Verification and Validation of Viswalk for Building Evacuation Modelling

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Verifiering och validering av Viswalk för utrymningsmodellering av byggnader

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Abstract

This thesis is evaluating the pedestrian modelling software Viswalk for the use as a building evacuation model, by verifying and validating the model. In the verification, a procedure from the *National Institute of Standards and Technology (NIST)* is used as a basis to assess Viswalk's ability to represent pre-evacuation time, movement and navigation, exit usage, route availability and flow constraints. Seven tests are excluded due to delimitations of the thesis or limitations of the current version of the model. The verification tests show that Viswalk is able to represent the main core components of evacuation models that are under consideration. The model yields results that correspond with the expected results for all 10 verification tests that are performed. However, non-conservative flow rates can be obtained if the default input settings are used. In the validation, results from Viswalk are compared to four real life experiments including a corridor, a classroom, a theatre lobby and a stair, followed by an uncertainty analysis. With adjusted input settings the movement times deviate with 2-16 % from the experiments and with default input settings the movement times deviate with 12-95 %. The walking speed is an important parameter in the validation tests, even with substantial congestion, with up to 46 % increased movement times when the walking speeds are decreased with 25 %. In the validation it is also noted that the occupant densities in front of openings can differ with up to 45 % between the simulations and the experiments. Despite the aspects described above, results that are close to experimental results can be obtained if the user has a good estimation of the occupant demographics and is aware of the limitations of the model.

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Summary

Evacuation modelling is a useful tool to perform risk analyses. Evacuation models can be used during the identification phase of a risk analysis where possible risks are identified, for example where bottlenecks may occur, but also when analysing the consequences of specific events. Evacuation models can also be used when assessing and analysing different types of risk reducing actions, such as improvements of a building's fire protection design and to evaluate their suitability. By comparing the ASET (Available Safe Egress Time) to the RSET (Required Safe Egress Time) it can be evaluated if buildings can be evacuated safely in case of fire. The concept is used in performance-based design to conclude if the available evacuation time exceeds the required time for evacuation, thus analysing if a safe evacuation can take place. The RSET can be estimated with the use of computer simulation software and there is a large array of evacuation models for this purpose.

The simulation software Viswalk is developed by the *PTV Group* and can be used separately or as an add-on module to Vissim, which is used in transport planning and evacuation modelling. Viswalk is based on the social force model and allows for modelling of complex geometries with large numbers of occupants. The model can be used to analyse for example occupant movement times, flows through bottlenecks and route choice. Viswalk is used in a variety of fields but few studies have been carried out to evaluate the model for building evacuation purposes. It has been shown that the most important factor when fire protection engineers choose an evacuation model is the verification and validation of the model, which makes the need for an evaluation of the model evident.

The aim of this thesis is to provide an initial evaluation of Viswalk as a building evacuation model. Also, in the context of evacuation modelling, Viswalk's main strengths and weaknesses are identified and analysed. The focus of the evaluation is horizontal and vertical movement in buildings, which includes studying movement times and pedestrian flows. Vertical movement refers to movement on stairs and no technical resources such as escalators or elevators are included. The objective is to investigate how the model's representation of the main core components of evacuation models relates to known evacuation verification tests. The objective is also to evaluate how well the model can predict and reproduce pedestrian movement in a given situation by validating the model against previously performed real life experiments.

The first phase of the thesis is a literature study, which is initiated by studying risk management and the evacuation model's role in the risk management process. Additionally, fundamentals of Viswalk and previous verification and validation of the model are studied. Furthermore, methods for verification and validation are identified along with experiments to be used as benchmarks in the validation phase.

The second phase focuses on verification of Viswalk using a procedure suggested by the *National Institute of Standards and Technology (NIST)*, which is adjusted to fit the model. The verification focuses on the core components of evacuation models; pre-evacuation time, movement and navigation, exit usage, route availability and flow constraints. A total of 10 verification tests are performed which addresses specific sub-elements of the core components. The tests compare simulation results to theoretical expected results to evaluate the fundamental assumptions of the model using either a qualitative or quantitative method. Seven tests are excluded due to delimitations of the thesis or limitations of the current version of the model.

The third phase consists of validating Viswalk against previously performed real life experiments. Four small scale experiments are used as benchmarks and they include movement with different demographical and geographical setups consisting of a classroom, a corridor, a theatre lobby and a stair. Simulations are performed with both *default* and *specified input settings* to evaluate how different input settings impact the results. With *default input settings*, the model's standard input settings are used while with *specified input settings*, the input settings are adjusted to better agree with

the experiments. The simulation results are compared to the experimental results to determine if the model can predict and reproduce pedestrian movement in a given situation. To complement the validation, an uncertainty analysis is performed to address uncertainties associated with the tests. Uncertainties that are believed to have large impacts on the results are evaluated by performing sensitivity analyses.

The verification tests show that Viswalk is able to represent the main core components of evacuation models. The model yields results that correspond with the expected results for all 10 verification tests that are performed. It should however be noted that non-conservative flow rates can be obtained if the model's default input settings are used, which is important for the user to be aware of.

From the validation tests it is concluded that the model can predict and reproduce pedestrian movement in a given situation. In simulations with *specified input settings* the movement times deviate with 2-16 % and the flows deviate with 2-14 % from the experiments in all four validation tests. In simulations with *default input settings* the movement times deviate with 12-95 % and the flows deviate with 13-54 %. The validation tests that focus on horizontal movement yield movement times that are longer and flows that are lower, than in the experiments. This can be explained by the default occupant demographic settings in Viswalk which are specific to a certain occupant group of 30-50 year olds from the *IMO* guidelines *MSC/Circ. 1238.*

The default stair settings of the model produce occupant flows on stairs that are 20-45 % higher than in the experiment. A walking speed reduction can be assigned to the stair to obtain results that better agree with the experiment, which makes the model more user dependent. It should also be noted that separate walking speeds up and down the same stair cannot be defined. Another observation is that the occupants do not maintain the intended distance to the side walls in the beginning and end of stairs, which is important for the user to be aware of. This can decrease the movement times for single stairs with up to about 10 % and may have a larger impact in simulations with multiple stairs, such as high-rise buildings.

The results from the uncertainty analysis show that a decrease of occupant walking speeds of 25 % increases the movement times with 46 % in the evaluated scenario. Even with substantial congestion early in the evacuation process, the walking speed is an important parameter for scenarios similar to the ones under consideration.

The movement patterns of the occupants can deviate from real life experiments in certain situations. Occupants sometimes get stuck between close obstacles when given low walking speeds, which should be taken into consideration when simulating confined spaces. It is also observed that some occupants tend to idle beside openings and partially block other occupants that are trying to exit. The results indicate that the line formation is wider and the density is higher close to the opening than in the experiments. This is important for the user to be aware of since the densities are central when performing for example toxicity assessments or when designing exit routes.

Despite the aspects described above, Viswalk provides the user with the ability to adjust parameters and calibrate the model for specific areas. Results that are close to experimental results can be obtained if the user has a good estimation of the occupant demographics and is aware of the limitations of the model.

Sammanfattning

Utrymningsmodellering är ett användbart verktyg för att utföra riskanalyser. Utrymningsmodeller kan användas under identifieringsfasen av en riskanalys där möjliga risker identifieras, till exempel var flaskhalsar kan uppstå, men även vid konsekvensutredningar av specifika händelser. Utrymningsmodeller kan också användas för att utvärdera och analysera olika typer av riskreducerande åtgärder, såsom förbättringar av en byggnads brandskydd och för att bedöma deras lämplighet. Genom att jämföra ASET (Available Safe Egress Time) med RSET (Required Safe Egress Time) kan det utvärderas om byggnader kan utrymmas säkert vid händelse av brand. Konceptet används vid analytisk dimensionering och går ut på att avgöra om den tillgängliga tiden för utrymning är längre än den krävda tiden, vilket innebär att säker utrymning kan ske. För att uppskatta RSET kan datorprogram användas och det finns många olika program, med varierande komplexitet.

Viswalk är ett simuleringsprogram utvecklat av *PTV Group* och kan användas fristående eller som en tilläggsmodul till Vissim, som används för trafikplanering och utrymningsmodellering. Med Viswalk kan simuleringar göras av komplexa geometrier och stora mängder människor. Programmet använder social force-modellen och kan användas för att analysera exempelvis förflyttningstider, flöden genom trånga utrymmen och vägval. Viswalk används inom många olika områden, men det har gjorts få studier för att utvärdera om programmet är lämpligt att använda i i utrymningssyfte. Det har visats att den viktigaste faktorn när en brandingenjör väljer utrymningsprogram är att programmet har verifierats och validerats, vilket tydligt visar behovet av att utvärdera Viswalk ytterligare.

Syftet med examensarbetet är att tillhandahålla en initial utvärdering av Viswalk som ett verktyg för att modellera personers utrymning av byggnader. Syftet är även att identifiera och analysera Viswalks huvudsakliga styrkor och svagheter som utrymningsprogram. Utvärderingen fokuserar på horisontell och vertikal förflyttning i byggnader, vilket inkluderar förflyttningstider och personflöden. Vertikal förflyttning syftar till förflyttning i trappor och inkluderar inte tekniska hjälpmedel såsom rulltrappor eller hissar. Målet är att undersöka hur Viswalks framställning av utrymningsprograms huvudkomponenter relaterar till kända verifieringstester. Målet är också att utvärdera hur bra Viswalk kan förutse och återge personers förflyttning i givna situationer genom att validera programmet mot tidigare utförda utrymningsförsök.

Arbetets första del består av en litteraturstudie, vilken inleds genom att utforska riskhantering och utrymningsprograms roll i riskhanteringsprocessen. Dessutom studeras Viswalks grundläggande antaganden och funktioner samt att tidigare utförda verifieringar och valideringar av programmet undersöks. Dessutom identifieras metoder för verifiering och validering av utrymningsprogram samt utrymningsförsök som ska användas i valideringen.

Arbetets andra del fokuserar på att verifiera Viswalk enligt en arbetsgång som föreslås av *National Institute of Standards and Technology (NIST)*, vilken anpassas för det undersökta programmet. Verifieringen analyserar utrymningsprograms huvudkomponenter; förberedelsetid, förflyttning och navigering, användandet av utgångar, vägval samt begränsningar av flöde. Totalt tio verifieringstester görs och de utvärderar specifika element inom huvudkomponenterna. Testerna jämför resultat från simuleringar med teoretiskt förväntade resultat och undersöker på så sätt grundläggande antaganden, med antingen kvalitativa eller kvantitativa metoder. Sju tester utesluts på grund av arbetets avgränsningar eller begränsningar hos den nuvarande versionen av programmet.

Den tredje delen av arbetet består av att validera Viswalk mot tidigare utförda utrymningsförsök. Utgångspunkten för valideringen utgörs av fyra småskaleförsök, där resultaten jämförs med simuleringar. Försöken har olika geografiska och demografiska förutsättningar och består av utrymningsförsök av ett klassrum, en korridor, en teaterlobby och en trappa. Simuleringar utförs både med programmets standardinställningar och med specificerade inställningar, för att på så sätt undersöka hur olika inställningar påverkar resultaten. Med programmets standardinställningar används

inställningar som är förvalda i programmet medan med specificerade inställningar anpassas inställningarna för att överensstämma med försöken. Simuleringarna jämförs med försöken för att avgöra om Viswalk kan förutse och återge personers förflyttning i givna situationer. Valideringen kompletteras med en osäkerhetsanalys som analyserar osäkerheter associerade med de utförda testerna. Osäkerheter som tros ha stor påverkan på resultaten analyseras vidare genom känslighetsanalyser.

Verifieringstesterna visar att Viswalk kan framställa utrymningsprograms huvudkomponenter. Programmet ger resultat som korresponderar med förväntat resultat i samtliga tio verifieringstester som utförs. Det bör dock noteras att icke-konservativa flöden kan erhållas om modellens standardinställningar används, vilket är viktigt för användaren att vara medveten om.

Genom valideringstesterna fastställs det att programmet kan förutse och återge personers förflyttning i givna situationer. I simuleringar med specificerade inställningar skiljer sig förflyttningstiderna med 2-16 % och flödena med 2-14 % från försöken i samtliga fyra valideringstester. I simuleringar med programmets standardinställningar skiljer sig förflyttningstiderna med 12-95 % och flödena med 13-54 %. Valideringstesterna som fokuserar på horisontell förflyttning ger förflyttningstider som är längre och flöden som är lägre än i försöken, vilket kan förklaras genom att Viswalks standardinställningar för personers egenskaper är specifika för gruppen 30- till 50-åringar enligt *IMO*s riktlinjer *MSC/Circ. 1238*.

Programmets standardinställningar för trappor ger personflöden i trappor som är 20-45 % högre än i försöken. En gånghastighetsreducering kan tilldelas trappan för att erhålla resultat som stämmer bättre överens med försöket, vilket gör programmet mer användarberoende. Det bör även tilläggas att olika gånghastigheter uppför och nedför samma trappa inte kan definieras i programmet. En annan observation är att simulerade personer inte håller avståndet till väggarna i början och slutet av trappor, vilket är viktigt för användaren att vara medveten om. Fenomenet kan minska förflyttningstiderna för enstaka trappor med upp till ungefär 10 % och kan ha större betydelse i simuleringar med flertalet trappor, såsom höghus.

Resultaten från osäkerhetsanalysen visar att en minskning av simulerade personers gånghastigheter med 25 % ökar förflyttningstiderna med 46 % i det undersökta scenariot. Trots omfattande trängsel i ett tidigt skede av utrymningen är gånghastigheten en viktig parameter i scenarier som liknar de undersökta försöken.

Simulerade personers rörelsemönster kan avvika från utrymningsförsök i vissa situationer. Personer kan ibland fastna mellan närliggande hinder när en låg gånghastighet ansätts, vilket bör tas i beaktning vid simuleringar av trånga utrymmen. Det observeras även att vissa personer tenderar att avvakta bredvid dörröppningar och delvis blockera andra personer som försöker gå ut genom dörren. Resultaten indikerar att köformationen nära öppningen är bredare och densiteten är högre i simuleringarna än i försöken. Det är viktigt för användaren att vara medveten om detta eftersom densiteterna är centrala vid exempelvis toxicitetsbedömningar eller vid utformning av utrymningsvägar.

Trots ovan beskrivna aspekter ger Viswalk användaren möjlighet att justera parametrar och kalibrera programmet för specifika användningsområden. Resultat som ligger nära försöksresultat kan erhållas om användaren kan göra en bra uppskattning av populationens egenskaper och är medveten om programmets begränsningar.

Terminology and Definitions

Core components	Five main components that divide human behaviour elements in evacuation situations into five different areas; 1) pre-evacuation time, 2) movement and navigation, 3) exit usage, 4) route availability and 5) flow constraints (Ronchi et al., 2013a)
Evacuation model	A computer simulation model that can be used to simulate pedestrian movement in an evacuation process
Flow	The number of occupants that pass a certain geographical point during a defined time interval (persons/second = p/s)
Flow rate	The number of occupants that pass a certain geographical point per meter width during a defined time interval (persons/meter width/second = p/m/s)
Occupant	An arbitrary simulated person in an evacuation model, characterized mainly by walking speed and body size (Ronchi et al., 2013a)
Pedestrian	A general real life person that is characterized mainly by walking speed and body size
Pre-evacuation time	The time it takes from a fire cue until the occupant starts moving towards an exit (Ronchi et al., 2013a)
Verification	*"The process of determining that a calculation method implementation accurately represents the developer's conceptual description of the calculation method and the solution of the calculation method"* (International Standards Organization, 2008)
Validation	*"The process of determining the degree of which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method"* (International Standards Organization, 2008)
Vissim	A simulation program developed by the *PTV Group* that can be used to simulate pedestrian and vehicle traffic and their interaction
Viswalk	A simulation program that can simulate movement of large amounts of pedestrians

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1 Introduction

The following chapter contains an introduction where a short background is given, followed by the aim and objective of the thesis. The chapter continues with a description of the method and limitations and delimitations of the thesis. Lastly it is specified which version of the model that is evaluated.

1.1 Background

To determine whether people in a building can evacuate safely in case of fire, fire protection engineers have long used the so called ASET/RSET concept. The ASET (Available Safe Egress Time) and RSET (Required Safe Egress Time) concept is used in performance-based fire safety engineering design to compare the available evacuation time to the required evacuation time (Poon, 2014). A method of estimating the RSET is through evacuation modelling programs, i.e. computer software used to calculate an estimation of the evacuees' total evacuation time. Many different types of evacuation models are available (Lovreglio, Ronchi & Borri, 2014) and the development of more advanced models is in the proceeding.

PTV Vissim is a simulation program, developed by the *PTV Group*, which can be used to model traffic and pedestrian flows. Vissim can be used in variety of areas, from transport planning to evacuation modelling, and can be used by many different professions. With the add-on module PTV Viswalk it is possible to simulate large numbers of pedestrians and flows, both inside buildings and outside. Viswalk is based on the social force model developed by Helbing and Molnár (1995) which can reproduce some aspects of human behaviour (PTV, 2014).

The most important factor, which has been shown in a survey, for fire protection engineers when choosing an appropriate evacuation model is the validation and verification of the model (Ronchi et al., 2013b). Validation is important to be able to quantify and assess the accuracy and suitability of simulation models for fire evacuation analyses (Lovreglio et al., 2014). When using an evacuation model it is therefore important that the model is verified and validated for the intended use, so that a good estimation of the RSET can be made.

