribution was also scattered in a wider range.

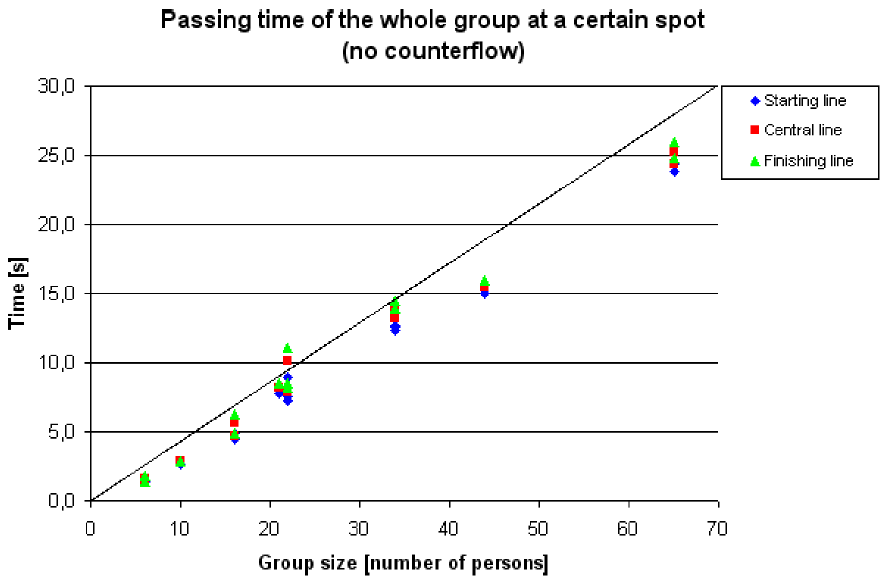

Figure 21 Passing time measured in the experiment for case 1.1 and case 1.2 taken from (Kretz et al., 2006)

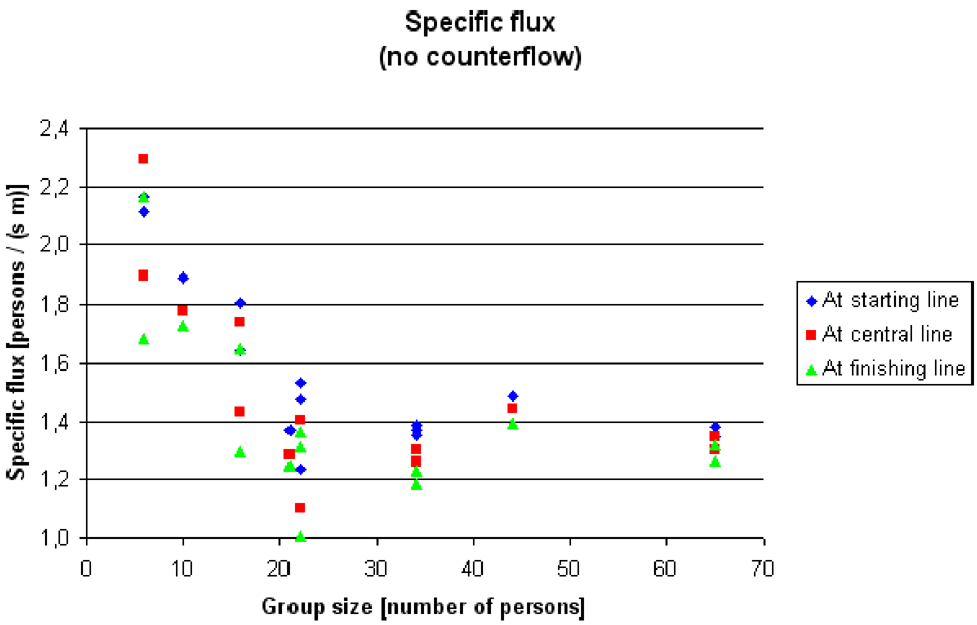

Figure 22 Flow rate measured in the experiment for case 1.1 and case 1.2 taken from (Kretz et al., 2006)

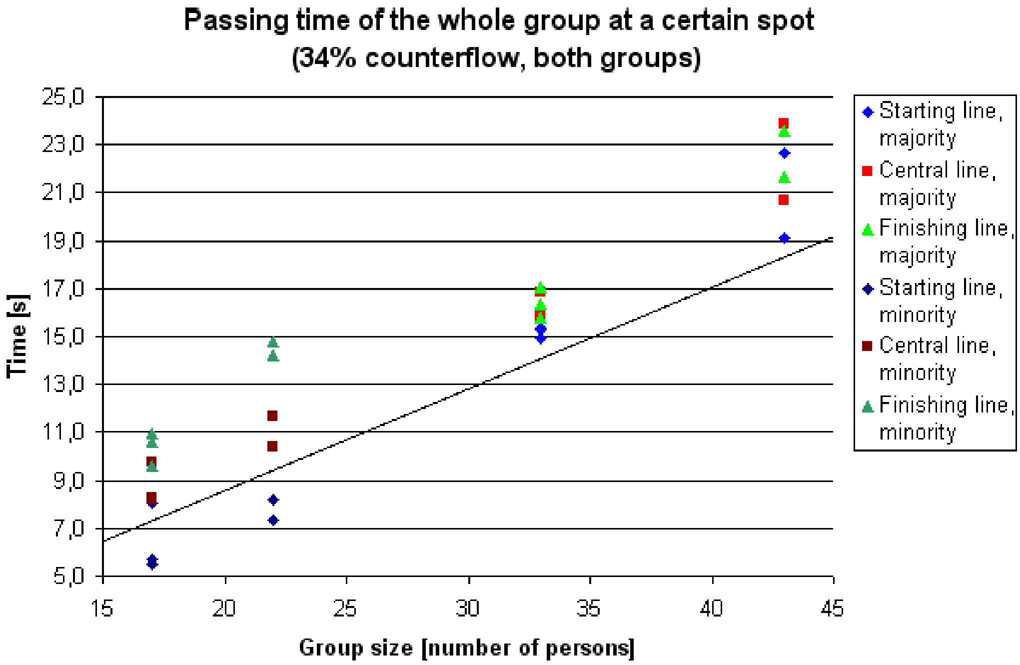

Figure 23 Passing time measured in the experiment for case 2 taken from (Kretz et al., 2006)

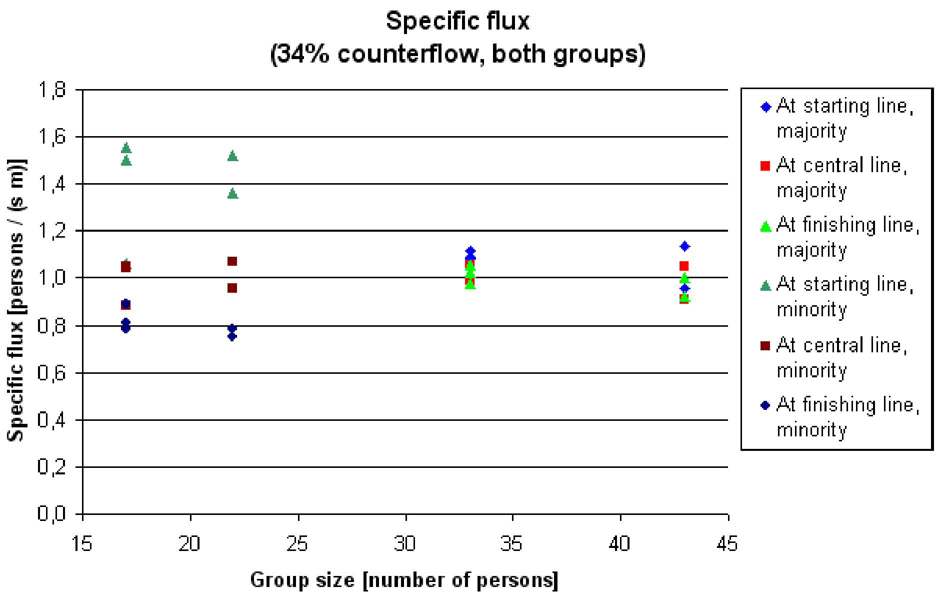

Figure 24 Flow rate measured in the experiment for case 2 taken from (Kretz et al., 2006)

Test 28. Route/Exit choice

The simulation scenario and experimental data were referred from the experiment conducted by Ronchi, Nilsson, & Gwynne (2012).

Brief description:

Way-finding systems are often installed in buildings, tunnels, etc. How to simulate the functionality of the system in the simulation is a problem. Based on the experimental data, the user-judged probability was used in this test to conduct an implicit simulation.

Chosen route/exit:

Simulated results were listed in table 18 with a pre-defined and measured probability of the usage of different way-finding system. The difference between them was calculated as well.