Previous studies have been carried out, both by the model developers and by third parties, to calibrate and evaluate features of Viswalk. One of the calibration methods used by the developers includes the *RiMEA* guidelines, which are a set of basic tests to verify and calibrate walking speeds, flows through openings, etc. However, there are currently no further studies that focus on evaluating Viswalk for building evacuation modelling or validating the model against real life evacuation experiments. Since the verification and validaton of a model is essential both from a risk management perspective and from a user perspective, the need for a third party evaluation of Viswalk for building evacuation modelling is evident.

1.2 Aim and Objective

The aim of this thesis is to provide an initial evaluation of Viswalk as a building evacuation model. The evaluation focuses mainly on the model's representation and prediction of pedestrian movement in buildings. The aim is furthermore to identify the model's main strengths and weaknesses in a context of building evacuation modelling.

The objective is to investigate how the model's representation of the main core components of evacuation models relates to known evacuation verification tests. The objective is also to evaluate how well the model can predict and reproduce pedestrian movement in a given situation. Futhermore, the uncertainties associated with the results from the validation are identified and analysed.

1.3 Method

The method used in the thesis can be divided into four main phases; Literature Study, Verification, Validation and lastly Discussion and Conclusions. The Validation and Verification (V&V) phases can also be divided into three different sections; Data Collection, Results and Analysis. The workflow of the thesis with the four different phases can be seen in Figure 1.

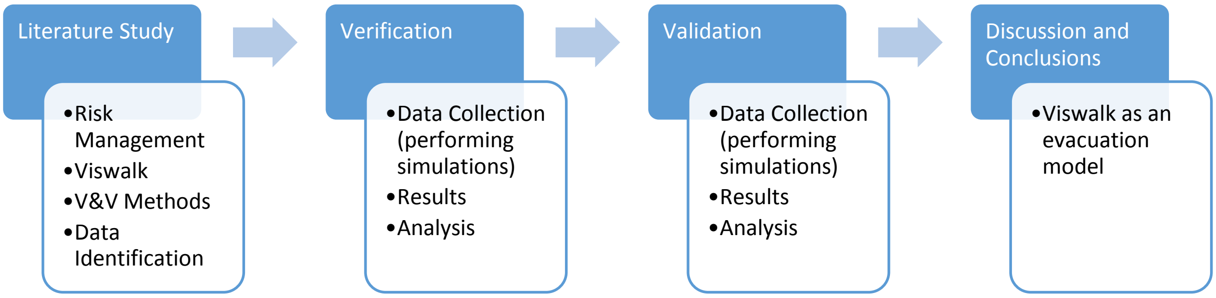

Figure 1. The four main phases of the thesis.

1.3.1 Literature Study

The initial phase of the thesis consisted of a literature study where four main areas were examined, see Figure 2.

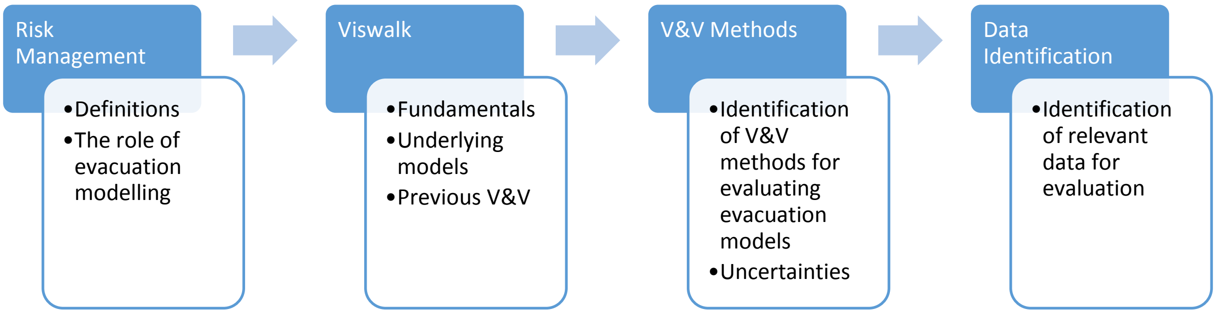

Figure 2. The different examined areas of the literature study.

Information for the literature study was collected through *Lund University's* database LUBsearch, which includes a vast number of databases with journals and e-books. Furthermore the search engine Google and the database arXiv were used to find articles. Initially, the keywords used were intended to get a wide scope of articles and included words such as Vissim and validation of evacuation models, which resulted in large amounts of search results.

The initial search was followed by more narrow keywords, which are presented in Table 37 in *Appendix A*. The search for information included reading the abstracts of the articles and reports that were found, in order to decide if they had any relevance to the different areas examined. As the initial search was done, the relevant articles were studied thoroughly. Articles and reports were also provided by the three supervisors from *Tyréns*, *Lund University* and *PTV Group*. With their knowledge in the studied areas, they had a lot of information to share.

1.3.1.1 Risk Management
Since evacuation modelling can be seen as a part of the risk management process, the literature study began with a general description of the risk concept and the risk management process. Information was found through data base searches. The role of evacuation modelling in risk management was clarified and information about evacuation modelling for risk management was studied.

1.3.1.2 Viswalk
Fundamental theory about the evacuation model and its underlying assumptions were studied, mainly through the user manual and databases. This was an important step on the way to get an understanding of the model, which enabled suitable verification and validation tests to be chosen, and also improved the analysis of the results. The literature study also included identification and a description of previous research and studies regarding verification and validation of Viswalk to get an overview of the work already done. This was made to enable continued work on validation and verification of Viswalk without repeating previous tests. Also, earlier work was found through the program developers, who themselves had performed tests and had a good knowledge about previous work by others.

1.3.1.3 V&V Methods
Furthermore, the literature study included identification and analysis of methods used for verification and validation of evacuation models. The information was found through database searches and literature recommended by the supervisor from *Lund University*. Three different verification methods were identified; a set of verification tests already performed by the developers, named *RiMEA* (Rogsch et al., 2014), a set of verification tests for maritime application (International Maritime Organization, 2007) and a set of tests developed by the *National Institute of Standards and Technology (NIST)* together with researchers from *Lund University* (Ronchi et al., 2013a). Furthermore, uncertainty in the context of evacuation modelling was researched. This area was necessary to form a background to the validation phase, where uncertainties were an important factor to be studied.

1.3.1.4 Data Identification
The last task of the literature study was to find suitable data from previously performed evacuation experiments that could be used in the validation process of Viswalk. The data-sets were found through database searches and through the supervisor from *Lund University*. Several evacuation experiments were found in the literature and these were studied to determine if the experiments could be used for the validation process.

A total of four experiments were chosen to be used in the validation, based on certain criteria. Firstly, experiments were chosen that were well documented to enable a meaningful validation to be performed. The experimental data-sets included a description of the geometric and demographic conditions of the experiments. Secondly, experiments that had been performed several times with similar conditions were desirable so that the results were not only a single value of the measured quantity. Thirdly, experiments were chosen that included horizontal or vertical movement together with occupant flows through openings or on stairs.

1.3.2 Verification
The second phase of the thesis consisted of performing the verification tests identified in the literature study. The verification evaluated the capability of Viswalk compared to theoretical tests, divided into five core components of evacuation modelling. From the three verification methods identified in the literature study, the tests from the *NIST* procedure were chosen for the verification of Viswalk. These tests were chosen since the test procedure was most extensive, comprehensive and up to date compared to the other two identified procedures. Furthermore, one of the identified methods was intended for maritime applications and the other method had already been used by the model developers.

Seven tests in the *NIST* procedure were excluded due to delimitations of the thesis or limitations of the current version of the model. *Verification test 2.6 – Occupant incapacitation, 2.7 – Elevator usage* and *2.10 – People with movement disabilities* were not performed since these sub-elements are not studied in the thesis.

Verification test 2.5 – Reduced visibility vs walking speed involves the physical impacts on occupants due to smoke which is not available in the studied version of Viswalk. *Verification test 2.9 – Group behaviours* evaluates the model's ability to simulate a group of occupants that are moving together and awaiting each other on their way to an exit. This type of group behaviour is not included in Viswalk and this test was therefore not performed. *Verification test 3.2 – Social influence* studies how the occupants' routes are influenced by other occupants and how the exit choices may change due to social influence. This specific type of social influence is not available in the model and the test was therefore excluded. *Verification test 3.3 – Affiliation* requires a sub-model that allows the occupants to be familiar with an exit, i.e. they prefer to use known exits. Viswalk does not include a sub-model like this and the test was not performed.

The remaining 10 verification tests were performed by following the instructions of the test procedures. Some tests were slightly adapted to fit the specific model being tested, which was described in the test modifications. If the test description did not specify explicit simulation properties, the model's default settings were used. As the model uses distributions with km/h as input for walking speeds, the desired walking speeds in m/s were adjusted to fit the model. This means that a uniform distribution of 3.6-3.61 km/h was used when a walking speed of 1 m/s was specified in the test description.

The performed tests consisted of six quantitative and four qualitative tests. The qualitative verification tests were performed with 10 simulations each, to detect potential discrepancies in the results. To determine how many simulations that should be performed in each quantitative verification test, a simple convergence method was applied to the results. The method used is similar to the convergence method used by Ronchi and Nilsson (2014). Firstly, 10 runs were performed where the mean of the studied test results was calculated after each run. This mean was referred to as the cumulative mean. To study the convergence of two consecutive cumulative means a convergence measure (in %) was calculated according to Equation 1.

$$\text{Convergence Measure} = \left|\frac{CM_n - CM_{n-1}}{CM_n}\right| \qquad \text{(Equation 1)}$$

where

CM_n = the cumulative mean of n runs

CM_{n-1} = the cumulative mean of n-1 runs

The convergence measure was used to evaluate how the results from the simulations were affected by the number of runs. A convergence acceptance criterion was defined for each verification test, for example 1 %, which served as a threshold of when the cumulative mean was sufficiently stable. If the convergence criterion was not exceeded in the five last consecutive runs, no further runs were performed. If the convergence criterion was exceeded additional runs were performed until the criterion was fulfilled for the five last consecutive runs.

The results from the verification tests were analysed by comparing the results to the expected results in accordance with the *NIST* procedure (Ronchi et al., 2013a). *Verification test 1.1 – Pre-evacuation time distributions* and *Verification test 2.4 – Assigned occupant demographics* were analysed with hypothesis testing to determine if the simulation results belonged to a specific pre-defined probability distribution. In the first stage of the hypothesis testing the null hypothesis and the alternative hypothesis were described. The null hypothesis was that the obtained sample from the simulation results came from the assigned probability distribution. The alternative hypothesis was that the results did not come from the assigned probability distribution.

When the hypotheses were clarified and the simulations were done, an Anderson-Darling goodness-of-fit test was performed on the sample. This was done with the software Minitab 17 and resulted in p-values of the empirical distribution function. The p-value was analysed in comparison to the level of significance to enable conclusions about if the null hypothesis could be rejected or not. The level of significance was chosen as 5 % for *Verification test 1.1 – Pre-evacuation time distributions* and *Verification test 2.4 – Assigned occupant demographics*. If the p-value exceeded 0.05 the null hypothesis was not rejected and if the p-value was less than 0.05 the null hypothesis was rejected. A more extensive explanation of the hypothesis testing approach used in the tests can be found in *Appendix A.*

After comparing the simulation results to the expected results conclusions were made about Viswalk's ability to reproduce the tested sub-elements adequately.

1.3.3 Validation

The third phase of the thesis consisted of performing validation tests to compare results from the model to real life data from previously performed evacuation experiments. A total of four experiments were identified in the data identification phase that served as benchmarks for the validation tests, including a corridor, a classroom, a theatre lobby and a stair. The validation was divided into four main sections, one for each test performed, where the tests were described and the results were presented and analysed.

The main focus of the validation was movement, mainly horizontal, but also vertical movement. Movement was chosen since it is one of the core components of evacuation models and it has a large impact on the results provided by models used for fire evacuation analyses. There were also previously performed evacuation experiments that could be used as benchmarks for analysing movement, which is a primary condition to enable a validation to be performed.

Each validation test was performed with at least two different sets of input settings, named *default* or *specified settings*. The *default settings* were used to evaluate how the simulation results related to real life experimental results, when using the model's standard input settings. This was done to analyse the model's fundamental assumptions and the user's degree of impact on the results. When using the *specified input settings*, the occupant demographics (age, gender, walking speeds, etc.) were adjusted to fit the experiments. This enabled an evaluation to be made of Viswalk's ability to predict movement times and occupant flows through openings and on stairs, compared to real life evacuation experiments. One of the validation tests, *Validation test 4 – Stair experiment*, was performed with an additional set of *specified input settings*, which included specifying the occupants' walking speeds on stairs.

In *Validation test 2 – Classroom experiment*, the occupants' routes were defined when using the *specified input settings* to fit the routes from the experiment. The experiment used as benchmark for this test was the only one in the validation that included descriptions of the occupants' route choices. Thus, this was the only validation test were the occupants' routes were specified when performing the validation tests. All tests also had only one exit that the experiments focused on and no exit choices of the occupants were therefore studied.

To determine the number of simulations to be performed in each validation test, the convergence method described in section *1.3.2 Verification* was used. The convergence criterion for the cumulative movement time means was set to 1 %. A low criterion was chosen to ensure that a sufficient number of simulations were performed.

The analyses of the validation tests were performed by comparing the experimental results to the simulation results when using the different input settings. The main focus was on movement times and occupant flows and the comparisons were made by calculating the differences between the results, both in percentage and absolute values.

1.3.3.1 Uncertainty Analysis

As a part of the validation of Viswalk an uncertainty analysis was performed where uncertainties associated with the simulation results and with the experimental data were identified and analysed. The identification of uncertainties was performed through brainstorming with the four different types of uncertainties identified and described in section *2.3.3 Uncertainties in Evacuation Modelling*, as a basis. After the identification phase, four uncertainties were chosen for further analysis. These uncertainties were chosen since they were estimated to have a large impact on the validation results and they were possible to analyse further.

To analyse the chosen uncertainties, sensitivity analyses were performed using scenarios from the validation tests. The method for the uncertainty analyses consisted of modifying specific uncertain parameters to study how the resulting movement times and occupant flows were affected by these parameter modifications. The results from the uncertainty analysis were used as a basis for the discussion and conclusions of the validation tests and to analyse the results.

1.3.4 Discussion and Conclusions

The final phase of the thesis revolved around discussing the findings and the results from the verification and validation tests. The strengths and weaknesses of the model from a fire evacuation modelling perspective and how Viswalk related to the applied verification and validation tests were discussed. Conclusions were made about the results and the surrounding uncertainties from the validation tests were discussed.

1.4 Limitations and Delimitations

The thesis focuses on fire building evacuation of able-bodied pedestrians, which means that movement disabilities are not taken into consideration when performing the verification and validation tests. Furthermore, movement in elevators, escalators or other technical resources is not examined in the thesis. The verification process follows an existing predefined method, which is adjusted to fit the specific model. This means that verification tests that are not suitable due to limitations of the model are excluded. The current version does not model fire, smoke or some of the aspects of human behaviour related to building evacuation, and tests regarding these features are excluded.

The validation focuses on pedestrian movement, which includes both horizontal and vertical movement. The validation is delimited to studying mainly movement times, flows through openings and flows on stairs. The number of experiments is delimited to four small scale experiments that are used as benchmarks for the validation tests.

The uncertainty analysis is restricted to primarily analysing uncertainties that have large impacts on the results from the validation. Uncertainties with smaller impacts are analysed and discussed briefly.

1.5 Model Version

The version of the model that is evaluated is PTV Viswalk 7.00-01.

2 Literature Study and Fundamentals

The following chapter consists of a literature study which serves as a basis for the thesis. The literature study is divided into four sections; Risk Management, Fundamentals of Viswalk, Verification and Validation Methods and finally Data Identification.

2.1 Risk Management

The following section is divided into two separate parts. The first part consists of a description of the risk concept and the risk management process. The second part addresses evacuation modelling and its role in the risk management process.

2.1.1 What is Risk/Risk Management?

There are many different definitions of risk. However, there is no definition that is generally accepted and agreed on. The word risk is used in different disciplines with different meanings, for example social risks, economic risks, safety risks, etc. (Kaplan & Garrick, 1981). The definitions include for example risk as uncertainty, an event, a probability or an expected value. According to some definitions, risk can refer to both wanted and unwanted outcomes, often surrounded by uncertainty (Aven & Renn, 2009).

A commonly used definition is one proposed by Kaplan and Garrick (1981). According to their definition, risk can be defined as a set of triplets, i.e. the answer to three questions;

- *"What can happen? (i.e., What can go wrong?)*
- *How likely is it that that will happen?*
- *If it does happen, what are the consequences?"* (Kaplan & Garrick, 1981, p. 13)

Kaplan and Garrick refer to this definition as a quantitative definition where the probability and consequence of an event can be quantified. The definition can therefore be appropriate to use for example in a quantitative risk analysis (QRA). It is essential to define the risk concept to enable meaningful risk analyses to be made in the risk management process.

Risk management can be defined as *"..the systematic application of management policies, procedures and practices to the tasks of analysing, evaluating and controlling risk*" (Harms-Ringdahl, 2004, p. 14). Risk management should always be performed as a structured process with continuous improvements and there are several different ways to do this (Davidsson et al., 2003).

The risk management process can be divided into several phases or components. These phases are (Davidsson et al., 2003):

- Risk analysis } Risk assessment
- Risk evaluation }
- Risk reduction/control
- Follow up

Risk analyses are performed in order to identify risks, their probabilities and consequences. A risk analysis starts with a description of the system, the system's boundaries, the aim and the delimitations of the analysis (Davidsson et al., 2003). Thereafter, potential risks that can affect the current system are identified through a suitable risk identification method. The identified risks are then analysed and their probabilities and consequences are estimated qualitatively, quantitatively or through a combination of these.