	Green light, 1Hz	Blue light, 1Hz	No light
Pre-defined probability	0.75	0.5	0.25
Measured probability	0.68	0.46	0.20
Standard deviation	0.47	0.50	0.44
Difference	9.3%	8.0%	20.0%

Table 18 Usage percentage of three different way-finding systems

Since this is an implicit simulation, the results were compared with values defined by the tester. From table 18, the simulated results matched the expected results well except a significant difference of 20% for no-light test. Overall, FDS+EVAC could indirectly simulate the route/exit selection with way-finding systems, but the pre-condition was that a set of reliable experimental data of the usage of different way-finding systems should be available. The experimental data used in this test was still rough. The test highly relies on the judgement of the tester to decide the probabilities of the usage of different way-finding systems.

Test 29. Bottlenecks at openings

The simulation scenario and experimental data were referred from the experiment (Nicolas, Bouzat, & Kuperman, 2017).

Brief description:

This test was conducted by using the social force model embedded in FDS+Evac to replace the placid walk and hurried walk condition of agents from a global view. Behaviours of selfish agents, such as overtaking, are not able to be represented in accuracy by using FDS+Evac since there is no sib-model corresponding to this component.

Flow condition:

Averaged maximum flow rate and averaged flow rate were measured for both cases. Results were listed in table 19.

	Averaged maximum flow rate (p/s)	SD of averaged maximum flow rate	Averaged flow rate (p/s)
Case 1	0.83	0.07	0.52
Case 2	1.17	0.11	0.90

Table 19 Results of flow rate for case 1 and case 2

Since the definition of selfish agents cannot be accurately represented in FDS+EVAC due to the lack of information, a general comparison was conducted.

Compared the experimental data from table 20 with the results of simulation from table 19, the experimental flow rate had larger values. From the randomly selected video frame from the experiment (figure 25), a fact can be found that the bottleneck can allow more than one participant to pass through simultaneously. This was not allowed in an FDS+Evac simulation since the width of an opening where agents can pass through should be at least 0.7 m. In this test, the width was 0.75 m. It was confirmed by observing simulations that only one agent passed through the bottleneck at the same time in the simulation. Therefore, the simulated flow rate was lower than the experimental data.

Crowed condition	Defined selfish level	Selfish level (%)	Density (p/m^2)	Flow rate (p/s)
Placid walk	0	0	2.69	1.01
	30	45	4.09	1.35
	30	47	4.94	1.41
	60	71	6.04	1.71
Hurried walk	0	0	3.70	1.26
	10	18	4.49	1.39
	60	71	7.63	2.20
	90	92	8.26	2.36
	100	100	8.98	2.41

Table 20 Experimental data (Nicolas et al., 2017). The crowds have two global walking conditions: placid walking and hurried walking condition. In each condition, the percentage of agents behaving as selfish was listed in selfish level volume. Selfish agents tend to overtake other agents who walk politely. Here, the selfish level was the real percentage of selfish agents measured from the experiment, which was usually higher than the defined percentage.

Figure 25 A screenshot of the experiment (Nicolas et al., 2017). Two people moving through the door was captured. It was not observed in the FDS+Evac simulation

Density:

Since FDS+EVAC cannot directly output the information of density, the density can only be done by observation and rough calculation. The density in the area close to the bottleneck was higher in case 2. It was around 4.4 p/m2. In case 1, the density was around 3 p/m2. Compared with the experimental results, the simulated flow rate was lower when the density was close.

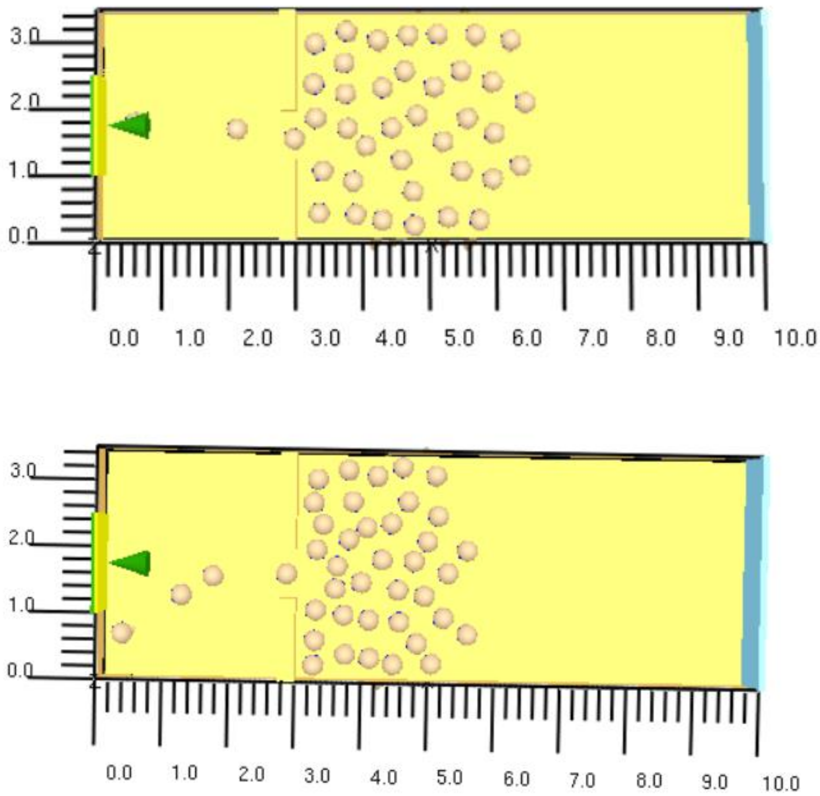

Figure 26 Screenshot of the flow rate. Density was roughly measured based on the distribution of agents. The screenshot above was for case 1. The screenshot below was for case 2. The density was higher in case 2

Test 30. Reduced visibility vs walking speed

The simulation scenario and experimental data were referred from the experiment(Enrico Ronchi et al., 2018).

Brief description:

Walking speed was affected by the concentration of the smoke. In this test, the extinction coefficient of smoke was set to 0.75/m. The simulation conducted to find the relationship between walking speed in smoke and without smoke by using FDS+Evac simulator. Results were compared with experimental data.

Waking speed:

Table 27 listed walking speed in and without smoke of all ten agents. Averaged walking speed was also calculated. Hand calculation was based on the equation 1 below which is from FDS+Evac User Guide. α and β are 0.706 m/s and -0.057 m^2/s (Frantzich & Nilsson, 2003), respectively. Figure 28 compared the walking speed in/without smoke. Figure 29 gave the comparison of relative speed and unobstructed speed from the simulation. Relative speed means the value of obstructed speed divided by unobstructed speed. Figure 30 is the figure for the same relationship but from the experiment. Figure 31 showed the relationship between obstructed speed vs extinction coefficient from the experimental data. Figure 32 and 33 showed the relationship between obstructed speed and unobstructed speed with/without smoke.

Comparison:

From table 27, simulated walking speed was reduced by smoke around 11.5% compared with the speed without smoke on average. Hand-calculated walking speed in smoke was 1.50 m/s which is around 0.1m/s (0.6%) slower than pre-defined speed (1.6m/s). From figure 28 and 31, the distribution of the speed in smoke matched well in ranges. Compared with figure 29 and 30, the distribution of relative walking speed and unobstructed walking speed was almost the same but slightly faster in values. One reason may be that there was less human uncertainty such as hesitation was considered. Meanwhile, the walking speed in smoke in FDS+Evac was based on former experimental data. It should be mentioned that the difference can be found when the simulated results are compared with other experimental data. This shortage was also reported in FDS+Evac user guide. Figure 32 and 33 showed the relationship of obstructed speed vs unobstructed speed. The experimental data set were almost below the diagonal line and in the range of 1 to 2 of the x-axes and 0.5 to 2 of the y-axes, which was the area where the simulated results laid on.