The next phase of the risk management process is risk evaluation. Through the risk analysis, risks have been identified and their probabilities and consequences represent a measure of how severe the risks are. In the risk evaluation phase it is determined whether the identified risks should be accepted or not.

This can be done in many different ways, for example through pre-defined risk criteria (Davidsson et al., 2003). The risk analysis and risk evaluation phases can together be referred to as risk assessment.

In the risk reduction phase, possible risk reducing measures are examined in order to reduce or eliminate risks identified in the risk analysis. Unacceptable risks are reduced to an acceptable level and risks that are acceptable but can be reduced by simple measures are resolved. Finally, the risk reducing measures are evaluated and followed up to ensure that their desired effects are achieved (Davidsson et al., 2003).

The risk management process also includes continuous monitoring and risk communication between all parts of the process and with the surroundings (Davidsson et al., 2003). Risk management is an iterative process where the risk reducing measures must be continuously evaluated and new risks must be identified and analysed (Davidsson et al., 2003).

2.1.2 Evacuation Modelling as a Part of the Risk Management Process

Evacuation modelling is a useful tool to perform risk analyses. Evacuation models can be used during the identification phase of a risk analysis where possible risks are identified, for example where bottlenecks may occur, but also when analysing the consequences of specific events. Evacuation models can also be used when assessing and analysing different types of risk reducing actions, such as improvements of a building’s fire protection design and to evaluate their suitability.

In the 1980’s a concept with ASET/RSET was developed, see for example Cooper (1983) and Sime (1986). Since then the concept has been widely used in the field of fire protection engineering (Poon, 2014). The concept relies on estimating the ASET (Available Safe Egress Time) which is the time it takes before critical conditions are obtained in for example a building, and the RSET (Required Safe Egress Time) which is the time needed from ignition to a point where all occupants have left the building. These estimations are then compared in order to establish if the occupants safely can evacuate in case of fire.

There are mainly two approaches used in fire protection design, i.e. prescriptive-based design and performance-based design. Prescriptive-based design is based on specific rules and regulations that describe how the building should be designed. This type of design can be equated with a “cookbook” solution where for example the maximum walking distances to emergency exits are specified and the building is designed according to these specifications. In performance-based design the building is instead designed so that a specific objective is fulfilled, for example that the building can be evacuated safely in case of fire. It then has to be shown that the current design of the building can fulfil this objective. A way to do this is by using the ASET/RSET concept described above.

The use of evacuation time calculations in performance-based design to estimate building safety and to assess building fire protection designs is increasing (Kuligowski, Peacock & Hoskins, 2010). Calculations of evacuation times can be carried out both with simple hand calculations and computational models. Hand calculations are usually flow-based and applied on certain areas where there are constraints of the movement of occupants, such as doorways. To meet the demands of a more realistic or efficient evacuation calculation, computational models are used (Kuligowski et al., 2010).

As described above, evacuation modelling is an important part of the risk management process when identifying and analysing risks associated with fire and building evacuation. Evacuation modelling is essential in performance-based fire protection design and when evaluating building evacuation safety. As buildings become more and more complex, the need of advanced evacuation models increases.

2.2 Fundamentals of Viswalk

PTV Vissim is a simulation program developed by the *PTV Group (Planung und Transport Verkehr AG)*. Vissim can be used to simulate pedestrian and vehicle traffic and their interaction. The program can be used in a variety of areas, from traffic planning to evacuation modelling and by many different types of operators, such as architects, fire protection engineers and community planners. With Vissim alone it is possible to model up to 30 pedestrians and their interactions with for example cars, trains, traffic lights and busses (PTV, 2014).

With the add-on module Viswalk it is possible to simulate large amounts of pedestrians both outside and inside buildings. Viswalk can therefore be used to study pedestrian movement in complex situations such as stadiums, train stations and traffic intersections. The program makes it possible to analyse for example route choice and where bottlenecks may occur (PTV, 2014). A basic setup of a hotel building in the interface of Viswalk is shown in Figure 3.

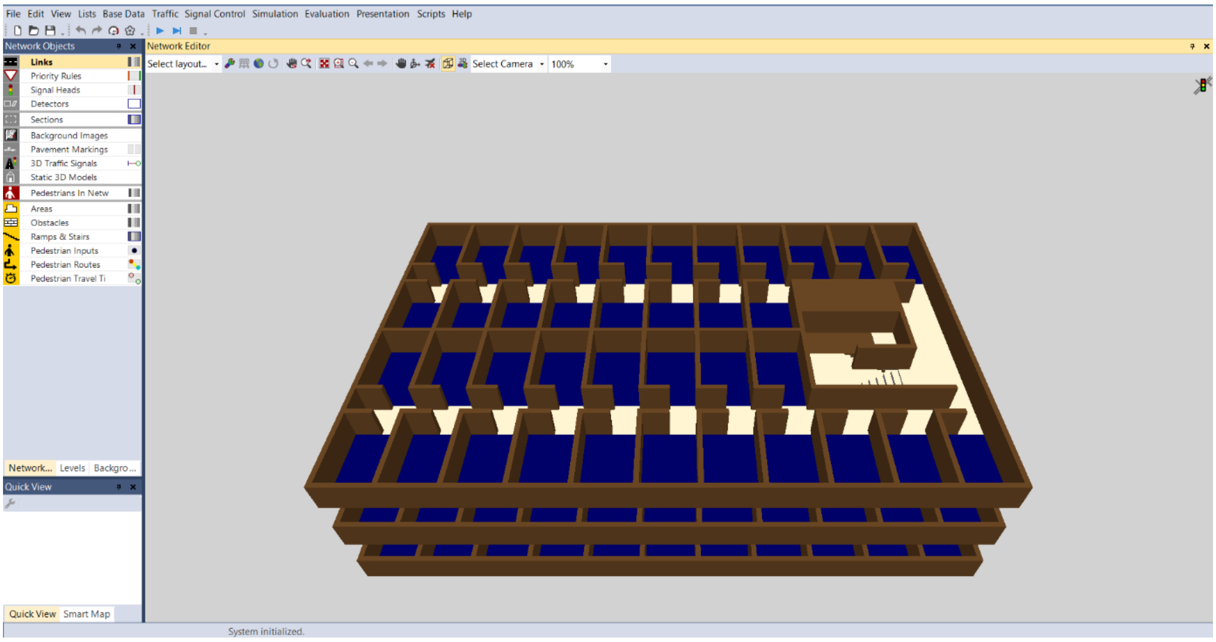

Figure 3. A basic setup for a hotel building in the interface of Viswalk.

2.2.1 The Social Force Model

Viswalk is based on the social force model by Helbing and Molnár (1995) which can reproduce some aspects of human behaviour (PTV, 2014). The social force model belongs to the family of self-driven particle models which was introduced by Vicsek et al. (1995). Self-driven particle models can be used to describe the collective motion of for example groups of animals or bacterial migration (Aldana & Huepe, 2003). The group is modelled by a collection of particles where each particle is autonomous. The speed of each particle is constant and the direction of movement is based on local rules, resulting from the behaviour of other particles.

The social force model is based on the assumption that a number of different forces act on pedestrians, resulting in a single social force that describes the pedestrian’s motivation to move. The social force can either be an acceleration force or a deceleration force depending on the pedestrian’s perceived information about the environment (Helbing & Molnár, 1995). A general equation of the social force written as a sum of different attractive and repulsive effects can be seen below with a following description of each term used.

$$\vec{f_i}(t) = m_i \frac{d\vec{v_i}}{dt} = m_i \frac{v_i^0(t)\overrightarrow{e_i^0} - \vec{v_i}(t)}{\tau_i} + \sum_{j(\neq i)} \vec{f_{ij}} + \sum_w \vec{f_{iw}} \qquad \text{(Equation 2)}$$

The term $\vec{f}_i(t)$ in Equation 2 describes the individual's total motivation to move in a certain direction at a specific time (t) (Helbing & Molnár, 1995). The term m_i refers to the mass of the individual. The two last terms on the right hand side in Equation 2 describe the repulsive effects of other pedestrians (ij) and walls (iw), that keeps the individual at a certain safety distance (Helbing & Johansson, 2010). According to the social force model each pedestrian wants to move with a certain speed in a certain direction ($v_i^0(t)\overrightarrow{e_i^0}$). The pedestrian then adapts his current velocity ($\vec{v_i}(t)$) to the velocity he would prefer and he does this within a relaxation time (τ_i) (Helbing & Johansson, 2010). An acceleration term can be used to describe this phenomenon (Helbing & Molnár, 1995), which is the first term on the right hand side in Equation 2.

The pedestrian's movement is also affected by how close by other pedestrians are. Pedestrians often want to keep a distance from other pedestrians and not get too close, especially to persons that they do not know. This can be represented by a repulsive effect that depends on the preferred speed and the density of pedestrians. The closer a pedestrian gets to another person the stronger this repulsive effect gets (Helbing & Molnár, 1995). This effect is represented by the second term on the right hand side in Equation 2.

Pedestrians are also affected by how close they are to different objects, such as handrails, walls, counters, etc. To avoid collisions with the objects and to be able to move in an unhindered way, pedestrians tend to keep a certain distance from objects. The closer a pedestrian gets to an object the more he has to adjust his behaviour and movement to avoid the object. This phenomenon can be represented by a repulsive effect that drives the pedestrian away from the object (Helbing & Molnár, 1995). In Equation 2, this effect is represented by the third term on the right hand side.

Objects or persons can also have an attractive effect on a pedestrian, for example if the persons know each other or if the object is a window with an attractive view. This effect is time dependent since a person's interest tends to decrease with time. This is why pedestrians tend to form spontaneous groups (Helbing & Molnár, 1995). This attractive effect can either be written as a separate term in Equation 2 or be included in the other terms. In Viswalk the attractive effects can be modified by the user by changing parameter values.

The effects described above can now be summarised to an equation that describes a pedestrian's total motivation to move. The social force model also includes a fluctuation term to account for deviations from the pedestrian's normal response to the attractive and repulsive effects. The social force model can then be written as (Helbing & Molnár, 1995):

$$\frac{d\vec{w}}{dt} = \vec{f_i}(t) + fluctuations \qquad \text{(Equation 3)}$$

where

$d\vec{w}/dt$ = changes of the pedestrian's preferred velocity
$\vec{f_i}(t)$ = the sum of all attractive and repulsive effects (the social force)

The social force model has been revised and added to since the original setup. A number of specifications have been suggested to change certain parts of the model. Helbing, Farkas and Vicsek (2000) introduced a change to the social force model, with the circular specification. Another modification of the model is called the elliptical specification II (Johansson, Helbing & Shukla, 2007). The specifications alter, for example, how the social forces affect the pedestrians in relation to each other as well as objects in the environment. Viswalk includes both the circular specification and the elliptical specification II. The different variants are calculated separately and summed up as a whole when implemented in Viswalk[1].

2.2.2 Route Choice

Viswalk allows for different approaches when performing simulations. As the model has a basis in traffic modelling, there is an option to use origin-destination matrices (OD matrices), which display the relation between pedestrian areas and only requires the user to specify the pedestrian volume per hour. With the use of OD matrices, Viswalk internally calculates pedestrian inputs and pedestrian routes (PTV, 2014). The other way to perform simulations in Viswalk is to specify the pedestrian inputs and pedestrian routes by hand. The choice between the two approaches is a matter of user preference and external conditions such as in what form data is available.

There are two types of routes in Viswalk, namely static routes and partial routes. A static route simply directs a pedestrian from a defined start area to a defined end area. There can be arbitrarily many static routes in the same model setup, and the ratio of pedestrians following the different static routes is determined by the user. Each route starts with a routing decision, either static or partial, and may have a number of specified intermediate destinations before the end area (PTV, 2014).

Partial routes are used in order to change a pedestrian’s route at a local level to the defined partial route. This makes the pedestrian diverge from the original route until the partial route is completed. A partial route can either be static or dynamic. For static partial routes the user defines how many pedestrians that should use each route by ratios. This option excludes Viswalk’s pedestrian route choice algorithms and gives the user full control of the exit choice and path of the pedestrians.

In some scenarios, for example in a train station where the pedestrians are stressed, it could be more suitable to assume that the pedestrians choose the routes that they believe are the fastest rather than the shortest. This can be modelled in Viswalk by using the dynamic potential or dynamic partial routes, where the ratios of pedestrians using each partial route are calculated by the software. The route choices of the pedestrians are then dependent on the shortest movement time, i.e. the shortest time it takes for a pedestrian to walk from the starting point of the partial route to the end point, queue length, density or the number of pedestrians on a specific area (PTV, 2014).

When using the dynamic potential, the direction of the pedestrian’s estimated shortest movement time has to be calculated, which is done in three steps (Kretz et al., 2011). In the first step, a map is calculated which consists of the estimated or expected walking speeds in a small area. The walking speeds are dependent on for example other occupants and the geometry of the setup. In the second step, the movement times of all small areas starting from the destination area are integrated numerically, which result in a field or map of estimated movement times from each small area to the destination. The third and final step consists of calculating the gradients of the areas containing occupants (Kretz et al., 2011). The negative gradients are then used as the directions of the desired velocities of the pedestrians in each area (Kretz, 2012b). At least one pedestrian has to finish each dynamic partial route before Viswalk can estimate which route has the shortest movement time (PTV, 2014).

2.2.3 Movement on Stairs

To model stairs or stairwells in Viswalk the user first needs to define at least two levels with different heights. A stair that connects the different levels can then be inserted with the *Ramps & Stairs* function and the stair’s design is defined by the user. The user defines the stair’s length and width as well as the steps’ dimensions and the amount of steps. By default, the pedestrians’ desired walking speeds on stairs measured along the incline of the stair are the same as their desired walking speeds for

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[1] Dr. Tobias Kretz, *PTV Group*, E-mail conversation 2014-11-17.

horizontal movement[2]. This means that the horizontal speed projection is reduced when the pedestrians move on stairs instead of along a horizontal plane, see Figure 4 below. The horizontal projections are the same for stairs going upwards or downwards, making the default walking speeds in stairs independent of the vertical direction. The horizontal walking speed is consequently an important factor when evacuating vertical movement in Viswalk.

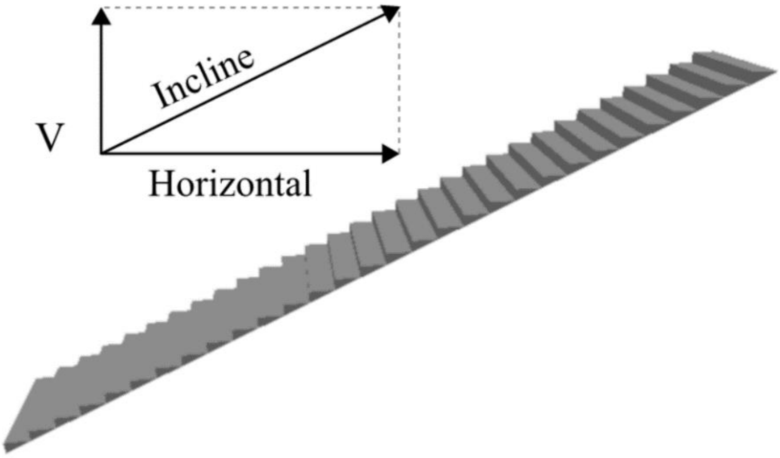


Figure 4. The horizontal projection of occupant walking speed (V) on stairs.

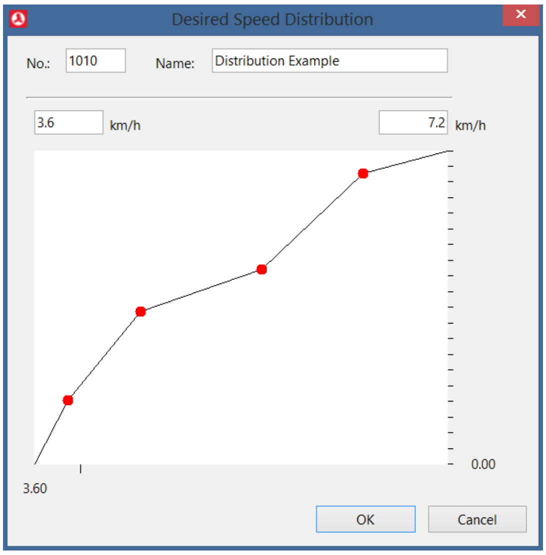
Viswalk also gives the option to set specific walking speeds for individual stairs. This is useful when the default walking speed does not represent the supposed movement on stairs. Different walking speed distributions may be set to increase or decrase the walking speeds compared to the default values.

2.2.4 Using Probability Distributions

In Viswalk, it is possible to use probability distributions for input parameters such as the pedestrians' walking speeds. By default, uniform probability distributions are used for the pedestrians' walking speeds. These distributions are recommendations from the *IMO* guidelines and two different pedestrian demographic groups are used with different walking speed distributions (International Maritime Organization, 2007). The first group consists of males in the ages 30-50 years with walking speeds between 0.97 and 1.62 m/s. The second group consists of females in the same age interval with walking speeds between 0.71 and 1.19 m/s. By default, the pedestrian input ratios of males and females are equal.

It is also possible for the user to add other walking speed distributions by specifying their cumulative distribution function in Viswalk. This is done by specifying their maximum and minimum values along with data points, in km/h, that determine the shape of the distribution, see Figure 5. This makes it possible to add any type of distribution for the pedestrian walking speeds.

Pre-evacuation time distributions can be added by the user in the same way as described above. However, it is also possible to choose a normal


Desired Speed Distribution

No.: 1010

Name: Distribution Example

3.6 km/h

7.2 km/h

Figure 5. The interface for specifying walking speed distributions in Viswalk.

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[2] Dr. Tobias Kretz, *PTV Group*, E-mail conversation 2014-09-12.

distribution and specifying its mean and standard deviation for the pre-evacuation time.