Agent	1	2	3	4	5	6	7	8	9	10
Speed in smoke (m/s)	1.84	1.39	1.22	1.27	0.99	1.39	1.31	1.54	1.37	1.54
Speed without smoke (m/s)	2.07	1.54	1.37	1.46	1.11	1.52	1.48	1.75	1.55	1.75
Hand-calculated speed in smoke (m/s)					1.50					
Average speed in smoke (m/s)					1.38					
Average speed without smoke (m/s)					1.56					

Figure 27 Results of the speed in and without smoke of 10 agents

Equation 1:

$$v_i^0(K_s) = Max\left\{v_{i,min}^0, v_i^0\left(1 + \frac{\beta}{\alpha}K_s\right)\right\}, \qquad \alpha = 0.706\frac{m}{s}, \beta = -0.057\frac{m^2}{s}$$

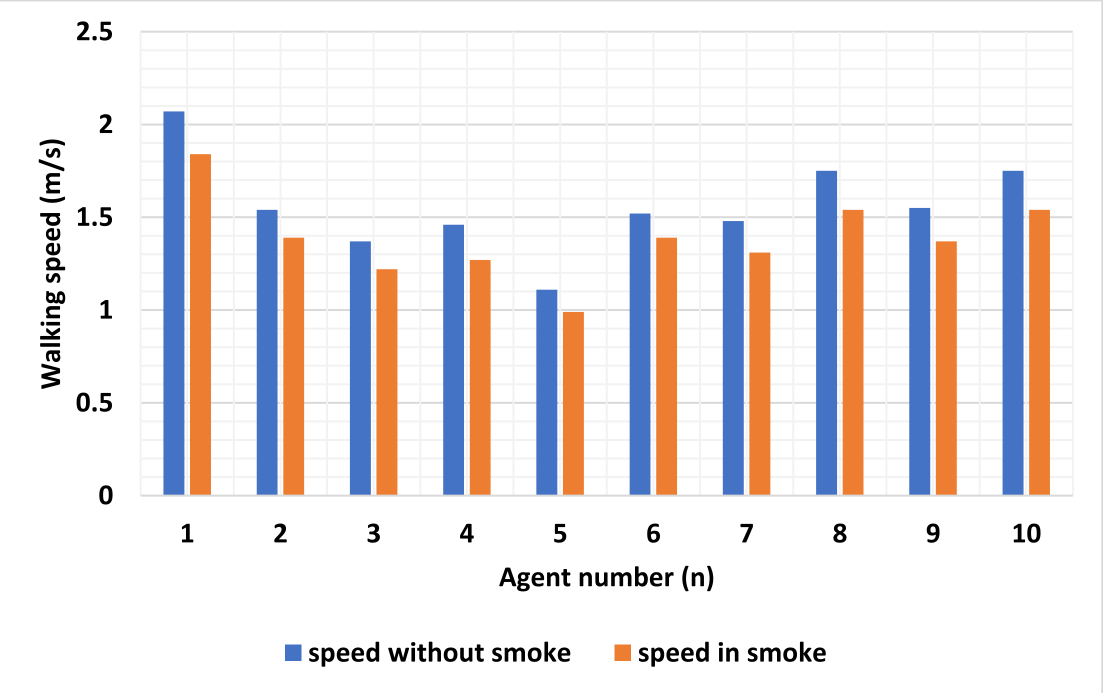

Figure 28 Simulated results of walking speed of 10 agents in smoke and without smoke. The extinction coefficient of the smoke was 0.75/m

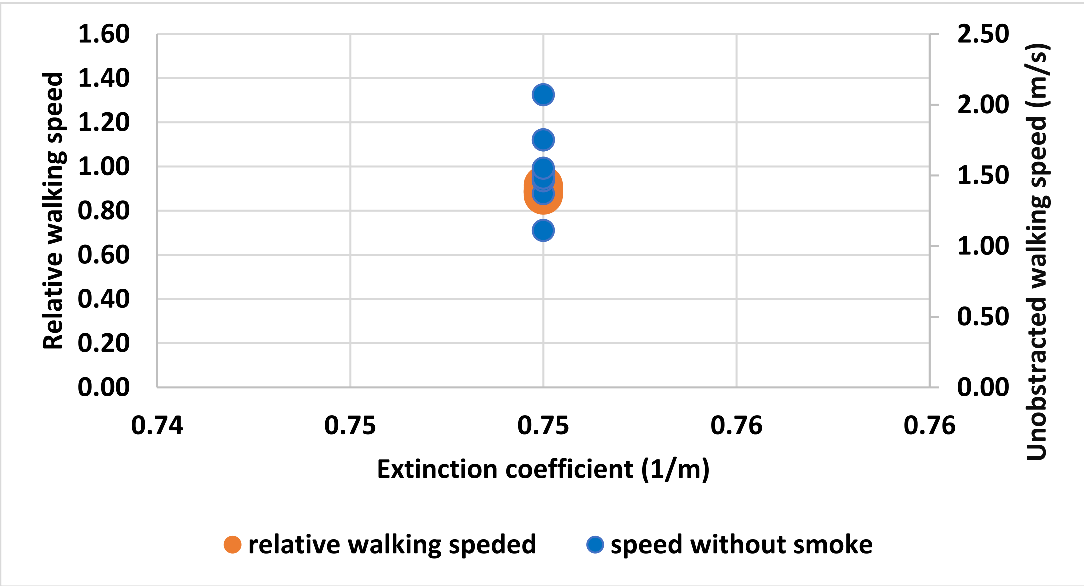

Figure 29 Simulated results of comparison of relative speed and unobstructed speed

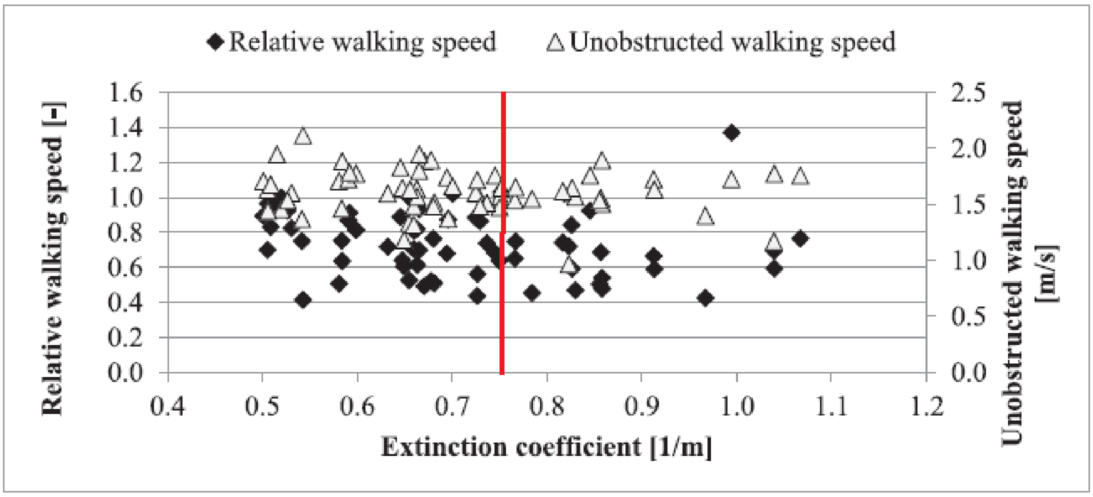

Figure 30 Experiment results of comparison of relative speed and unobstructed speed taken from (Ronchi et al., 2018).

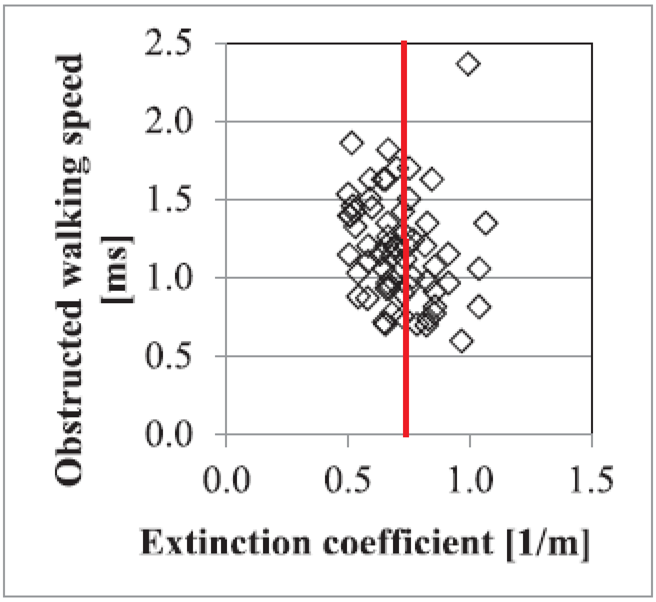

Figure 31 Experiment data on the relationship between obstructed speed vs extinction coefficient taken from (Ronchi et al., 2018).

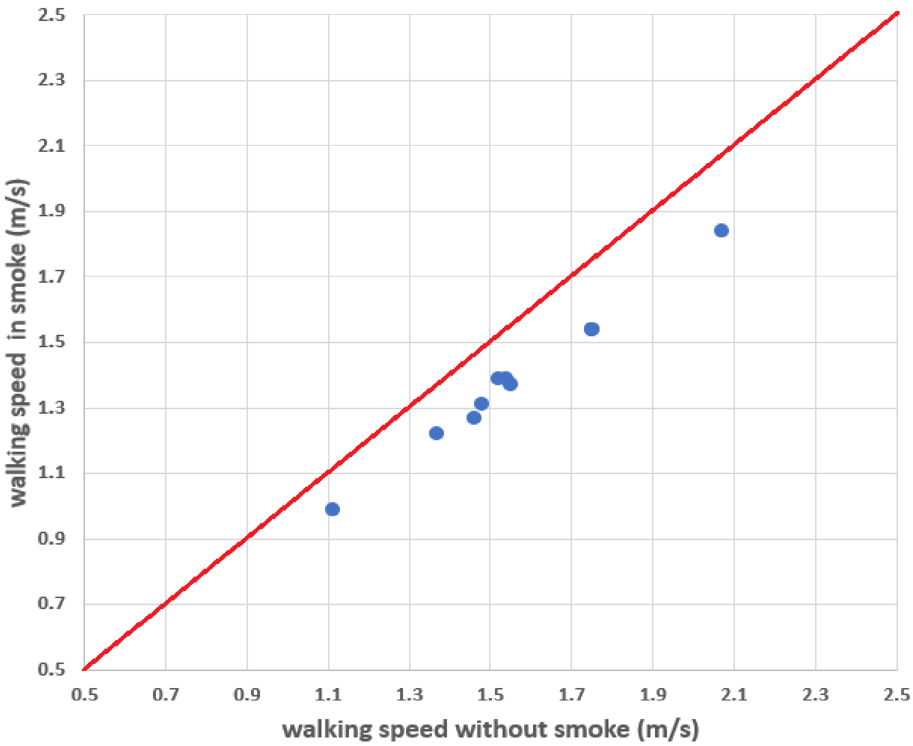

Figure 32 Simulated results of 10 agents in the relationship of obstructed speed (walking speed in smoke) vs unobstructed speed (walking speed without smoke)

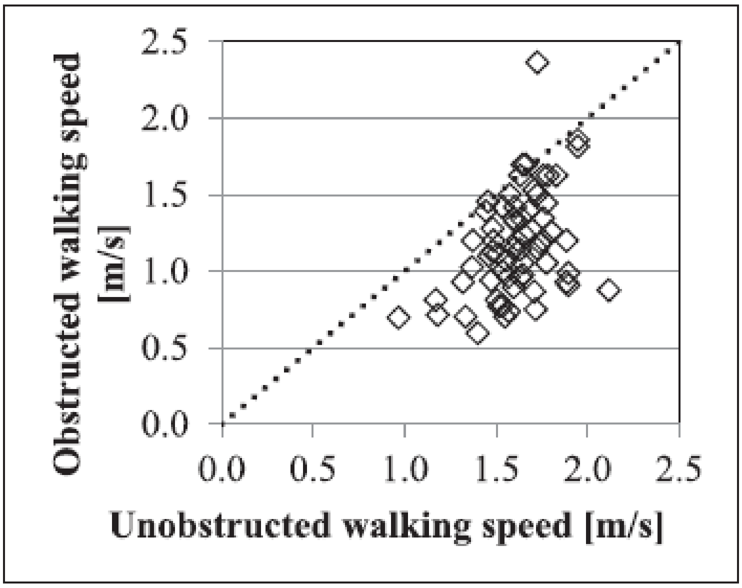

Figure 33 Experimental data of the relationship of obstructed speed vs unobstructed speed taken from (Ronchi et al., 2018).

Global validation

Test 31.

Results and comparison:

The flow rate was measured on each floor. Time interval of 1 second and 5 seconds were used in the calculation, respectively.

Density was not precisely measured in FDS+Evac since the model does not have an explicit output function. Therefore, the calculated density is based on the area of the geometry (floor landing, landing and horizontal area of flight). Densities on floor landings, landings and flight (horizontal) were separately calculated by dividing the number of agents to the area.

Time interval of 1 second:

As expected, the flow rate fluctuates when the time interval of 1 second was used to capture the flow rate condition as figured 34 shows below. Meanwhile, the results just laid on 0 p/ms, 0,83 p/ms and 1.67 p/ms these three values of flow rate. Therefore, considering the case with a time interval of 1 second it was decided to not plot a fundamental diagram since the trend between the flow rate and the density would be clearer with flowrates calculated based on larger time intervals.

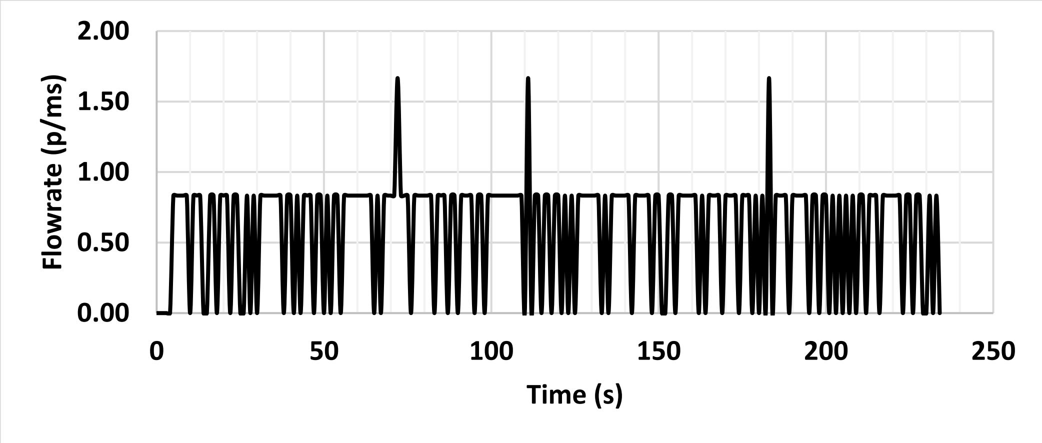

Figure 34 An example of the measured flow rate on the 1st floor with a time interval of 1 second

Time interval of 5 seconds:

Flow rates were measured in the time interval of 5 seconds on every measure line on each floor of the simulated building. Fundamental diagram was plotted in the same figure in colour blue. Since the building has identical geometry on each floor, the measured averaged flow rates showed the similarity in values on different floors. Density was measured in a time interval of 1 second so that an averaged value of density was used to represent the density corresponded to the averaged flow rate. Table 21 showed the calculated results of flow rates and densities. Therefore, fundamental diagrams were plotted as figure 35, figure 36. The range of x-axes and y-axes were identical as figure 37 which is the fundamental diagram for downward stairs from various sources of experimental results (Burghardt et al., 2013) for easier comparison.

In figure 37, data points in figured 35 and figure 36 have been plotted based on table 21 by different types of red spots. The data points in figured 35 and 36 showed a clear increasing trend. As figure 37 showed, all simulated data points laid in a reasonable range related to the experimental data.

The comparison of the results with another model named Simtread is under the data processing. Therefore, the results will not be listed here. A simple comparison was made in Appendix 2.

Averaged flowrate	Density on floor	Density on landing	Density on flight
p/ms	p/m^2		
0.33	1.52	2.38	0.75
0.50	1.78	2.33	0.78
0.67	1.94	2.19	0.87
0.83	2.07	2.20	0.94
1.00	2.55	2.36	1.14