2.2.5 Previous Studies

The program developers have performed several validation and verification studies in order to calibrate Viswalk. In the following section, previous studies that are relevant to this thesis are presented in order to identify and to give a background of what already have been studied and what this thesis’ validation and verification study should focus on.

Kryh (2013) compared how flows and densities in and in front of escalators from simulations in Viswalk differed from the results of hand calculations and field studies at Malmö Central Station in Sweden. He also analysed what parameters in Viswalk that affeced the flows and densities and proposed how the parameters could be changed to better match the results from the field studies. A total of six field studies were performed, where four of them were in the same location and the other two were in a separate location. The results were then compared to totally 700 simulations in Viswalk with 70 different parameter configurations. The simulations were performed with the same geometric conditions as the field studies, with the same velocities in the escalators and with the same ratio of pedestrians choosing to use the escalators. The author concluded that the results from the field studies and from the simulations in Viswalk agreed well and that small parameter adjustments could be made in order to further calibrate the software.

Multi-directional flows in Viswalk have been studied by Kretz (2012a). In the study, the author used Viswalk as an example of how specific parameter adjustments affected the corresponding movement times. 72 pedestrians were placed in a circular pattern with one pedestrian each 5 degree. When starting the simulation each pedestrian had to walk and change places with the pedestrian on the opposite position of the circle. This created multi-directional flows in the centre of the circle and the writer studied how parameter adjustments affect the movement patterns and the movement times in order to make the simulations more realistic. The authors concluded that with parameter adjustments, the results from the simulations were realistic. It should however be noted that this was a fictitious scenario that were used for calibration rather than to study a common scenario.

Bamberger et al. (2014) studied how experimental data from crossing flows corresponded with simulation data from Viswalk. The experiment was performed in a German school and was set up to make pedestrian flows cross each other in a 90 degree angle. The results from the study showed that when the default parameters were used the results from Viswalk were conservative. However, with a few parameter adjustments that corresponded better with the population, the results from the simulations and the experiment agreed well.

Viswalk has also been evaluated with the *RiMEA* guidelines, which included 14 different tests to verify and calibrate the model. The tests focused on basic abilities of the model such as walking speeds, movement around corners and route choice. More information about the *RiMEA* guidelines can be found in section *2.3.1 Verification of Evacuation Models*. The results showed that Viswalk was able to model the basics of pedestrian dynamics with a good accuracy.

As mentioned above, there are several previous calibration tests and studies performed with Viswalk. However, no previous validation of Viswalk against real life building evacuation experiments has been found in the literature. Single small-scale real life experiments have been found that focus on pedestrian dynamics but no full-scale real life evacuation experiment has been found in the literature.

2.3 Verification and Validation Methods

The following section contains a description of different methods commonly used for verification and validation of evacuation models. The section also includes an examination of uncertainties associated with evacuation modelling.

2.3.1 Verification of Evacuation Models

The term verification has many definitions in a variety of areas, but in the evacuation modelling community there is a globally accepted definition. The definition is applied in this thesis and refers to verification as *"the process of determining that a calculation method implementation accurately represents the developer's conceptual description of the calculation method and the solution of the calculation method"* (International Standards Organization, 2008).

There is no international standard for verification procedures used in the field of evacuation models (Ronchi et al., 2013a). However a number of methods for verification have been used in the verification process of evacuation models. To give an overview, three of these methods will be presented below.

1) The main guidelines for verification of evacuation models are presented within the *MSC/Circ.1238*, by the *International Maritime Organization (IMO)* (Ronchi et al., 2013a). The *MSC/Circ.1238* guidelines are intended to be used in maritime applications, i.e. when focusing on evacuation modelling of ships (International Maritime Organization, 2007). The guidelines describe 11 different tests that should be performed in the verification process. The first tests (Test 1-7) are intended as elementary component testing. The remaining tests (Test 8-11) are meant to investigate how the models are including human behaviour (International Maritime Organization, 2007). Every test is described in detail to enable a comprehensive setup of the test. Additionally, the relevant output data is described, either quantitative or qualitative, and a description of the expected result is included (International Maritime Organization, 2007). The *MSC/Circ.1238* guidelines also mention functional verification as a way for the user to verify that the model is used correctly in the intended field. This is not meant to be done with a test. Instead the functional verification is done by reviewing the technical documentation from the developer to ensure that the model is used within its limitations.

2) The *IMO* guidelines have been modified for the use in building evacuation situations. One of these modified procedures is the German *RiMEA* guidelines. The guidelines form a standard for evacuation calculations in buildings for German-speaking establishments (Rogsch et al., 2014). The *RiMEA* guidelines modify and develop the tests suggested in the *IMO* guidelines further and these tests are more comprehensive and useful for the verification process of building evacuation models. However the *RiMEA* guidelines do not offer tests intended to evaluate special features that many of the building evacuation models include today (Ronchi et al., 2013a).

3) In a technical note from the *National Institute of Standards and Technology (NIST)*, the authors propose and discuss a more extensive procedure for validation and verification of evacuation models (Ronchi et al., 2013a). This procedure is also a modification of the *IMO* guidelines, but it provides a more comprehensive setup of tests. The aim of the *NIST* report is to create a dialogue as a base for a standardized way of validation and verification, rather than a final guideline (Ronchi et al., 2013a). As opposed to the earlier mentioned guidelines, the *NIST* procedure is based on a series of core components regarding evacuation models. These core components divide human behaviour elements in evacuation situations into five different areas; 1) pre-evacuation time, 2) movement and navigation, 3) exit usage, 4) route availability

and 5) flow constraints (Ronchi et al., 2013a). The *NIST* procedure includes a total of 17 tests which are presented in Table 1 with their core components and sub-elements.

Table 1. The verification tests from the *NIST* procedure with their core components and sub-elements (Ronchi et al., 2013a).

Core Component	Test Number	Sub-Element
1	1.1	Pre-evacuation time distributions
2	2.1	Speed in a corridor
	2.2	Speed on Stairs
	2.3	Movement around a corner
	2.4	Assigned demographics
	2.5	Reduced visibility vs walking speed
	2.6	Occupant incapacitation
	2.7	Elevator usage
	2.8	Horizontal counter-flows (rooms)
	2.9	Group behaviours
	2.10	People with movement disabilities
3	3.1	Exit route allocation
	3.2	Social influence
	3.3	Affiliation
4	4.1	Dynamic availability of exit
5	5.1	Congestion
	5.2	Maximum flow rates

The first core component, pre-evacuation time, is the time it takes from a fire cue until the occupant starts moving towards an exit (Ronchi et al., 2013a). This time is often described with a probability distribution, and the *NIST* procedure suggests one test to verify the models capability to do so.

The second component, movement and navigation, includes 10 different tests and focuses on the horizontal and vertical movement of the occupants. Some of the tests have an analytical point of view, meaning that they verify model components in comparison with mathematical formulas. The other tests have more of a qualitative approach and focus on the verification of human behaviour sub-models used by the evacuation model, compared to behavioural theories (Ronchi et al., 2013a).

The third component, exit usage, is investigated by three separate tests. One of the tests is intended to verify if the occupants in the evacuation model have an accurate exit usage. Depending on the evacuation model, the exit choice may be calculated by sub-models or pre-defined by the user. The two other tests include social models in the evacuation process, which are included in some of the new evacuation models (Ronchi et al., 2013a).

The fourth component, route availability, is tested by a verification of dynamic availability of exits. This means that exits may be accessible in different stages of the evacuation, due to smoke or other shifting variables (Ronchi et al., 2013a).

The fifth and last component, flow constraints, refers to occupant movement when effected by each other. The verification focuses on occupant walking speeds, densities and flows when constrained by nearby occupants (Ronchi et al., 2013a).

2.3.2 Validation of Evacuation Models

Validation is a widely used term in different fields of science and with a somewhat varying meaning. The definition often used in evacuation modelling and applied in this thesis is that validation is the *"process of determining the degree of which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method"* (International Standards Organization, 2008).

The used definition of validation is somewhat ambiguous and leaves unanswered questions. Some of the questions are raised in the report by Ronchi et al. (2013a). How to define the degree of accuracy, i.e. the acceptance criteria, is important to take into account when performing a validation. This may have a great impact on the results of the validation. Other important questions are how and by whom the validation is performed. There is no simple or generally accepted method for validation to answer how a validation should be performed. Furthermore, there are few real life evacuation experiments with sufficient data documentation to allow for the validation of an evacuation model. The lack of data-sets makes validation of the whole evacuation process difficult and forces the validation to focus on separate aspects of the evacuation process. Some aspects of evacuation are not fully evaluated, which makes the validation of such aspects difficult to perform due to the lack of understanding of the occupant behaviour involved (Ronchi et al., 2013a).

When an evacuation model simulation is performed there are certain input parameters provided by the model itself, and some parameters that are added and changed by the user. The varying degree of knowledge about the simulated scenario may affect the outcome of the simulation (Lord et al., 2005). To specify the extent of user input in a simulation, three different setups can be defined.

The most basic setup for an evacuation simulation is called a blind calculation. In this kind of setup only the most fundamental input is provided by the user, including solely the geometric structure of the setup. This means that mainly the model's default input values are used (Lord et al., 2005).

A specified calculation is when there is more information available about the evacuation scenario. This setup is based on a more specified scenario than the blind calculation and is provided with geometrical specifications and occupant characteristics (Lord et al., 2005). The decreased need of user assumptions makes the simulation more accurate and involves less uncertainty.

The setup with the least amount of model input uncertainty is called open calculation. This setup is based on experimental results from an actual evacuation, or simulations made with an already validated evacuation model. Most of the input parameters are set by the user to reproduce the simulations as similar to the actual scenario as possible (Lord et al., 2005).

2.3.3 Uncertainties in Evacuation Modelling

One important aspect of the validation process of evacuation models is to handle uncertainties. There are different kinds of uncertainties present in the validation process and they can be divided into four categories (Ronchi, Reneke & Peacock, 2014; Hamins & McGrattan, 2007);

- Model input uncertainty
- Measurement uncertainty
- Intrinsic uncertainty
- Behavioural uncertainty

Model input uncertainty describes the uncertainties with the way input-data is used in the evacuation model (Lovreglio, Ronchi & Borri, 2014). As an example, there is uncertainty involved with resembling the walking speed of occupants from an experiment with a probability distribution in the evacuation model (Ronchi, 2014).

Measurement uncertainty revolves around the collection of data and the techniques for measuring that data (Lovreglio et al., 2014). In evacuation experiments, measurement uncertainty can be present in the way occupant walking speed is measured and collected (Ronchi, 2014).

Intrinsic uncertainty is linked to the mathematical and physical formulations used by the evacuation model (Ronchi, 2014). Using the occupant walking speed parameter as an example, the intrinsic uncertainty depends on how the evacuation model mathematically represents the movement of occupants (Ronchi, 2014).

Behavioural uncertainty is related to human behaviour in evacuation situations (Ronchi et al., 2014). This sort of uncertainty can be interpreted in two different ways (Ronchi, 2014). One way to see it is that the human actions in an evacuation situation are somewhat problematic to predict. A different interpretation is that behavioural uncertainty is closely connected to the human behaviour itself, and the uncertainty is constricted by the limited knowledge about human behaviour.

The impact of behavioural uncertainty can be taken into account by methods to study the variability of the results from the evacuation model (Ronchi, 2014). Evacuation models can support the use of probabilistic distributions of input parameters and further include algorithms that produce variability beyond the users' control (Ronchi, 2014). Implementing a method for uncertainty analysis allows for an evaluation of the variability of occupant behaviour in evacuation simulations (Ronchi, 2014).

2.4 Data Identification

In the following section, previously performed experiments are described that serve as a basis for the validation process. Further information about the experiments can be found in the literature specified in each section.

2.4.1 Corridor Experiment

Pedestrian movement through a corridor has been studied in an experiment by Frantzich, Nilsson and Eriksson (2007). The experiment was performed at *Lund University* in Sweden with students as participants and they were filmed with three video cameras as they walked through the corridor. The width of the opening at the end of the corridor was varied in five different test scenarios.

The corridor was 9.6 m long and 1.6 m wide and had been built with boxes and panels made of wooden particle boards and studs. At the end of the corridor there were two boxes which could be moved to vary the opening width. The heights of the boxes and panels were 2.0-2.4 m and the corridor was open at the top to enable the video cameras to film the participants from above. The layout of the corridor and the opening is shown in Figure 6 below. Figure 7 shows a schematic drawing of the layout, seen from above the configuration.

Figure 6. The layout of the corridor and the end opening (Frantzich et al., 2007).

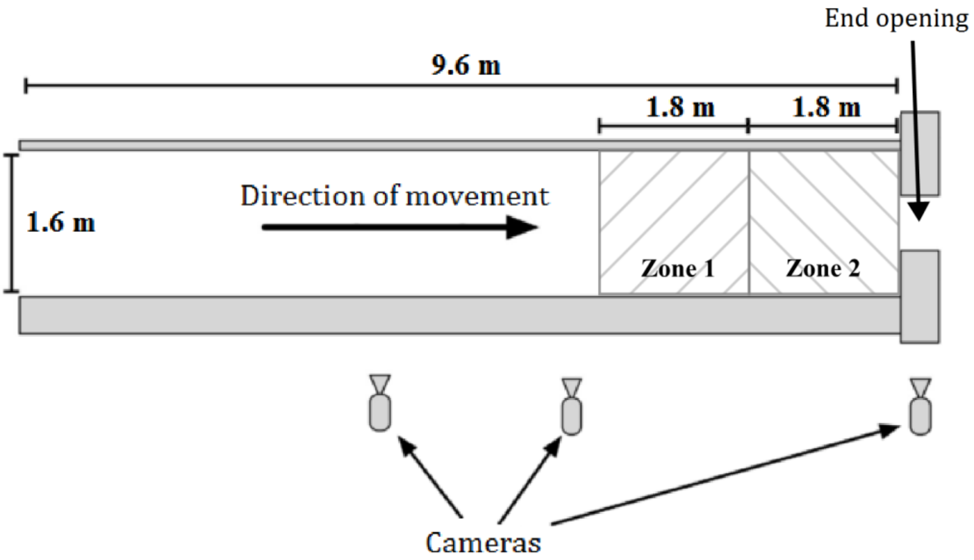

Figure 7. A schematic drawing of the configuration seen from above (Frantzich et al., 2007).

A total of 42 students in the ages 20-30 years participated in the experiment. Seven participants were females and 35 were males and all participants were aware of that they participated in an experiment. It is not stated if the participants were informed about the objective of the experiment.

Before walking through the corridor, the participants lined up in a ~2 m wide queue in front of the corridor. In the first scenario, each participant walked through the corridor individually to measure their unhindered walking speeds. The remaining scenarios were performed with the participants walking through the corridor as a group. Additional information about the five scenarios is shown in Table 2.

Table 2. Descriptions of the five scenarios in the experiment (Frantzich et al., 2007).

Scenario	Number of Trials	Configuration	Individual/Group Performance
A	83	Completely open corridor	Individual
B	6	Corridor with a 60 cm end opening	Group
C	6	Corridor with a 75 cm end opening	Group
D	6	Corridor with a 90 cm end opening	Group
E	5	Corridor with two 75 cm end openings	Group

To enable an analysis of the results, the boxes and panels of the corridor were marked with 13 marks, resulting in 13 small areas. This made it possible to calculate each participant's walking speed in Scenario A. For Scenario B-E the total movement time, the flow through the opening and the density in two zones denoted Zone 1 and 2 in Figure 7 were calculated. The flow was calculated in five seconds intervals and presented as a mean for each scenario. Only the stable flows were included in the calculations, i.e. deviant flows from the start and end of each trial were excluded. The total movement time was defined from when the first occupant passed the first mark 2.4 m into the corridor, to when the last occupant exited through the end opening.

The results from the experiment are presented in the validation, see section *4.1.2 Results*.

2.4.2 Classroom Experiment

A total of 30 students were studied as they evacuated a classroom by Guo, Huang and Wong (2012). The classroom size was 5.7 x 13.1 m and the room had one exit with a width of 0.85 m. A schematic drawing of the classroom is shown in Figure 8. There were obstacles in the classroom consisting of 78 desks, 78 chairs, a computer workbench, a platform and a lectern. The participants were located in chairs with desks in front of them and the chairs folded up when the participants stood up, giving them more space.

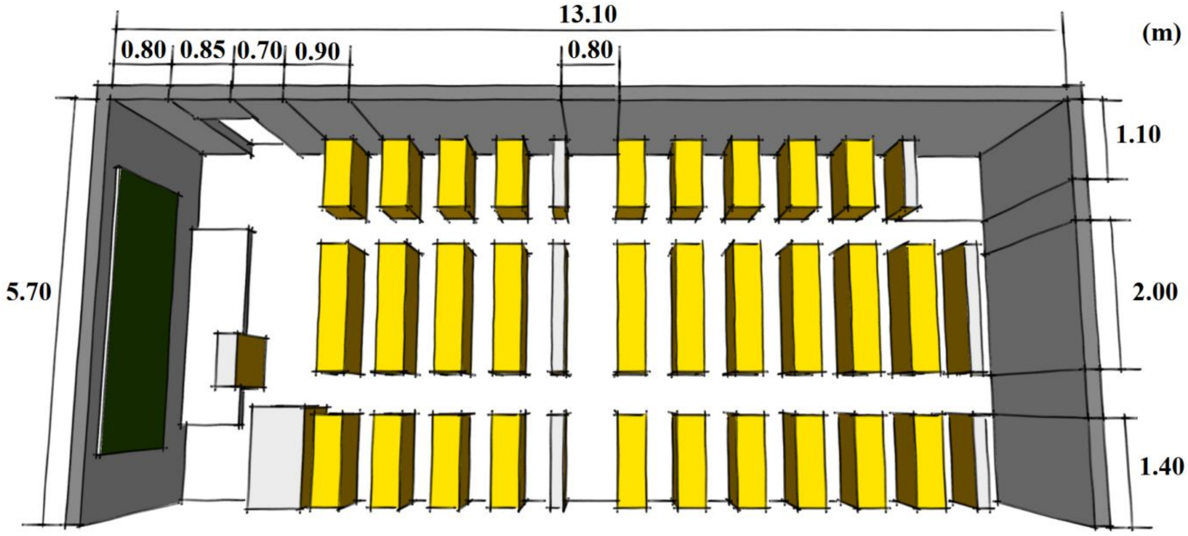

Figure 8. A schematic drawing of the classroom.