Table 21 Avenged flow rate and corresponding averaged densities

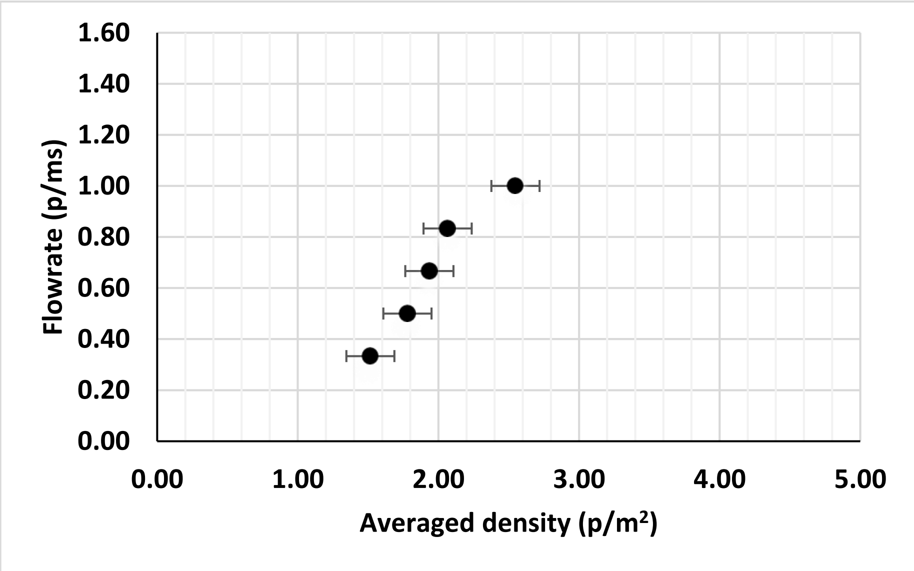

Figure 35 Fundamental diagram of floor landings with error bar

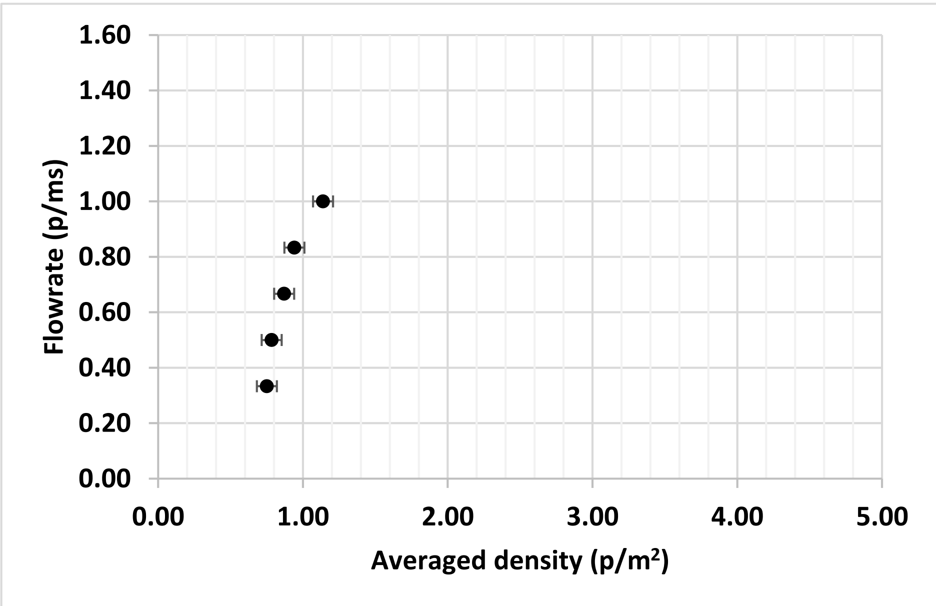

Figure 36 Fundamental diagram of flights with error bar

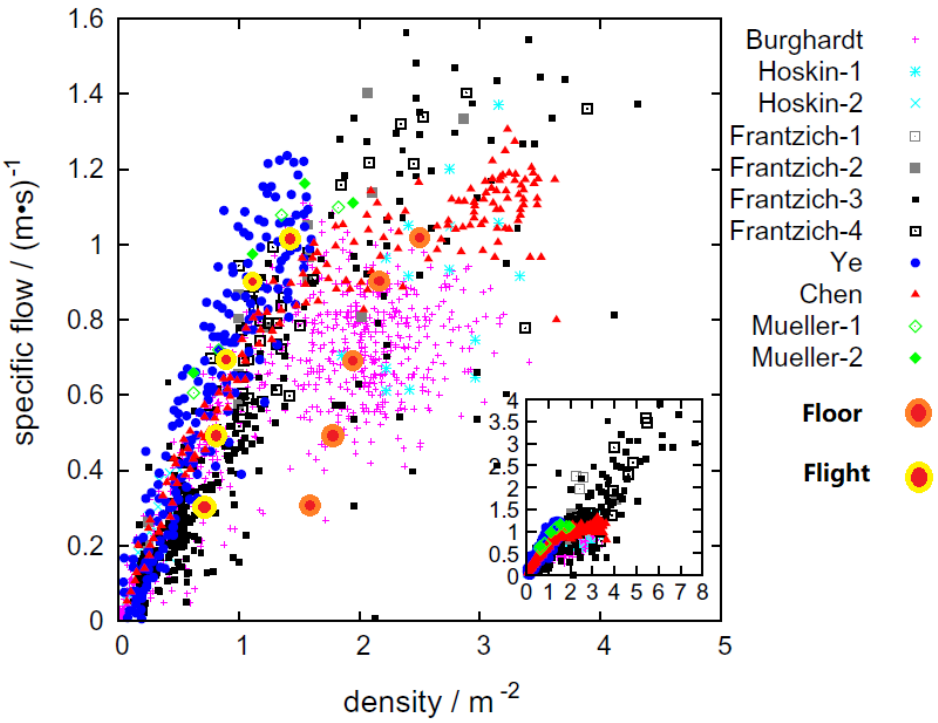

Figure 37 Screenshot of the fundamental diagram for downward stairs from various sources of experimental results (Burghardt et al., 2013). Simulated results were represented in three different red spots with edges in different colours

Graphic visualisation of the simulation:

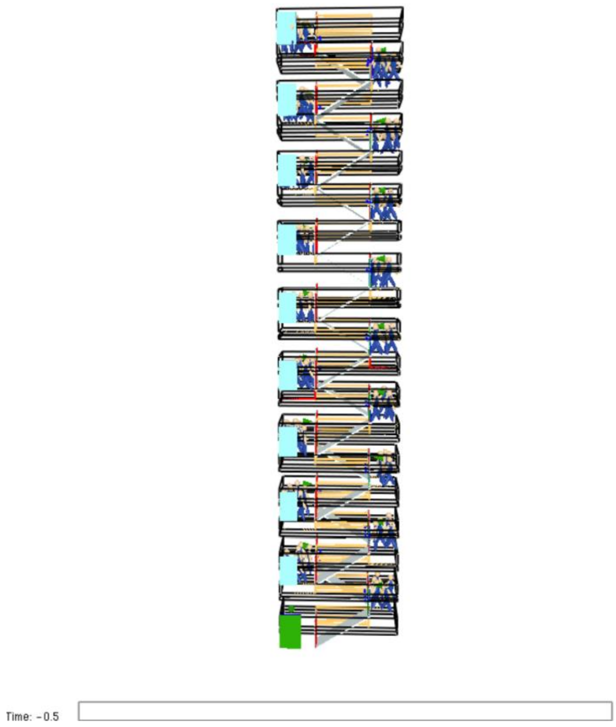

Figure 38 Screenshot at 0 seconds. Agents on floor landings and landings are placed, but agents on flights are waiting to move in

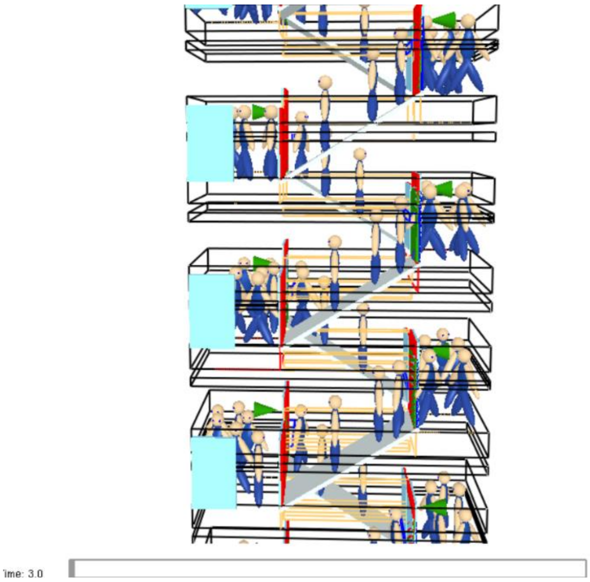

Figure 39 Screenshot after 3 seconds. Agents moved into the flights before other agents started to move

Figure 40 Screenshot after 80 seconds

8 Discussion

In this section, the test procedures with results will be compared and discussed. Issues and challenges of evacuation models will be analysed based on the performance of FDS+Evac simulator in this thesis.

8.1 Comparison with existing verification test procedures

This thesis reviews the developing test procedure of the ISO V&V Standard and gives possible suggests of the improvement. Since the ISO test procedure is primarily based on the NIST test procedure, the comparison will mainly revolve around the NIST test procedure and ISO test procedure. The RiMEA test procedure will be included as well since some tests are designed based on tests from it. It should be mentioned that the final version of the test list may be changed due to further improvements in the ISO test procedure.

Twenty-one verification tests are contained in the ISO V&V test procedure for verifying basic components in evacuation models. Compared with the NIST test procedure, four new tests were added in the test list. They are:

Test 12. Stair flow rates
Test 13. Relationship between walking speed, unidirectional flow and density
Test 17. Route choice
Test 21. Escalator usage

Test 12 and test 21 were newly designed tests for verifying the flow rate on stairs and the usage of an escalator, separately. It is of great importance for an evacuation model to have the ability to represent flow condition on stairs in both upward and downward directions, which was just being verified horizontally in test 5.2 in the NIST test procedure. This test also gives a highlight on assumptions and methods of simulating the flow rate on stairs. For instance, the results can be different by using the user-defined walking speed on stairs or the default algorithm of controlling the walking speed on stairs. Test 21 was designed to verify the function of a simulated escalator as a new building-specific component. Escalators are equipped as a structural component in modern buildings in high frequency such as shopping malls, libraries, office buildings, etc. Therefore, this new test broadens the usability of the ISO test procedure to fit the latest development in the field of architecture. More components could be added in the test list of building-specific components as emerging structural components in the future.

Test 3, 4, 10, 13, 16, 17 and 20 were modified from existing test procedures to fit buildings for a better application. Test 3 was designed to verify the assignment of walking speed on stairs. It was improved from test 2.2 in the NIST test procedure by reducing the length of the simulated stair from 100 meters to 10 meters, which makes the test scenario more reasonable since it is rare for a stair/ramp with 100 meters length in reality. In test 4, the test method was improved for test 2.3

in the NIST test procedure by adding factors for quantitative verification; for instance, walking speed, flow rate, density, etc. Moreover, the measurement of flow rates entering and exiting the corner was required in the test. The author suggested that it is better to place more agents than just twenty in the simulation if the flow rate is going to be measured since the results could be more sensitive to a smaller number of agents passing through. The fluctuation of the flow rate can have a negative impact on the result analysis. More corners with different configuration (with an angle of 60 degrees or 180 degrees) were also be considered in this test, which provides a thorough consideration of possible scenarios for verification. Test 10 was modified by giving more 50 agents (150 in total) in the room rather than only 100 agents in test 5.1 form the NIST test procedure. The test also changed the movement direction from downward to upward. It has the same configuration and evacuation scenario as test 13 in the RiMEA test procedure. The reason to have 150 agents could be that a steady flow can be generated for a longer time so that the congestion at the bottom of the stair can be observed clearly. However, the author argued that the movement direction on the stair should be tested in both upward and downward direction if the setting of the walking speed on the stair is not deterministic. Otherwise, only one direction is sufficient if the speed can be set deterministic in the model. Test 16 and test 20 were slightly modified based on test 3.3 and test 2.7, separately, from the NIST test procedure. Test 16 and 20 remained the same configuration and evacuation scenario but being given more suggestions in the user's actions. The ISO document suggests that in test 16 more agents should be used in case of macroscopic models in which occupant movement is represented only at an aggregate level based on a computer-assisted algorithm. It also suggested that additional tests are required if sub-models can simulate the multiple lifts in test 20. More details were provided in the user's actions for conducting more comprehensive verification tests.

Test 13 and test 17 were new tests but modified based on tests from the RiMEA test procedure. Test 13 was designed to verify the relationship between walking speed, uni-direction flow and density in a corridor with different initial densities of agents. It has the almost same testing purpose as test 4 (Measurement of the fundamental diagram) designed in RiMEA. However, the scale of the geometry was reduced to a 100-meter long corridor with a 2-meter width rather than a 1000-meter length and 10-meter width corridor. This improvement makes the simulation with less computational requirements, but the relationship is measurable. Meanwhile, this test can verify the ability of models to represent a uni-direction flow, which is a highly frequent scenario in reality. For instance, a corridor of a stadium or a crowd moving in a corridor-like geometry in an underground system at morning peak. Test 17 was designed to verify whether agents can use the closest route in the scenario to reach the final exit rather than use a longer route. This test was modified from test 14 in the RiMEA test procedure with more accurate descriptions. It is of great importance for evacuation models capable of representing this closest route choice in the simulation since it is reasonable for ordinary people to choose a shorter route rather than a longer route to evacuate in the real world if other factors are not considered such as affiliation. However, the route choice may vary in different evacuation models since the methods of defining different floors, assigning routes to agents and building the geometry may lead to different results of the route choice. For instance, a door has to be generated to link a stair to make the stair functional in FDS+Evac. If the tester defines that agents know this door as a familiar exit, the stair route will be used with high frequency. Otherwise, agents prefer to use the longer route on the same floor.

Therefore, this test can review the limits of models on the movement and navigation algorithm and remains the tester to be aware of these limitations.

In the NIST test procedure, tests for verification were divided into two categories: analytical verification and emergent behaviour verification (Ronchi et al., 2013). Analytical verification refers to component testing where the results can be made by simple mathematical equations or evidence. Emergent behaviour verification refers to a qualitative evaluation of the results of evacuation models which reflect the current knowledge on human behaviour in fire. It was replaced in the ISO test procedure by four more precise categories: basic components, behaviour components, fire-people iteration components and building-specific components. The last two categories are newly divided categories but very significant in the verification of evacuation models since an evacuation always come up with smoke and fire, and these building-specific components such as lifts/elevators are standard equipment in most modern buildings. The importance of the knowledge of human behaviour and the combination of human behaviour with fire science are emphasized here. Meanwhile, the test procedure can catch up with the latest development of buildings.

8.2 Comparison with existing validation test procedures

The lack of experimental data-sets is always a difficulty for validation of evacuation models. Meanwhile, evacuation models could be designed and built starting from a set of specific experimental data (Ronchi et al., 2013). For instance, the smoke concertation used in the calculation of reduced walking speed in FDS+Evac is based on the results of the experiment conducted by Frantzich and Nilsson (2003) where larger smoke concentrations were used from the experiments by Jin(1978). Therefore, the same experimental data should be used in the validation testing since this could lead to a narrow application field and end up with self-proving. It can cause another problem that the results will have significant differences when the model is used in the simulation of other scenarios. Despite these difficulties, the NIST test procedure briefly provided a list of possible experimental data for verification of main core components of evacuation models. It was simply represented with suggested variables and sub-elements such as stairwells, way-finding installations, etc.

A list of methods (tests) for analysing the results was suggested in the new ISO document as mentioned in section 2.3 in this thesis. These methods were listed in each validation test and classified as primary recommended tests and secondary recommended tests. It gives the tester a clear message about the must-do objectives in a validation test and the data which the tester should look for in the experiment. However, even the primary recommended tests could not be adequately represented since the selected experiment may just offer partial data. For instance, BOX 27 (counter flows) listed that the primary recommended tests are method B (Arrival times comparison for the whole scenario) and method D (Comparison of flow through exits/doors), but only the data of flow rate are available in the selected experiment while the arrival times comparison for the whole scenario cannot be found instead of passing times in a certain distance in the scenario. Methods cannot always be wholly fulfilled since the limits of the availability of data always exit.

Based on table 2 in section 3.4, the new ISO document provides a comprehensive list of recommended experimental data. It has more than one data-sets available for each validation test, which gives the tester more choice when selecting data and deciding validation objects. Different models/simulators usually have different levels of ability to simulate the same scenario, which is because the algorithm embedded is various from one model to another. Another reason is that only single data-sets is not enough for validating a model which is going to be applied in different scenarios. Single data-sets may not be representative for all possible results in evacuation simulation. Data from multiple sources and multiple simulations for a selected scenario can fully cover the assessment of uncertainties of human behaviour which should be taken into consideration when analysing the results.

A list of full evacuation scenarios was proposed in the global validation section in the ISO document. Compared with the NIST test procedure which just gave one suggested data-sets, this list covered the various types of behaviours and scenarios in case of a building fire. The model tester should perform the current list of tests and adopt all test methods, if possible, for global validation to assess the performance of the tested model in different scenarios. However, as the ISO document mentioned, this list should not be considered exhaustive because a further application may be identified by the model users. The problem of the lack of full-scale experimental data-sets also exits for global validation.

Open validation and blind validation were proposed in the ISO document. Which type of validation should be conducted is up to how much information the tester currently has and the type of analysis under consideration. In this thesis, the validation tests were designed based on the selected experiments. These experiments contain detailed information about the scenario such as properties of agents, geometry, etc. The most important is the output which is the benchmark data-sets used for validation. Therefore, all conducted validation tests were open validation tests.

8.3 Issues and challenges for evacuation models

The development of evacuation models has been accelerated by increasing computational power and the study of human behaviour. Evacuation modelling becomes one of important means in the performance-based design. Many evacuation models/simulators are in the market these days. For instance, the most-known models include Pathfinder (Avenue, 2011), STEPS (STEPS, 2019), Simulex (Integrated Environmental Solutions Ltd., 2015), buildigEXODUS (Galea.e.t, 2004) and FDS+Evac (Korhonen, T., & Hostikka, 2009). These models have different approaches and the ability to simulate the movement of agents and represent the evacuation scenario. Therefore, verification and validation are introduced to assess the performance of these models. In this thesis, FDS+Evac simulator(Korhonen, T., & Hostikka, 2009) has been used to go through tests form the new ISO document and identify the benefits associated with the usage of the comprehensive V&V procedure from the ISO standard. Significant issues are picked up and discussed in this section. Issues are also introduced in detail in each test in appendix 2.