The participants were informed about them participating in an experiment where they were asked to evacuate a classroom. It is not stated to what degree the participants were informed about the objective of the experiment. Totally six pairs of trials were performed were each pair consisted of one trial where the participants had to wear blindfolds and one trial where they had full vision. The participants were filmed with two video cameras that documented their movement and the occupant flow through the door of the classroom. The participants started moving directly when they got the evacuation command and the movement time measurement started with the command and ended as the participant left the room. The results are presented as individual movement times with the participants’ route choices specified.

The results from the experiment are presented in the validation, see section *4.2.2 Results*.

2.4.3 Theatre Experiment

After a theatre performance in 1998 at the *AF* facilities in Lund, the crowd were studied as they left the lobby through a door opening (Frantzich et al., 2007). A total of 50 persons were studied in the experiment and their total movement time was measured with a video camera. The door opening was placed in a corner of the lobby and the width of the opening was 0.9 m. A schematic drawing of the lobby can be seen in Figure 9 and Figure 10.

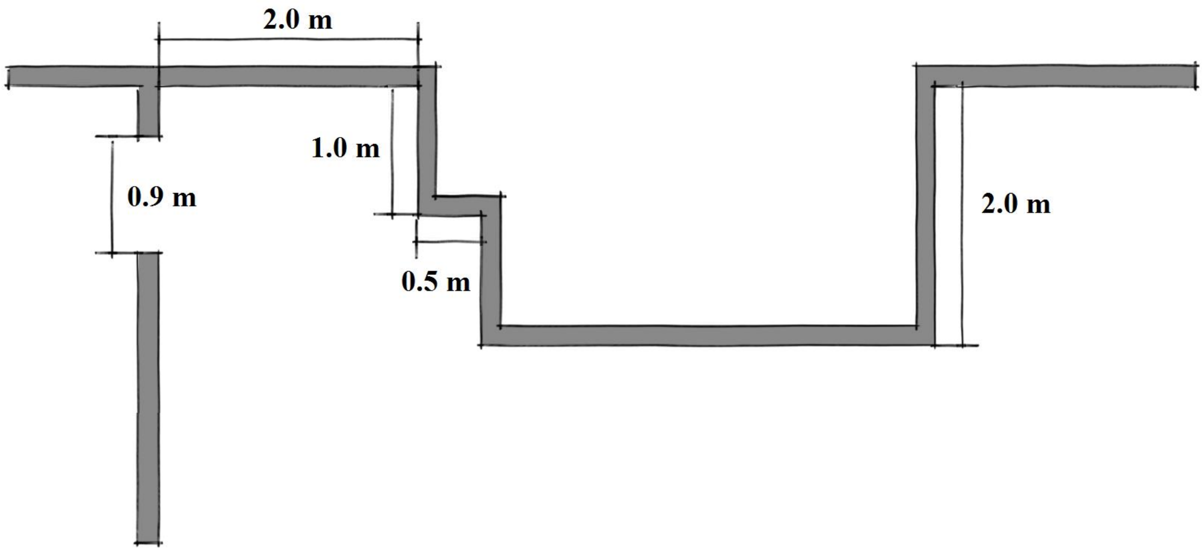

Figure 9. A schematic drawing of the theatre lobby.

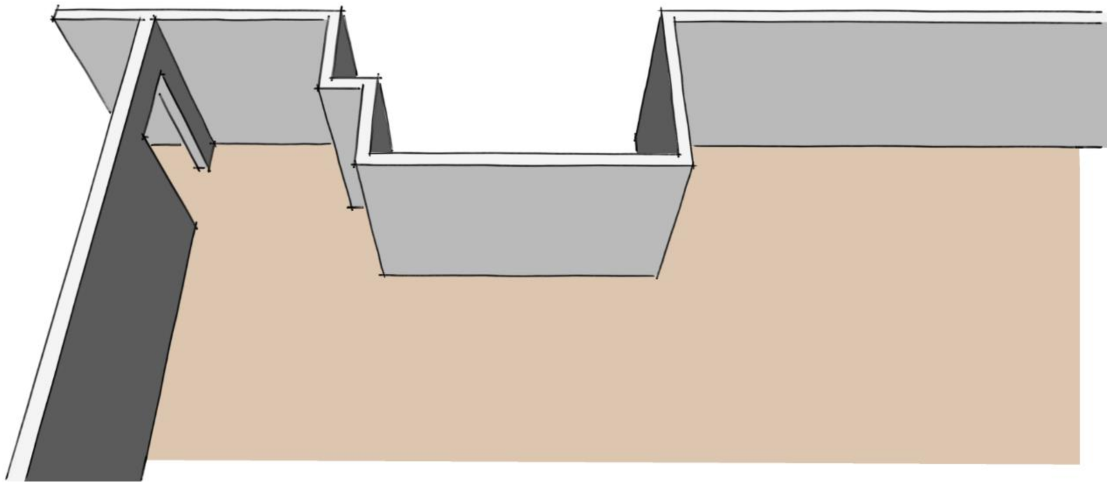

Figure 10. A schematic 3D-drawing of the theatre lobby.

The participants were not informed about the experiment and the population consisted of similar proportions of males and females in approximated ages of ~15-70 years with an emphasis on ~30 years. On the other side of the door there was a stair to the bottom level. The time measurement was only performed when the door opening width was the limiting flow factor. It is stated in the article that during the experiment, the density in front of the opening was high. It is however not specified in greater detail.

The results from the experiment are shown in Table 3 below.

Table 3. Results from the experiment in the theatre lobby (Frantzich et al., 2007).

Scenario	Number of Participants	Flow (p/s)	Time (s)
A	51	1.25	41

2.4.4 Stair Experiment

After a theatre performance in 1994, observations were made to study occupant movement down stairs (Frantzich et al., 2007). The observations were made at the *AF* facilities in Lund and the participants were not informed about the experiment. The results were documented with a video camera and there were about the same proportions of females and males participating. The age of the participants varied from ~15-70 years with an emphasis on ~30 years. It should be noted that the participants were not the same as in the experiment described in section *2.4.3 Theatre experiment*, but the occupant demographics were similar.

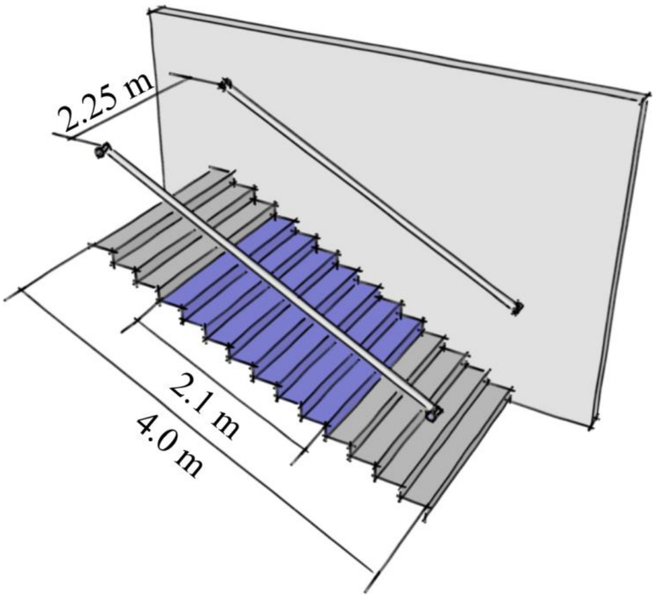

Figure 11. A schematic drawing of the stair.

The stair had a total length of 4 m and a width of 2.25 m between the railings. The measurements were made in a 2.1 m long section on the stair. The vertical distance between each step was 0.15 m and the depth of each step was 0.30 m, resulting in a 26 degree slope. There was a wall with a railing on one side of the stair and only a railing on the other side, see Figure 11. A total of two observations are presented in Table 4, with different numbers of participants.

Table 4. Results from the stair experiment at the *AF* facilities (Frantzich et al., 2007).

Experiment	Direction of Movement	Number of Participants	Time (s)	Flow (p/s)
1	Downwards	91	83	1.11
2	Downwards	61	52	1.17

3 Verification of Viswalk

The following chapter consists of a verification of Viswalk in accordance with the verification tests suggested in the *NIST* procedure by Ronchi et al. (2013a). 10 tests are performed consecutively, starting with a short test description followed by modifications that are made when performing the test. The expected results according to the *NIST* procedure are presented together with the simulation test results. Finally an analysis of the results is performed to determine Viswalk's ability to reproduce the tested sub-element.

Table 5 below includes all the tests suggested in the *NIST* procedure. Seven tests are not performed due to delimitations of the thesis or limitations of the model, which is described in greater detail in section *1.3.2 Verification*.

Table 5. Descriptions of the verification tests from the *NIST* procedure.

Core Component	Test Code	Sub-Element	Will be Performed	Comment
1	1.1	Pre-evacuation time distributions	Yes	
2	2.1	Speed in a corridor	Yes	
	2.2	Speed on stairs	Yes	
	2.3	Movement around a corner	Yes	
	2.4	Assigned demographics	Yes	
	2.5	Reduced visibility vs walking speed	No	Not included in the evaluated version of Viswalk, but is currently under development
	2.6	Occupant incapacitation	No	Excluded due to the delimitations
	2.7	Elevator usage	No	Excluded due to the delimitations
	2.8	Horizontal counter-flows (rooms)	Yes	
	2.9	Group behaviours	No	Not explicitly included in the model
	2.10	People with movement disabilities	No	Excluded due to the delimitations
3	3.1	Exit route allocation	Yes	
	3.2	Social influence	No	Not explicitly included in the model
	3.3	Affiliation	No	Not explicitly included in the model
4	4.1	Dynamic availability of exit	Yes	
5	5.1	Congestion	Yes	
	5.2	Maximum flow rates	Yes	

3.1 Verification Test 1.1 – Pre-Evacuation Time Distributions

Verification test 1.1 – Pre-evacuation time distributions evaluates the model's ability to reproduce pre-defined distributions of pre-evacuation times.

3.1.1 Test Description

Create a room with a size of 5 x 8 m with a 1 m wide exit and place 10 occupants at random starting positions in the room. Select a pre-defined pre-evacuation time distribution from the distributions embedded in the model and run the simulations. Repeat the test for all selectable pre-defined distributions available (e.g. normal, log-normal, etc.).

3.1.1.1 *Test Modifications*

The test is modified so that the occupants do not walk out of the room when their pre-evacuation time ends. The exit area is assigned in the same room so that the occupants simply disappear when the pre-evacuation time is over. This is due to a less complex measurement technique when the movement time is not included in the total evacuation time of the occupants.

There is only one pre-defined pre-evacuation time distribution available in Viswalk, namely the normal distribution. However, it is possible to add other distributions by specifying the distribution's cumulative distribution function, which is described in section *2.2.4 Using Probability Distributions*.

The test is performed with two different types of distributions; the normal distribution and the lognormal distribution. Both types of distributions are evaluated using two different sets of parameter values, which generate four distributions in total. The varying parameter values are used to examine if the model can reproduce the same type of distribution with different parameters.

Lord et al. (2005) have compiled pre-evacuation time data of office and apartment buildings from several different sources and plotted these as probability distributions. The probability distributions used in this test are approximations of the distributions from Lord et al. (2005). They are not meant to be exact copies of the distributions suggested by Lord et al. (2005). Instead, the used distributions are approximations with similar shape and parameter values as the ones suggested in the report. The distributions are only examples of possible pre-evacuation time distributions that could be used and since the aim of the test is to evaluate the model's ability to reproduce pre-defined distributions of pre-evacuation time, the exact shape and parameters of the distributions are not the main focus in this test.

The chosen probability distributions are presented in Table 6 and Table 7 below. Figure 12 shows an example of one of the lognormal distributions.

Table 6. The chosen lognormal distributions that are used in the test.

Distribution	Location Parameter	Scale Parameter	Minimum (s)	Maximum (s)
Lognormal	4.2	0.5	10	300
Lognormal	5.0	0.7	10	1200

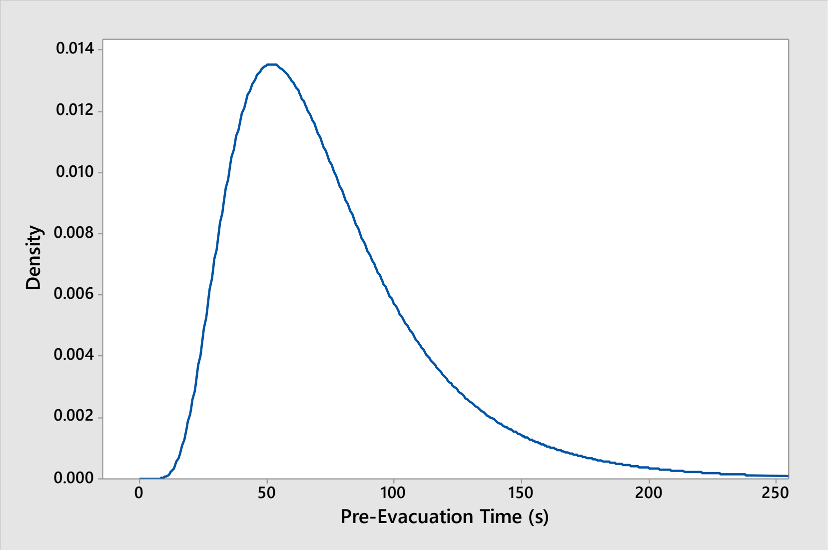

Figure 12. An illustration of the lognormal (4.2, 0.5) density function.

Table 7. The chosen normal distributions that are used in the test.

Distribution	Mean (s)	Standard Deviation (s)	Minimum (s)	Maximum (s)
Normal	70	30	0	370
Normal	100	20	0	300

A total of 10 simulations with 10 occupants per simulation are performed with each defined distribution, which result in 100 pre-evacuation times per distribution. To test if the resulting pre-evacuation times could come from the specified distributions, hypothesis testing is used with the Anderson-Darling method as described in section *1.3.2 Verification*, with the significance level of 5 %. The null hypothesis is that the pre-evacuation time obtained from the simulations comes from the specified distributions.

3.1.2 Expected Results

The occupants should start moving according to the selected pre-evacuation time distribution.

3.1.3 Results

The results from the simulations are presented in Table 8 below. Figure 13-16 show the empirical cumulative distribution functions from the simulations compared to their respective theoretical functions.

Table 8. Results from *Verification test 1.1 – Pre-evacuation time distributions.*

Distribution	P-Value	Figure
Lognormal (4.2, 0.5)	0.095	13
Lognormal (5.0, 0.7)	0.11	14
Normal (70, 30)	0.168	15
Normal (100, 20)	0.183	16

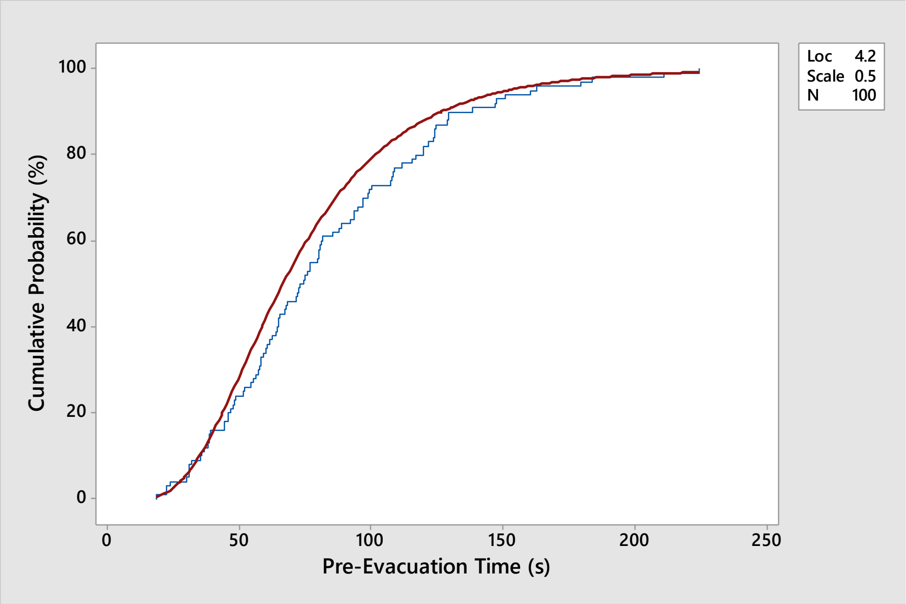

Figure 13. The empirical cumulative distribution function (the jagged line) compared to the theoretical lognormal (4.2, 0.5) distribution function (the smooth line). The empirical cumulative distribution function is based on 10 simulations with a total of 100 pre-evacuation times.

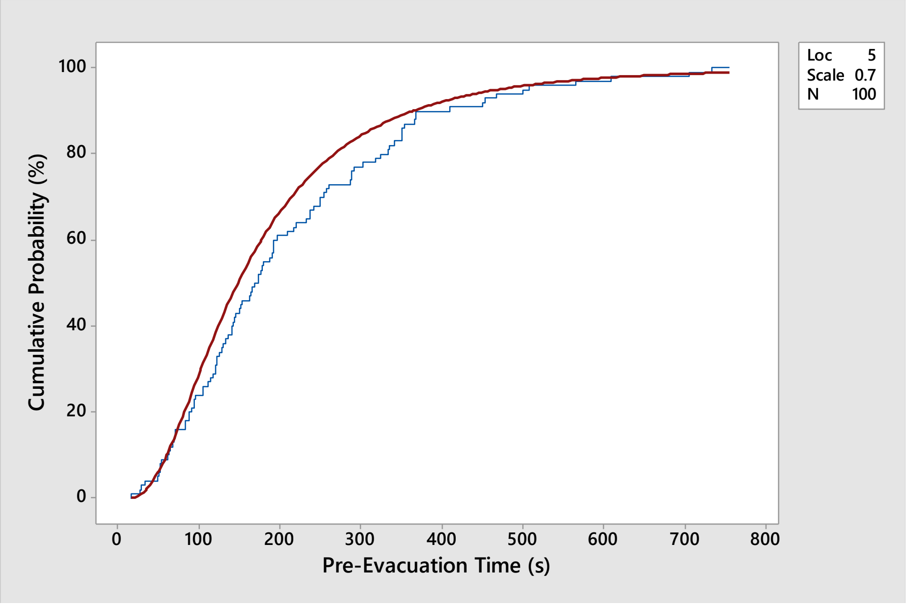

Figure 14. The empirical cumulative distribution function (the jagged line) compared to the theoretical lognormal (5.0, 0.7) distribution function (the smooth line). The empirical cumulative distribution function is based on 10 simulations with a total of 100 pre-evacuation times.

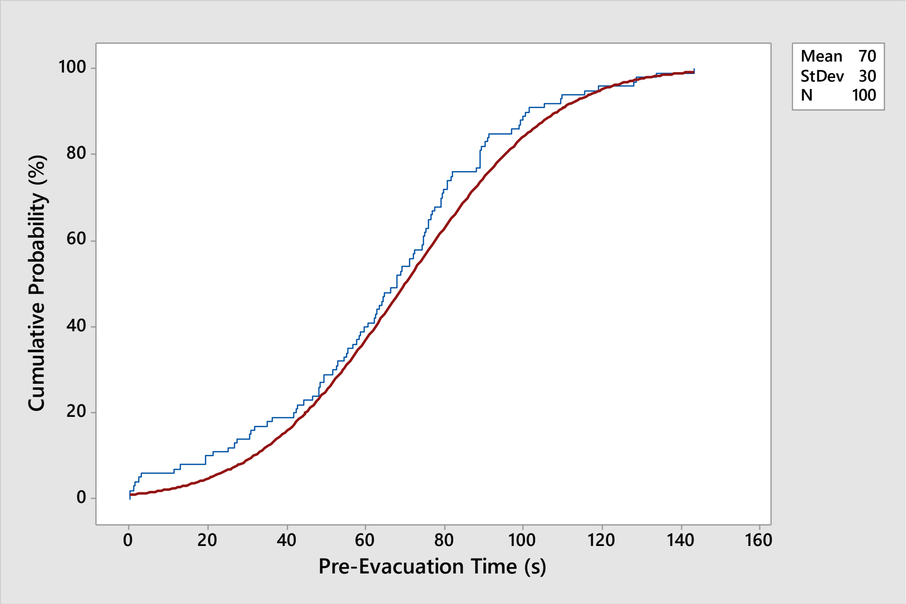

Figure 15. The empirical cumulative distribution function (the jagged line) compared to the theoretical normal (70, 30) distribution function (the smooth line). The empirical cumulative distribution function is based on 10 simulations with a total of 100 pre-evacuation times.

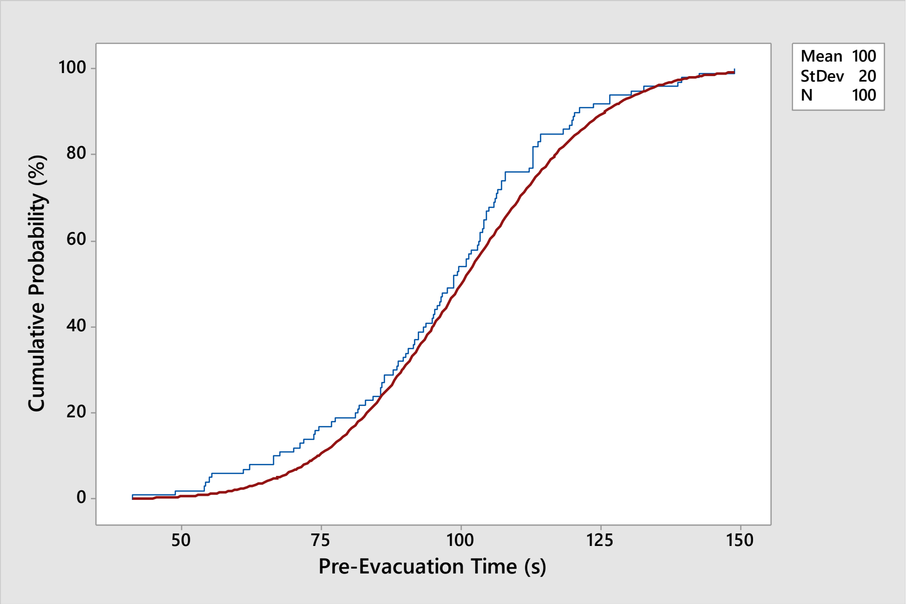

Figure 16. The empirical cumulative distribution function (the jagged line) compared to the theoretical normal (100, 20) distribution function (the smooth line). The empirical cumulative distribution function is based on 10 simulations with a total of 100 pre-evacuation times.

3.1.4 Analysis

The results presented in Table 8 show that the p-values are greater than 0.05. This means that there are no significant differences between the results and the expected results, given that the null hypotheses are true. Accordingly, the null hypotheses cannot be rejected which means that the results could come from the specified distributions.

The lognormal distributions have lower p-values than the normal distributions (0.095 and 0.11 compared to 0.168 and 0.183) which is expected. This could be due to uncertainties associated with specifying the lognormal distributions or with the random sampling algorithm in Viswalk. The cumulative distribution functions of other pre-evacuation time distributions than the normal distribution have to be defined manually by specifying data values which makes it difficult to define the exact requested distribution, especially for very small and large values, which results in uncertainties surrounding the user-defined distributions.

The empirical cumulative distribution functions in Figure 13-16 show relatively small deviations from the theoretical functions. Both empirical lognormal distributions overestimate the pre-evacuation times compared to the theoretical functions while the empirical normal distributions underestimate the pre-evacuation times. The deviations are however not significant which also result in not rejecting the null hypotheses. Despite some deviations, the empirical functions and the theoretical functions are similar and their overall shapes match, which supports the null hypothesis.

Both the p-values and the empirical cumulative distribution functions support the null hypothesis and the results from the simulations correspond with the expected results. The conclusion is that Viswalk is able to reproduce pre-defined distributions of pre-evacuation times.

3.2 Verification Test 2.1 – Speed in a Corridor

Verification test 2.1 – Speed in a corridor verifies the model's ability to reproduce and maintain an occupant's selected walking speed along a specified distance.

3.2.1 Test Description

Create a corridor with a size of 2 x 40 m (2 m wide and 40 m long). Insert one occupant with a walking speed of 1 m/s at the beginning of the corridor. The occupant should walk a total distance of 40 m to the end of the corridor.

3.2.1.1 Test Modifications

Since there is an acceleration phase in Viswalk, the corridor's length is extended to compensate for the lower walking speeds in the acceleration phase. The movement time measurement is placed on a 40 m long distance which is the wider area in Figure 17. The number of runs is determined with the method described in section *1.3.2 Verification*. The convergence criterion for the difference between two consecutive cumulative means is set to 1 %. The convergence criterion should be small since the emphasis of the test is to determine if the occupants reproduce and maintain the selected walking speed.

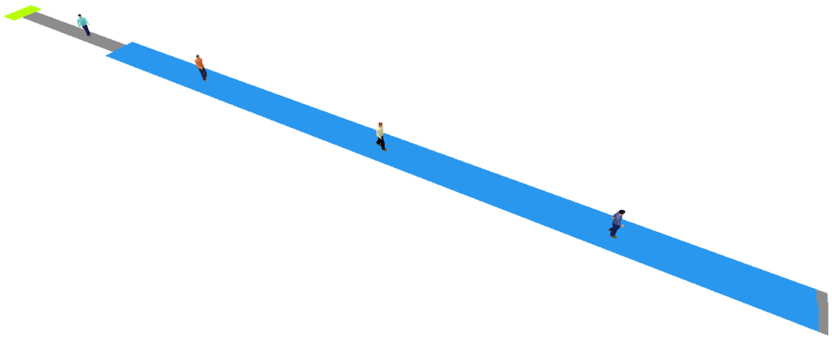

Figure 17. The setup of *Verification test 2.1 – Speed in a corridor.* The movement time measurements are performed in a 40 m long section.

3.2.2 Expected Results

The 40 m long corridor should be covered by the occupant in 40 s.

3.2.3 Results

The complete results from the test are presented in *Appendix B* while Table 9 below shows a summary of the results. The method that is used for calculating the required number of simulations is described in *1.3.2 Verification.*

Table 9. Results from *Verification test 2.1 - Speed in a corridor.*

Cumulative Mean (s)	Number of Simulations
39.9	10

3.2.4 Analysis

The results presented in Table 38 in *Appendix B* show that the movement time varies between 39.8 s and 40.0 s. The measured travel distance also varies from 39.9 m to 40.0 m. This can be explained by the method of measurement and the length of the simulation time steps. The walking distance in Viswalk is measured from the specific occupant's coordinates and not from the boundaries of the measurement area. This means that the measurement starts at the first time step as the occupant has entered the measurement area and not when the occupant passes the boundary of the area. With the same argument, the measurement ends at the specific coordinates of the occupant at the last time step before the occupant passes the end boundary of the measurement area.

As mentioned, the precision of the parameter measurements are also dependent on the length of each time step. In the test the default settings are used which means that each time step is 0.2 s. Since the walking speeds are set to ~1.0 m/s the maximum length measurement error is 0.2 m (1 m/s x 0.2 s) on each side of the measurement area. The total maximum length measurement error is therefore 0.4 m and the total maximum movement time error is 0.4 s.

The convergence measure is below 1 % for all simulations since the movement times only vary marginally. The five last consecutive simulations show that the convergence measure is stabilized below 1 % which means that no further simulations are required.

In summary, the movement time fluctuations are within the margin of error. The conclusion is that the model is able to reproduce and maintain an occupant's selected walking speed along a specified distance.

3.3 Verification Test 2.2 – Speed on Stairs

Verification test 2.2 – Speed on stairs verifies the model's ability to reproduce and maintain an occupant's selected walking speed up and down stairs along a certain distance.

3.3.1 Test Description

Create a 2 m wide and 100 m long stair (along the incline). Insert one occupant with a walking speed of 1 m/s at the beginning of the stair. The occupant should walk a total distance of 100 m upwards or downwards to the end of the corridor.

3.3.1.1 Test Modifications

Since there is an acceleration phase in Viswalk, the length of the setup is extended to compensate for the reduced walking speed as the occupant accelerates. The movement time measurement is placed on a 100 m long distance on the stairs. A total of 10 runs are performed in each direction (upwards/downwards). The walking speed is defined along the incline of the stairs. The required number of runs is calculated with a convergence criterion of 1 %. The convergence criterion should be small since the emphasis of the test is to determine if the occupants reproduce and maintain the selected walking speed in stairs.

3.3.2 Expected Results

The 100 m long stair should be covered by the occupant in 100 s upwards respectively 100 s downwards.

3.3.3 Results

The complete results from the tests are presented in *Appendix B* while Table 10 below shows a summary of the results.

Table 10. Results from *Verification test 2.2 - Speed on stairs.*

Direction of Movement	Cumulative Mean (s)	Number of Simulations
Upwards	99.94	10
Downwards	99.94	10

3.3.4 Analysis

The results presented in Table 39 in *Appendix B* show that the movement time varies between 99.8 s and 100.2 s. Some variation of the movement time is expected due to the walking speed distribution used (3.6-3.61 km/h). It is also noted that the measured travel distance varies about 0.2 m measured along the horizontal plane. As addressed in the analysis of *Verification test 2.1 – Speed in a corridor*, the travel distance and the movement time variation can be explained by the method of measurement and the time step length of the simulation. Since the length of each time step is 0.2 s and the walking speeds are ~1.0 m/s, the maximum length measurement error is 0.2 m (1 m/s x 0.2 s) on each side of the measurement area. The total maximum length measurement error is therefore 0.4 m and the total maximum movement time error is 0.4 s.

The convergence measures from the last five simulations are below the convergence criterion of 1 % for both walking directions and no further simulations are performed.

In summary, the movement time variations are within the margin of error. The conclusion is that the model is able to reproduce and maintain an occupant’s selected walking speed up and down stairs along a specified distance.

3.4 Verification Test 2.3 – Movement Around a Corner

Verification test 2.3 – Movement around a corner is used to evaluate the model’s ability to simulate movement around a corner and the system boundaries of the setup.

3.4.1 Test Description

Create the geometry shown in Figure 18.

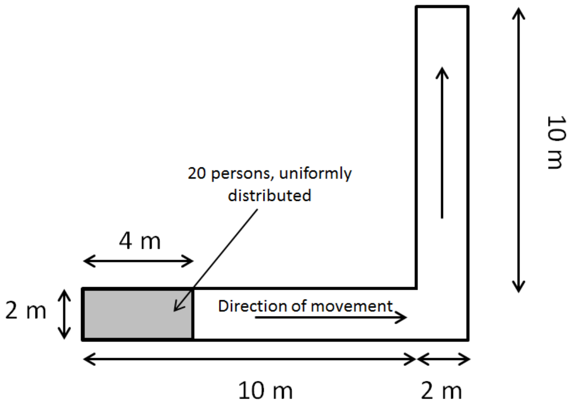

Figure 18. Geometry of *Verification test 2.3 – Movement around a corner* (Ronchi et al., 2013a).

Place 20 occupants at random positions in the starting area. The occupants should have a walking speed of 1 m/s and no pre-evacuation time.

3.4.1.1 Test Modifications

The test is performed without modifications.

3.4.2 Expected Results

The occupants should move around the corner to their destination without moving through the boundaries of the system.

3.4.3 Results

The occupants move through the configuration as Figure 19 shows.

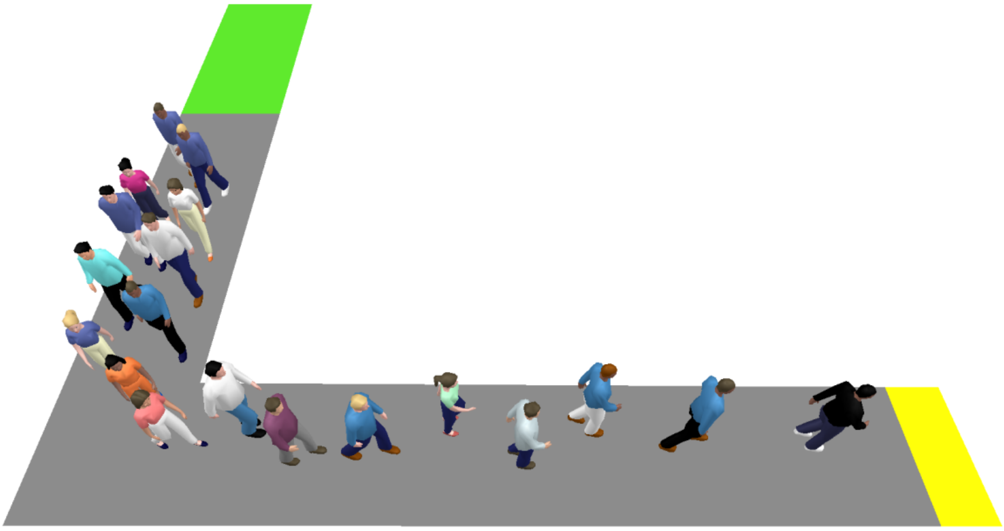

Figure 19. A screenshot from the results of *Verification test 2.3 - Movement around a corner.*

3.4.4 Analysis

Movement around the corner is unhindered and the occupants do not penetrate the boundaries, which corresponds with the expected results. The results show that Viswalk has an adequate way of simulating movement around a corner.

3.5 Verification Test 2.4 – Assigned Occupant Demographics

Verification test 2.4 – Assigned occupant demographics verifies the model's ability to reproduce selected occupant demographics (walking speed distributions).

3.5.1 Test Description

Create a room with a size of 100 x 100 m. Insert 100 occupants at random locations in the room and specify a distribution for their walking speeds. The occupants are assigned to exit the area in a certain direction.

3.5.2 Test Modifications

The test is performed with similar walking speed distributions as presented by Lord et al. (2005). The report suggests a separation into demographic groups of occupants with different walking speed distributions. The division is made into three different groups with respect to the occupants' ages. The following occupant groups are used: 18-29 year olds, 30-50 year olds and >50 year olds. However the two occupant groups younger than 50 years have the same walking speed distribution. Only one distribution is therefore used for these occupants in the test.

In the report by Lord et al. (2005), the exact type of walking speed distributions are not defined. They are only specified with mean, standard deviation, minimum and maximum values along with a plotted empirical probability distribution. In the test, the probability distributions from the report are approximated by normal distributions with similar properties. As discussed in section *3.1.1.1 Test modifications* the exact shape and parameter values of the distributions are not the main focus in these two tests. Instead, it is the model's ability to reproduce selected probability distributions that is evaluated. Table 11 displays the specific input parameters of the walking speed distributions for the separate occupant groups.