The author conducted all contained verification and validation tests except test 26 in the validation section. Issues relative to performance and limitations were found when tests were conducted by using FDS+Evac. These issues are more associated with the sub-model of components in verification, such as the limitation of initial density. In validation, issues are relative to both sub-models and approaches to represent the experimental environment; for instance, how to simulate the impact of way-finding systems in test 28.

Table 21 gave an overview of the ability of FDS+Evac to represent a component in accuracy. Term *explicitly, implicitly, partially and no* are used to answer the question '*Does the model include a sub-model able to represent the feature/behaviour included in the test?'* listed on the top of the table. This question also can be found at the 1st question in each full-version test report in Appendix 2. *Explicitly* means that the feature/behaviour required to be verified can be directly represented and modified by parameters embedded in the model. For instance, the assignment of the walking speed of agents can be directly defined by parameter VELOCITY_DIST (Korhonen, T., & Hostikka, 2009). On the contrary, *implicitly* means that the feature/behaviour can be represented, but the tester has little control of the simulation by modifying relevant parameters. An example is the simulation of the maximum exit flow rate, which has no parameters to control the flow rate directly but indirectly the width of the exit. *Partial* means that the sub-models do not have full functionality to represent the feature/behaviour or the performance is not currently satisfying compared with other sub-models.

Based on the classification above and table 21 below, FDS+Evac can represent around half of the verification tests (test 1-21) explicitly. There are parameters directly accessible to the tester to modify the simulation. However, it will arise another issue which is that the knowledge and expertise of the tester are required. For instance, test 1, 2, 3 and 5 requires a pre-set distribution and values of the pre-evacuation time and walking speed. The tester can use the default settings in FDS+Evac such as default walking speed of 'Adult'. However, to conduct a more reasonable and realistic simulation, these pre-set values better come out from experiments to make the results more representative. It is also required in some tests (for example, test 10) in the new ISO document that the choice of the characterisation of occupant demographics should be based on factors such as building use, nationality, etc., which means that the demographic has to be carefully chosen by skilled testers. Meanwhile, test 8 and 9 can be thought as typical examples since the pre-assigned exits to agents lead to a deterministic result based on the purpose of the tester. All these shows that FDS+Evac is a user-dependent evacuation simulator.

For those features/behaviours cannot be explicitly represented, the corresponding sub-models usually are very fundamental but critical algorithm embedded in the model. In FDS+Evac, four theoretical basic models control how the action of agents represents. They are agent movement model, counterflow collision avoidance model, fire and human interaction model and exit selection model. Except for the fire human interaction mode which has a particular application field, the other three basic models can be found in almost every test involving the movement of agents. For instance, test 6 is to verify the condition of horizontal counterflows. No parameters are offered to the tester to give direct control of the counter flow, but the results showed that the model can handle the counterflow without any long-term congestion or other problems. Another typical example is test 18: Reduced visibility vs walking speed. The algorithm of smoke concentration and walking speed embedded in FDS+Evac is based on a set of experimental data collected by Frantzich and Nilsson (2003) and Jin (1978). The data is like a black box, and the only input is the smoke concentration. The output of walking speed is taken from the results of the experiment, which makes any modification impossible for the tester. It even leads to a problem that the results can be very different in comparison with other experimental data. Therefore, the tester should pay more attention to the assumptions and background algorithm of each sub-model when FDS+Evac is used in the simulation.

Test 14 and test 15 are different from other tests since the group behaviour (test 14) and social influence (test 15) could not function well at this stage (Korhonen & Hostikka, 2008). Therefore, these models are already embedded in FDS+Evac but cannot be found in the FDS+Evac user guide.

FDS+Evac has been used to conduct validation tests except test 26 due to the lack of experimental data. In validation section, the critical point is not only which sub-model should the tester use but also how to use sub-models to represent the realistic scenario. For instance, test 24 (stairwell evacuation) is conducted based on the experimental data (E Ronchi et al., 2015) collected in a tall building. In the experiment, the impact of fatigue on walking speed is one of the main objects to analyse. Therefore, the tester has to think of the possible approach to simulate the impact of fatigue by using FDS+Evac. However, it was impossible to put the impact into the simulation since the sub-model used in the simulation (&STRS) does not have any option but a deterministic value of walking speed on the whole stairwell. Changing to another available sub-model could make the simulation of the impact of fatigue possible, for instance, using &EVSS sub-model. It is because that the speed can be defined in different height of the building by using &EVSS. An advantage of FDS+Evac is that it has many sub-models which make the tester have enough flexibility of choosing the most proper sub-models in the simulation. A comparison of choice of sub-models should be made in the geometry-building stage based on the purpose and expected results.

Since FDS+Evac does not directly provide flow rate and density as a part of the output data, the tester must calculate both manually based on the data collected by agent counters. For the flow rate, the most crucial factor is the time interval in the process of calculation and the time interval picked up for comparison. As figure 15 showed, the flow rate is more fluctuating when the number of agents is less. The choice of the time interval for the comparison can make the results totally different if the interval just contains a peak or a dip of the flow rate curve of 15 agents. The time interval in the process of flow rate calculation can also affect the final values of flow rate. Larger time interval typically averages more data points so that the calculated flow rate is less than that form a smaller time interval in general. It will cause fluctuation of results when the data compare with experimental data. The density of agents is not available in the output data as well, but there is a parameter for defining the initial density of agents in the geometry. The difficulty of manual calculation is the selection of measured area and the agent accounting. Smokeview provides the visual results of the simulation, but the measurement is still hard to be done in practice. Therefore, the author suggests that FDS+Evac should address this issue and provide solutions in the data analysis. Meanwhile, the usage of the initial density of agents has problems when placing agents in a scenario with high required initial density. The default method of placing agents in geometry is random but requires a minimum distance between agents. In test 13 (Relationship between walking speed, uni-directional flows and densities) and test 23 (Relationship between walking speed, uni-directional flows and densities), different initial densities were used as the input of the scenario. However, FDS+Evac cannot run the case with high initial density; for instance, 4 person/m^2 in test 13. It is because the required distance should be fulfilled if the default method is used to place agents while the geometry cannot provide enough space for both agents and the distance. The only way to solve this issue is to place each agent manually which can be possible if the number of agents is not too many. However, the scenario as test 13 has 480 agents (4 person/m^2) which make the manual method impossible in practice. The author argued that it might be possible to reduce the distance parameter in the social force (Korhonen, T., & Hostikka, 2009) to place more agents. More study is needed.

Challenges for FDS+Evac simulator can be identified based on the performance in the simulation of the ISO tests. The challenge is not just for FDS+Evac but also for other evacuation models. Plenty of sub-models embedded in models/simulators can ensure the model's usability and compatibility in various scenarios, particularly in scenarios with the newest development of buildings and knowledge of human behaviour in an emergency evacuation. Of cause, these sub-models should be verified and validated based on the available data. It gives another issue for model testing that suitable data are often rare. This challenge may accompany the development of evacuation models for a long time in the future. Accessible parameters in sub-models should be provided with clear descriptions for testers to modify the simulation to fit the real-world scenarios. A technical guide/user guide is necessary to be available with all descriptions of models, assumptions, limitations, etc. It is noted that the FDS+Evac user guide(Korhonen, T., & Hostikka, 2009) has some issues in the description of sub-models and assumptions. For instance, the default settings of social force parameters cannot be found in the section of the description of the parameters which makes the tester confused to understand the sub-model. Availability of skilled testers is another challenge for evacuation models equipping with many user-defined sub-models. Testers have to understand the logic behind the sub-model and be fully aware of the limitations in the application so that the sub-model can be correctly applied in the simulation. Therefore, basic knowledge of human behaviour and evacuation simulation is essential to testers. Data collection and analysis can be a challenge since the author found difficulties in the process when dealing with collected data from FDS+Evac. It will be great to abundant outputs available in the data collection stage. It will not only save the time spent on data analysis but also reduce the error that could happen in the data processing. Methods for data analysis are also crucial since the collected data are always enormous due to the multiple simulations and the requirement of capturing all possible human behaviours. Thanks to the data analysing tool made by Smedberg (Smedberg, 2019), the data analysis can be done with accuracy and speed.