A uniform distribution is used in one setup with the purpose of including more than one type of distribution in the test. The maximum and minimum values of the distribution are taken from the 30-50 year olds occupant group (Lord et al., 2005).

Table 11. The walking speed distributions of the three occupant groups used in *Verification test 2.4 - Assigned occupant demographics.*

Setup	Occupant Group	Distribution	Mean	Standard Deviation	Minimum	Maximum
1	18-29 year olds/ 30-50 year olds	Normal	1.12	0.25	0.25	1.9
2	>50 year olds	Normal	0.86	0.26	0.25	1.5
3	30-50 year olds	Uniform			0.25	1.9

One simulation is performed using each setup, which results in 100 walking speeds per distribution. The walking speeds are calculated by measuring the total distance walked by each occupant and dividing it with their movement time. To test if the resulting walking speeds from Setup 1 and 2 could come from the specified distributions, hypothesis testing is used with the Anderson-Darling method as described in section *1.3.2 Verification*, with a significance level of 5 %. The null hypothesis is that the obtained walking speeds from the simulations come from the specified distributions. Setup 3 is analysed by comparing the results presented in a histogram with the expected frequency of each histogram group since the Anderson-Darling test is not available for uniform distributions.

3.5.3 Expected Results

The occupants should be assigned a walking speed according to the selected walking speed distribution.

3.5.4 Results

Table 12 shows the results from the simulations while Figure 20 and Figure 21 below display the empirical cumulative distribution functions from the simulations compared to their respective theoretical function. Lastly, Figure 22 shows a histogram of the simulation results using the uniform walking speed distribution.

Table 12. Results from *Verification test 2.4 - Assigned occupant demographics.*

Setup	Distribution	P-Value	Figure
1	Normal (1.12, 0.25)	0.093	20
2	Normal (0.86, 0.26)	>0.250	21
3	Uniform (0.25, 1.9)	Not available	22

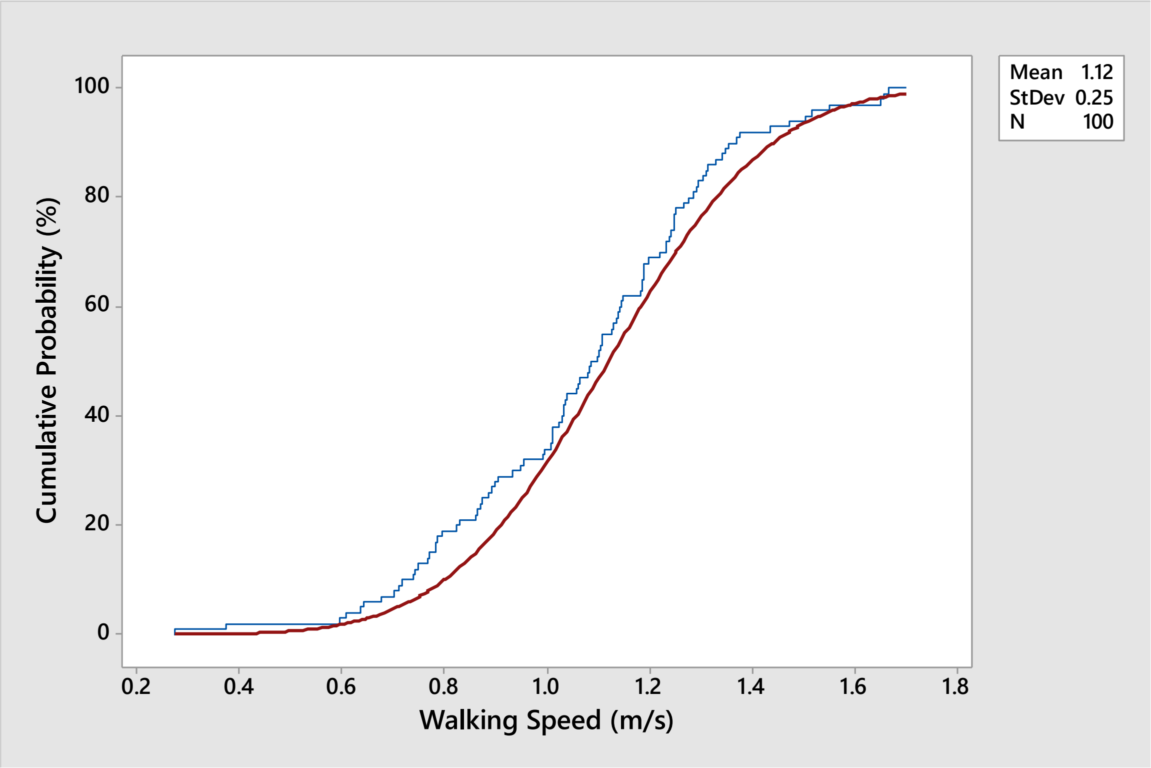

Figure 20. The empirical cumulative distribution function compared to the theoretical normal (1.12, 0.25) distribution function.

Figure 21. The empirical cumulative distribution function compared to the theoretical normal (0.86, 0.26) distribution function.

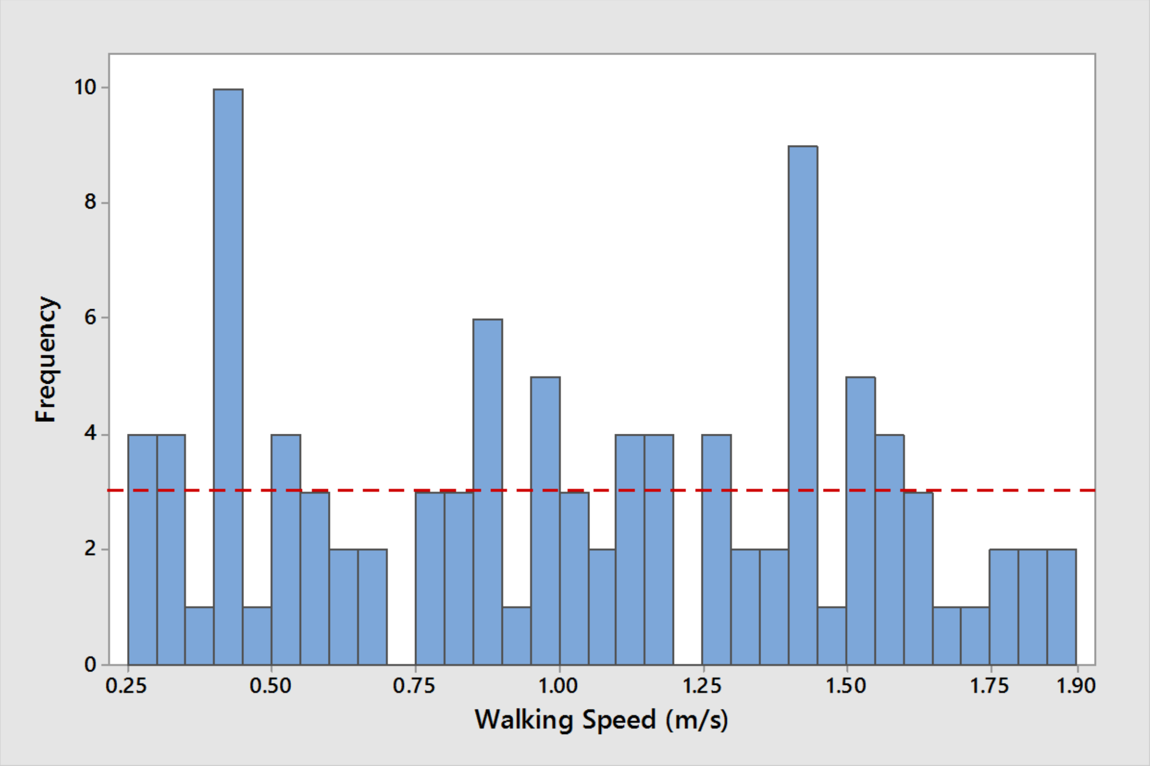

Figure 22. A histogram of the simulation results when using the uniform (0.25, 1.9) probability distribution. The dotted line shows the expected frequency.

3.5.5 Analysis

The results presented in Table 12 show that the p-values from Setup 1 and 2 are greater than 0.05 and there are no significant differences between the results and the expected results, given that the null hypotheses are true. This means that the null hypotheses cannot be rejected and the results could come from the specified distributions.

When studying the graphs in Figure 20 and Figure 21 it can be noted that the empirical cumulative density functions have a resemblance to their theoretical counterparts. The results show that the walking speeds are lower than the theoretical distribution suggests. This can be explained partially by the measuring technique, which determines the walking speed as a mean over the whole distance walked by the occupant, and partially by the random sampling algorithm. The mean walking speed would be lower because of the acceleration phase of the occupant and the possibility to get stalled by occupants with a lower walking speed.

The results from setup 3 show that the walking speeds of all occupants are within the expected range from 0.25 m/s to 1.9 m/s, see Figure 22. The dotted line in Figure 22 shows the expected frequency of ~3 occupants in each histogram group. This is due to the total of 100 occupants with 33 different groups. The frequency is in a range from 0 to 10, which shows fluctuations in the results. This could be due to the limited amount of data. The test is therefore performed again to obtain a larger sample.

A sample with 1000 occupants is assembled by performing 10 simulations with 100 occupants in each simulation, see Figure 23. This is done in order to determine the impact of a larger sample. The results show that most groups in the histogram have a frequency in the range between 20 and 40, which is close to the expected frequency of ~30. The expected frequency is calculated in the same way as before, with the number of occupants divided into 33 groups. The increased number of simulations indicates that the resulting frequencies start to align with the expected frequency as a larger sample is used. With the new results it is clearer that the results from the simulation come from the assigned uniform distribution.

Figure 23. A histogram of the simulation results when using the uniform (0.25, 1.9) probability distribution and performing 10 simulations with 100 occupants in each simulation.. The dotted line shows the expected frequency.

The results show that both simulations with the normal distributions and with the uniform distribution reproduce the assigned walking speeds in accordance with the expected results. The conclusion is that Viswalk has an adequate way of implementing walking speed distributions.

3.6 Verification Test 2.8 – Horizontal Counter-Flows

Verification test 2.8 – Horizontal counter-flows is used to verify the model's ability to simulate occupant counter-flows.

3.6.1 Test Description

Create the geometry shown in Figure 24.

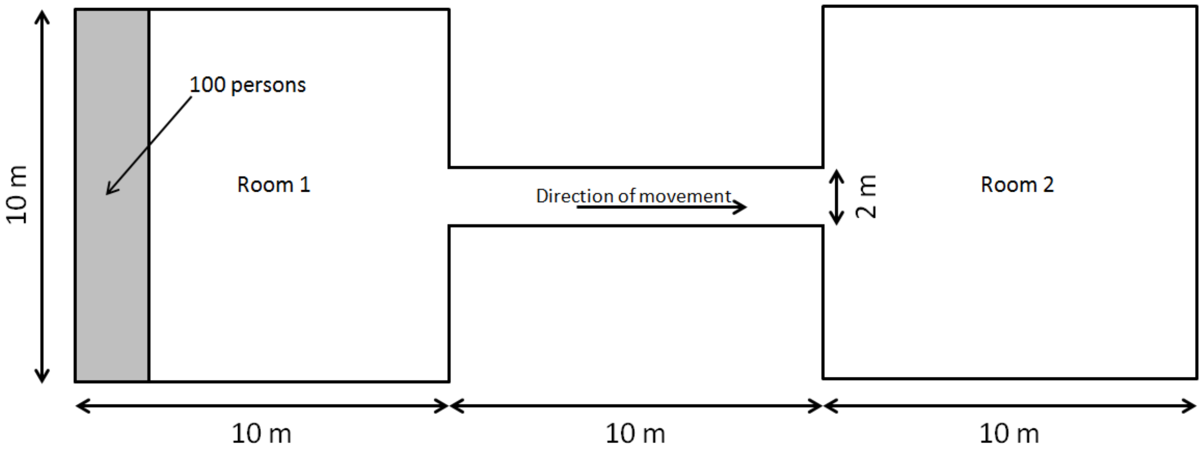

Figure 24. The geometry of *Verification test 2.8 – Horizontal counter-flows* (Ronchi et al., 2013a).

Place 100 occupants at random locations in the starting area. Set the pre-evacuation time to 0 s and select a suitable walking speed distribution for the occupants. Start the simulation and measure the time at which the last occupant from Room 1 enters Room 2. Run additional simulations with 10, 50 and 100 occupants in Room 2 moving to Room 1 and measure the time described above.

3.6.1.1 Test Modifications

The test includes 10 simulations for each setup with 0, 10, 50 and 100 occupants in room 2. The focus is to compare the magnitudes of the movement times from each setup to study if there is an increased movement time when the number of occupants in Room 2 increases. A convergence criterion of 10 % is considered to be sufficient since it is the magnitude and not the exact movement times that are evaluated in the test.

3.6.2 Expected Results

The time at which the last occupant from Room 1 enters Room 2 should increase when the occupant load in Room 2 increases.

3.6.3 Results

The complete results are presented in Table 41-44 in *Appendix B*, where the cumulative mean and convergence measure are shown for all setups and simulations. A summary of the results is presented in Table 13 below, were the cumulative mean of the last simulation for each setup is shown.

Table 13. Results from *Verification test 2.8 – Horizontal counter-flows.*

Setup Number	Number of Occupants in Room 2	Movement Time for the Last Occupant in Room 1 (s)
1	0	102
2	10	172
3	50	813
4	100	1745

A snapshot from a simulation with Setup 4 is presented in Figure 25 which shows the counter-flows after 80 seconds into the simulation.

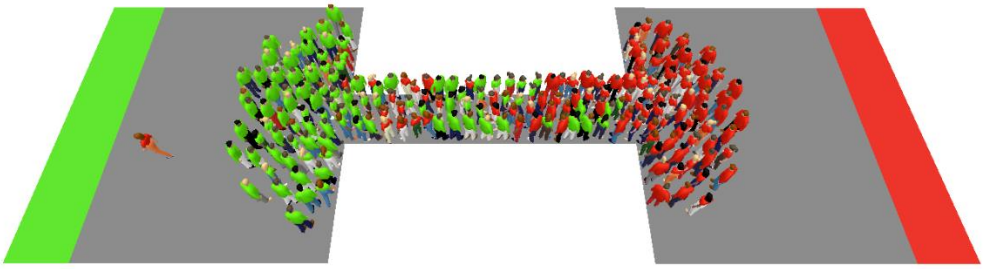

Figure 25. A screenshot of the counter-flow with 100 persons in each room after 80 seconds.

3.6.4 Analysis

The results from the simulations show that the time at which the last occupant from Room 1 enters Room 2 (movement time) increases with the number of occupants in Room 2, in accordance with the expected results. The movement time in setup 4, when 100 occupants are placed in each room is 1745 s when using the default settings. The movement time can be decreased by changing specific parameters such as the occupants' side preferences, i.e. on which side they should pass other occupants. For example, when setting the side preferences to the right or left side, the movement time in Setup 4 decreases to 850-890 s. There are also other parameters that can be changed e.g. queueing formation and straightness. However, the absolute values of the movement times in the setups are not the main focus of the test. The focus is to determine if the movement time increases with the number of occupants in Room 2. With the distinct difference of the movement times for each setup, the results show that the model is able to simulate occupant counter-flows in accordance with the expected results.

3.7 Verification Test 3.1 – Exit Route Allocation

Verification test 3.1 – Exit route allocation is used to verify the model's ability to assign user-defined exits to the occupants.

3.7.1 Test Description

Create the geometry shown in Figure 26.

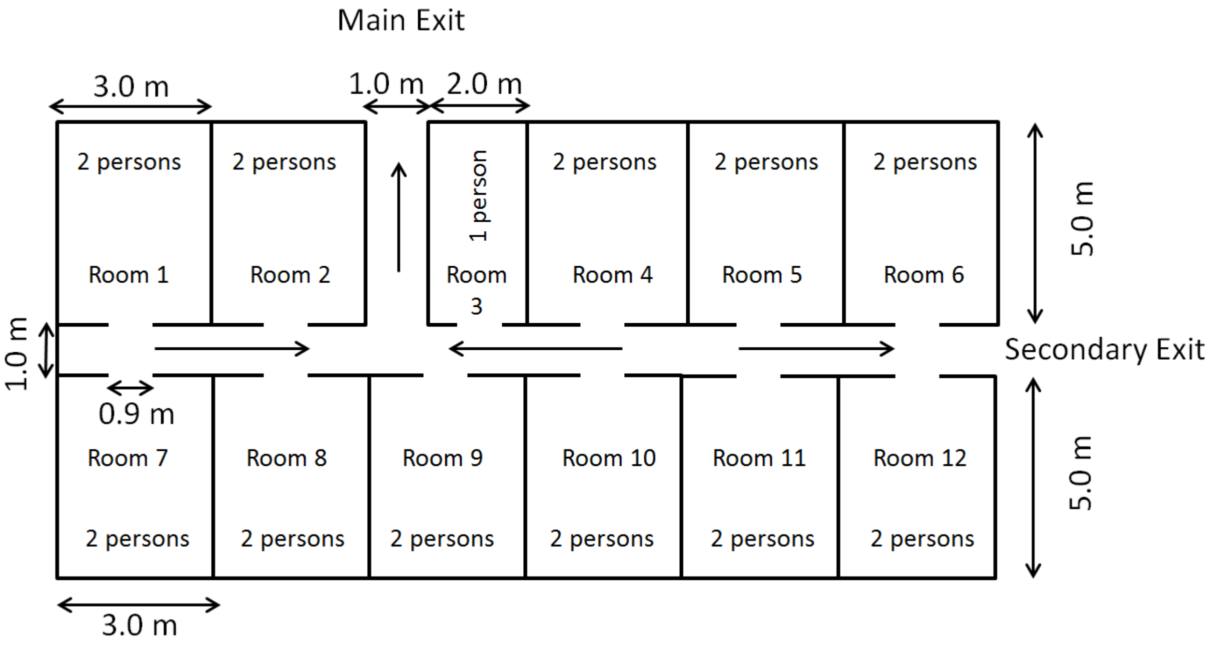

Figure 26. The geometry of Verification test 3.1 – Exit route allocation (Ronchi et al., 2013a).