Does the model include a sub-model able to represent the feature/behaviour included in the test?			
Test 1: **Pre-evacuation time assignment**	*explicitly*	**Test 2:** **Walking speed in a corridor**	*explicitly*
Test 3: **Walking speed on stairs**	*explicitly*	**Test 4:** **Movement around a corner**	*implicitly*
Test 5: **Assigned demographics**	*explicitly*	**Test 6:** **Horizontal counter-flows**	*implicitly*
Test 7: **People with movement disabilities**	*explicitly*	**Test 8:** **Exit route allocation**	*explicitly*
Test 9: **Dynamic availability of exit**	*explicitly*	**Test 10:** **Congestion in front of a flight of stairs**	*implicitly*
Test 11: **Maximum exit/door flow rates**	*implicitly*	**Test 12:** **Stair flow rates**	*implicitly*
Test 13: **Relationship between walking speed, uni-directional flows and densities**	*explicitly*	**Test 14:** **Group behaviour**	*explicitly*
Test 15: **Social Influence on exit choice**	*explicitly*	**Test 16:** **Affiliation to familiar exits**	*explicitly*
Test 17: **Route choice**	*explicitly*	**Test 18:** **Reduced visibility vs walking speed**	*implicitly*
Test 19: **Occupant incapacitation**	*implicitly*	**Test 20:** **Lift usage**	*explicitly*
Test 21: **Escalator usage**	*explicitly*	**Test 22:** **Pre-evacuation model**	*explicitly*
Test 23: **Relationship between walking speed, uni-directional flows and densities**	*implicitly*	**Test 24:** **Stairwell Evacuation**	*explicitly*
Test 25: **Flight of steps**	*explicitly*	**Test 26:** **Movement around a corner**	*Not conducted*
Test 27: **Counterflows**	*implicitly*	**Test 28:** **Route/exit choice**	*implicitly*
Test 29: **Bottlenecks at openings**	*implicitly*	**Test 30:** **Reduced visibility vs walking speed**	*implicitly*
Test 31: global validation: Full-scale validation in a 10-storey building	*explicitly*		

Table 22 Summarisation of the means of representation of features/behaviours by FDS+Evac in both verification and validation section. Test 1-21 are verification tests. Test 22-31 are

9 Conclusion

By applying the new ISO V&V standard by FDS+Evac simulator, benefits of the usage of the ISO test procedure can be identified. Essential components and sub-models embedded in FDS+Evac have been verified and validated so that an overview of the performance of the simulator is displayed to the tester including advantages and limitations in the simulation. The comparison between the new ISO test procedure and existing test procedures shows the more sophisticated design of the new ISO test procedure on the foundation of existing procedures. Meanwhile, the new ISO standard establishes a more comprehensive and acceptable benchmark for verification and validation of evacuation models for buildings. Another benefit is that by following the new ISO test procedure, the tester can grab basic knowledge of any simulator which is going to be tested and form a basic concept of the application field of the simulator.

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Lund, 2019

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12 Appendix

Appendix 1: List of verification tests in existing test procedures

1. IMO test procedure

Component testing

Test 1: Maintaining set walking speed in corridor

Description: this is a test for verifying whether the pre-set walking speed of an agent can be accurately simulated by passing through a specified length within an expected time.

Test 2: Maintaining set walking speed up staircase

Description: this is a test for verifying whether the pre-set upward walking speed of an agent on stairs can be accurately simulated by passing through a specified length within an expected time.

Test 3: Maintaining set walking speed down staircase

Description: this is a test for verifying whether the pre-set downward walking speed of agent on stairs can be accurately simulated by passing through a specified length within an expected time.

Test 4: Exit flow rate

Description: this is a test for verifying whether the flow rate of an exit/door can be reasonably simulated within a threshold, e.g. 1.33p/s as suggested.

Test 5: Response time

Description: this is a test for verifying whether the model can assign the pre-set response time (pre-evacuation time) to agents with the defined distribution.

Test 6: Rounding corners

Description: this is a test for verifying whether agents can successfully navigate around a corner without penetrating the boundary.

Test 7: Assignment of population demographics parameters

Description: this is a test for verifying whether the model can assign the pre-set walking speed to agents within its range and distribution type.

Functional verification

Tests are not provided.

Qualitative verification

Test 8: Counterflow – two rooms connected via a corridor

Description: this is a test for verifying whether the model can successfully simulate a counterflow without long-term stagnation and the relationship between evacuation time and the number of agents in counterflow.

Test 9: Exit flow: crowd dissipation from a large public room

Description: this is a test for verifying that the evacuation time should be doubled if one of the two exits is not available.

Test 10: Exit route allocation

Description: this is a test for verifying whether agents can use pre-allocated exits to evacuate without any problem.

Test 11: Staircase

Description: this is a test for verifying whether congestion can be generated at the base of the stairs under a specific oncoming flow rate.

2. RiMEA test procedure

Component testing

Test 1: Maintaining the specified walking speed in a corridor

Description: this is a test for verifying whether the pre-set walking speed of an agent can be maintained during the evacuation.

Test 2: Maintaining the specified walking speed up stairs

Description: this is a test for verifying whether the pre-set upward walking speed of an agent on stairs can be maintained during the evacuation.

Test 3: Maintaining the specified walking speed down stairs

Description: this is a test for verifying whether the pre-set downward walking speed of an agent on stairs can be maintained during the evacuation.

Test 4: Measurement of the fundamental diagram

Description: this is a test for verifying the real relationship between the walking speed and the density of agents in a one-way corridor.

Test 5: Pre-movement time

Description: this is a test for verifying whether the model has the ability to distribute pre-defined pre-evacuation time to agents properly.

Test 6: Movement around a corner

Description: this is a test for verifying whether agents have the ability to go around a corner without passing through boundaries successfully.

Test 7: Allocation of demographic parameters

Description: this is a test for verifying whether the model has the ability to assign the pre-set walking speed to agents within its range and distribution type.

Functional verification

Test 8: Allocation of demographic parameters

Description: this is a test for conducting parameter analysis of the walking speed of agents. Different walking speeds are used. The relationship between evacuation time and different walking speeds are plotted.

Qualitative verification

Test 9: Crowd of people leaving a large public space

Description: this is a test for verifying whether that the evacuation time should be doubled if one of the two exits is not functional.

Test 10: Allocation of escape routes

Description: this is a test for verifying whether agents can use pre-allocated exits to evacuate without any problem.

Test 11: Choice of escape route

Description: this is a test for verifying whether agents can automatically choose other better escape routes to evacuate under a congestion situation.

Test 12: Effect of bottlenecks

Description: this is a test for verifying the relationship between flow rate and congestion under the effect of a bottleneck.

Test 13: Congestion in front of a flight of stairs

Description: this is a test for verifying whether congestion can be generated at the base of the stairs under a specific oncoming flow rate.

Test 14: Choice of route

Description: this is a test for verifying whether agents can choose the shortest egress route in the evacuation scenario.

Test 15: Movement of a large crowd of pedestrians around a corner

Description: this is a test for verifying that the movement of persons around a corner affects the calculated evacuation time.

3. NIST test procedure

Verification

Core component - Pre-evacuation time

Test 1.1: Pre-evacuation time

Description: this is a test for verifying the ability of the model to distribute pre-evacuation times from a given distribution to agents.

Core component - Movement and navigation

Test 2.1: Speed in a corridor

Description: this is a test for verifying the ability to maintain assigned unimpeded walking speed of agents.

Test 2.2: Speed on Stairs

Description: this is a test for verifying the ability to maintain assigned upward and downward walking speed on stairs.

Test 2.3: Movement around a corner

Description: this is a test for verifying whether agents can navigate around a corner without passing through boundaries.

Test 2.4: Assigned demographics

Description: this is a test for verifying model ability to assign demographic parameters such as walking speed.

Test 2.5: Reduced visibility vs walking speed

Test 2.6: Occupant incapacitation

Description: these two tests are designed for verifying the influence of smoke/toxic gases on the agent movement.

Test 2.7: Elevator usage

Description: this is a test for verifying the model ability of the usage of an elevator.

Test 2.8: Horizontal counter-flows

Description: this is a test for verifying whether the model can simulate a counterflow scenario and the influence on the total evacuation time.

Test 2.9: Group behaviour

Description: this is a test for verifying whether the model could simulate the group behaviour in an evacuation scenario.

Test 2.10: People with movement disabilities

Description: this is a test for verifying the model's ability to simulate the influence of the disables, such as a disabled person in a wheelchair, on the movement flow and evacuation time.

Core component - Exit usage

Test 3.1: Exit route allocation

Description: this is a test for verifying the deterministic assignment of exits.

Test 3.2: Social influence

Description: this is a test for verifying the model's ability to simulate social influence among agents.

Test 3.3: Affiliation

Description: this is a test for verifying whether the model can simulate affiliation on the exit choice.

Core component - Route availability

Test 4.1: Dynamic availability of exit

Description: this is a test for verifying whether agents can change exit choice when the assigned exit is not available.

Core component - Flow condition

Test 5.1: Congestion

Description: this is a test for verifying whether the model can reproduce expected congestions.

Test 5.2: Maximum flow rates

Description: this is a test for verifying whether the simulated flow rates can remain in a specified range, such as no more than 1.33 p/ms.

Appendix 2: simulated tests and results of the ISO test procedure

NOT PUBLICLY AVAILABLE.