Place occupants in every room according to Figure 26, set the pre-evacuation time to 0 s and select a suitable walking speed distribution. Direct the occupants in room 1-4 and 7-10 to the main exit when evacuating. Direct the remaining occupants to the secondary exit.

3.7.1.1 Test Modifications

The test is performed without modifications.

3.7.2 Expected Results

The occupants should evacuate through the pre-defined exits.

3.7.3 Results

The results show that all occupants evacuate through the assigned exits, see Figure 27.

Figure 27. Screenshot from *Verification test 3.1 - Exit route allocation.*

3.7.4 Analysis

The simulation show that all occupants evacuate through the assigned exits in accordance with the expected results.

3.8 Verification Test 4.1 – Dynamic Availability of Exits

Verification test 4.1 – Dynamic availability of exits is performed to investigate if the model is able to change the occupants' routes during a simulation. The original route can for example become blocked due to the fire and the occupants then have to diverge from their original route.

3.8.1 Test Description

Create a room with a size of 10 x 15 m with one exit on each 15 m wall. The exits should be 1 m wide and placed at the same distance from one of the 10 m walls. Set the pre-evacuation time to 0 s and the walking speed to 1 m/s and place one occupant at the 10 m wall. After 1 s, one of the exits is blocked and cannot be used by the occupant.

3.8.1.1 Test Modifications

The occupant is assigned to exit 1 when the simulation starts and after 1 s the route is modified so that the occupant diverges towards exit 2. This is done with the *DecModel* function in Viswalk, which makes it possible to change the occupant's route choice at each time step.

3.8.2 Expected Results

The blocked exit should not be used by the occupant.

3.8.3 Results

The results from the simulation show that the occupant starts moving towards Exit 1 and then diverges towards Exit 2 after 1 s, see Figure 28.

Figure 28. Screenshot from *Verification test 4.1 - Dynamic availability of exits.*

3.8.4 Analysis

The results from the simulation correspond with the expected results.

3.9 Verification Test 5.1 – Congestion

Verification test 5.1 – Congestion involves congestion and how the model simulates flows when the occupant density is high.

3.9.1 Test Description

Create the geometry shown in Figure 29. Place 100 occupants in the starting area with the pre-evacuation time 0 s and a suitable walking speed distribution. When starting the simulation the occupants shall move through the configuration.

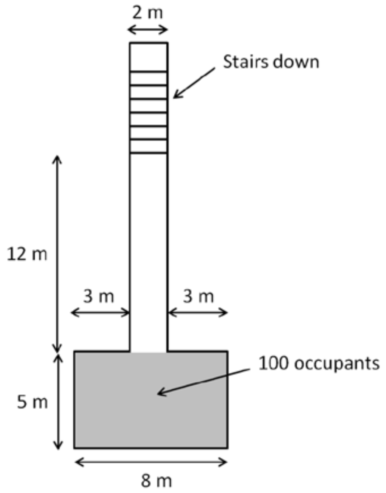

Figure 29. The geometry of *Verification test 5.1 - Congestion* (Ronchi et al., 2013a).

3.9.1.1 Test Modifications

The model's standard occupant demographic settings are used, which means that the occupants in the simulation have pre-defined walking speed distributions. This also means that the walking speeds measured along the incline of the stairs are the same as the horizontal walking speeds of the occupants when they are moving on a horizontal plane, as described in section *2.2.3 Movement on Stairs*. The incline of the stairs therefore have to be adjusted if the aim of the test is to study congestion in front of the stairs. The incline of the stairs is set to 38 degrees in the simulation.

3.9.2 Expected Results

As the occupants start moving through the configuration congestion should appear in front of the corridor. Congestion should also appear in front of the stairs.

3.9.3 Results

The simulation displays congestion both in front of the corridor and in front of the stairs. The congestion in front of the corridor after 30 s can be seen in Figure 30 below. Figure 31 shows the congestion in front of the stairs after 50 s (see the area denoted C).

Figure 30. Congestion in front of the corridor after 30 s.

Figure 31. Congestion in front of the stair (the area denoted C) after 50 s.

3.9.4 Analysis

The results show congestion in front of both the corridor and the stair, which correspond with the expected results.

3.10 Verification Test 5.2 – Maximum Flow Rates

Verification test 5.2 – Maximum flow rates is performed to study the model's representation of occupant flows through a door opening. The aim of the test is to measure the maximum occupant flow rate to ensure that the flow rate is conservative.

3.10.1 Test Description

Create a room of size 8 x 5 m with a 1 m wide opening in the 5 m wall. Place 100 occupants in the room with no pre-evacuation time and with a suitable walking speed distribution. When the simulation starts the occupants should exit the configuration through the opening, see Figure 32.

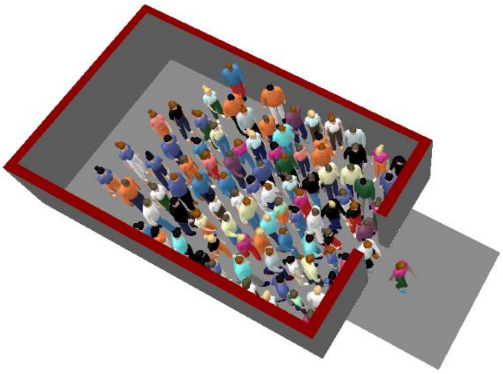

Figure 32. Screenshot from *Verification test 5.2 - Maximum flow rates.*

3.10.1.1 Test Modifications

The flow rate through the opening is calculated by placing a measurement area in the doorway. The time at which each occupant enters the measurement area is obtained. The flow rate is then calculated by dividing the number of occupants that enter the area within a specific time interval with the length of the interval. Time intervals of 10 s and 5 s are used in order to detect flow rate variations caused by the length of the time interval. The convergence criterion of the maximum flow rate is set to 1 %. A low criterion is chosen to have a strong indication that a sufficient number of simulations are performed.

The *NIST* procedure does not provide a maximum flow rate threshold that should be used in the test, but gives an example from the *IMO* guidelines, which is 1.33 p/m/s. This threshold is however for a population where 40 % are mobility impaired and where 72 % are older than 50 years. To determine the magnitude of probable maximum flow rates for other populations, a number of experiments are studied where pedestrian flow rates through openings have been measured.

Gwynne et al. (1998-99) have compiled pedestrian flow rate data for external doors from a large number of experiments and different sources which show a variation of the flow rate in the range of 1.25-2.0 p/m/s. More recent experiments regarding pedestrian flow rates have been performed by Kretz, Grünebohm and Schreckenberg (2006) who studied how the opening width influences the pedestrian flow through the opening. With an opening width of 1.0 m and 100 pedestrians they found that the flow rate was in the range of ~1.7-2.0 p/m/s. Similar flow rates have been obtained by Seyfried et al. (2009) who studied pedestrian movement through a 1.0 m wide opening in a corridor. The experiment resulted in a flow rate of ~1.9 p/m/s.

3.10.2 Expected Results

The maximum flow rate through the opening should not be too high, i.e. it should not exceed the flow rates presented in section *3.10.1.1 Test Modifications.*

3.10.3 Results

Table 14 shows a summary of the results from the simulations while the complete results are presented in Table 45 in *Appendix B.* The flow rates from simulation 1-5 are plotted as a function of time in Figure 33 and Figure 34, with two different lengths of the time intervals. Simulations 6-12 are plotted in Figure 47 and 48 in *Appendix B.*

Table 14. Results from *Verification test 4.2 - Maximum flow rates.*

Maximum Flow Rate (p/m/s)	Cumulative Mean (p/m/s)	Number of Simulations
1.80	1.72	12

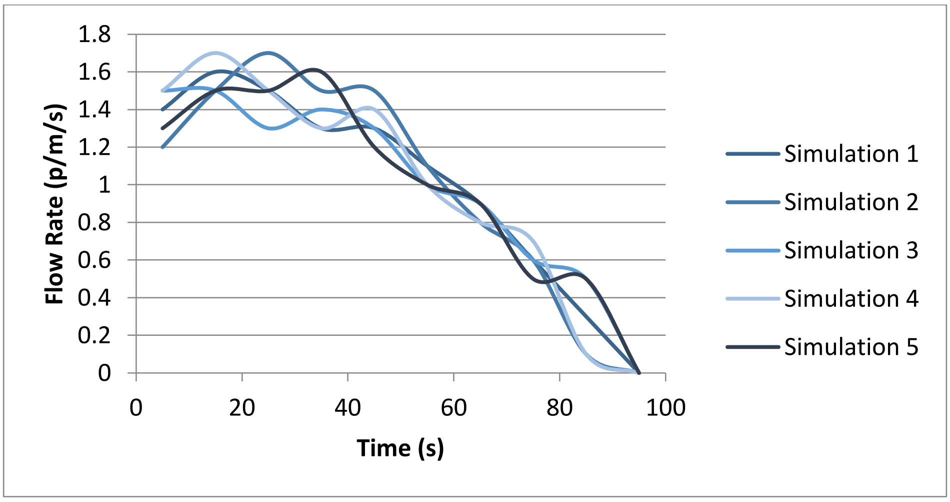

Figure 33. The flow rate from simulation 1-5 with 10 s flow rate intervals.

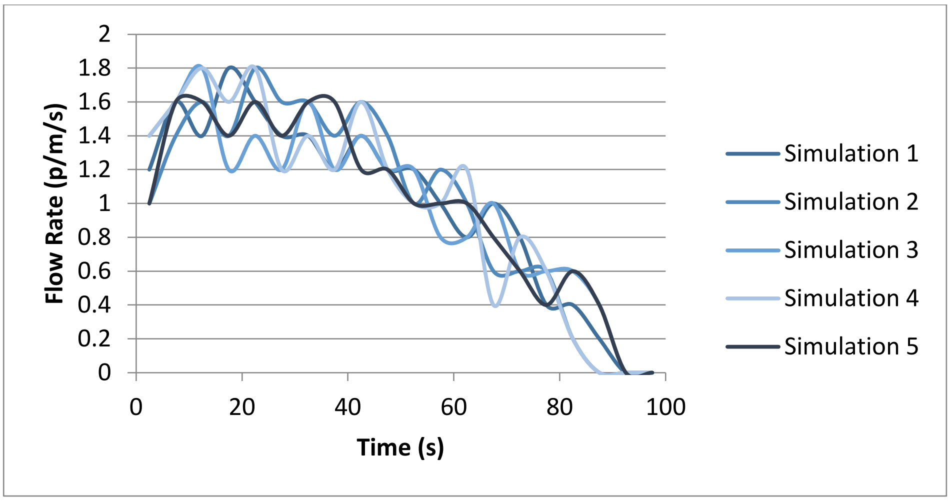

Figure 34. The flow rate from simulation 1-5 with 5 s flow rate intervals.

3.10.4 Analysis

The results show that the maximum flow rate through the opening is 1.8 p/m/s, which does not exceed the flow rates presented in section *3.10.1.1 Test Modifications.* All flow rate curves reach their maximum within the first 50 s of the simulations and the flow rates then decrease with time until all occupants have left the room. The results from this verification test are discussed further in chapter *5 Discussion.*

4 Validation of Viswalk

The following chapter contains four validation tests that compare experimental results from real life experiments to simulation results from Viswalk. The experiments are described in detail in section *2.4 Data Identification* and are used to analyse one of the core components of evacuation models, namely pedestrian movement.

4.1 Validation Test 1 – Corridor Experiment

The first validation test is based on the corridor experiment from *Lund University* (Frantzich et al., 2007), which are described in section *2.4.1 Corridor Experiment*. Four different scenarios (Scenario B-E) are included with varying opening widths at the end of the corridor. Scenario A is excluded since the model's ability to reproduce assigned walking speeds has already been evaluated in chapter *3 Verification of Viswalk.*

Validation test 1 – Corridor experiment is performed with two different sets of input settings, named *default* and *specified settings*. The first set, *default settings*, is used to perform a so-called blind calculation (see section *2.3.2 Validation of Evacuation Models*) where the model's standard input settings are used. The second set, *specified settings*, is used to perform a specified calculation where the measured walking speeds from the experiment are used.

4.1.1 Simulation Description

The corridor is constructed in Viswalk in accordance with the specified geometry, see Figure 35.

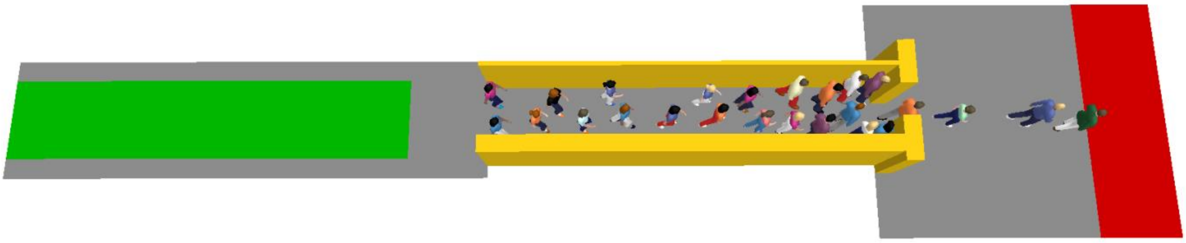

Figure 35. Screenshot from *Validation test 1 - Corridor experiment.*

The occupant starting area is created 2 m wide, 10 m long and placed 2 m in front of the corridor to resemble the starting formation from the experiment. On each side of the starting area there is additionally 0.5 m to compensate for fluctuations of the queue width as the occupants start moving through the corridor. At the end of the corridor there is a 6 m wide and 5 m long area which the occupants have to pass before they exit the configuration. Measurements are placed 2.4 m into the corridor and at the end opening to facilitate tracking of each occupant's movement through the corridor, in the same way as in the experiment.

When using the *specified settings* as input for the simulations, the occupants' assigned walking speeds are obtained from the experimental results from Scenario A, see Table 15.

Table 15. Walking speed distributions used for the specified settings in *Validation test 1 - Corridor experiment.*

Walking Speed (m/s)	Number of Observations
<1.0	0
1.0-1.1	1
1.1-1.2	0
1.2-1.3	0
1.3-1.4	7
1.4-1.5	6
1.5-1.6	18
1.6-1.7	19
1.7-1.8	19
1.8-1.9	10
1.9-2.0	2
2.0-2.1	1
>2.1	0
Total	83

The walking speeds for the *specified settings* are inserted in Viswalk by defining uniform probability distributions for each group in Table 15. The probability of an occupant to be assigned to a certain group is specified by using the *RelFlow* (relative flow) function in Viswalk. The *RelFlow* function can be used to specify the probability that a specific inserted occupant will be assigned to a certain occupant group with a certain walking speed distribution. For example, if the relative flow for occupant group A is set to 0.7 and the relative flow for group B is set to 0.3, the probability of an occupant to be assigned to each class is 70/30 %.

The probabilities to be assigned to each class are calculated by dividing the number of observations in each class with the total number of observations from the experiment. The male/female ratio is specified by dividing the number of males/females with the total number of occupants.

The flow is calculated using the same method as in the experiment by Frantzich et al. (2007). The number of occupants who exit through the opening during five second intervals are divided by the length of each time interval and presented as a mean for each scenario. Only the stable flows from each simulation are included in the calculations, which means that deviant flows from the start and end of each simulation are excluded. This is done to enable a comparison between the simulation results and the experimental results since this method is used in the experiment. An example of a chosen time interval for Scenario D from the experiment is shown in Figure 36 below (Frantzich et al., 2007). To analyse the impacts of the lengths of the chosen time intervals, a sensitivity analysis is performed in section *4.5.5.1 Sensitivity Analysis 1 – Time Interval Lengths*.

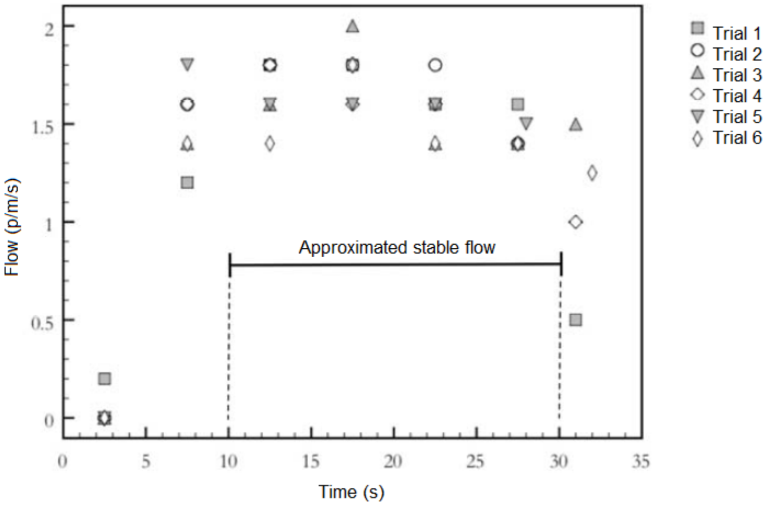

Figure 36. An example of when the flow is considered to be stable (Frantzich et al., 2007).

The movement time is calculated as the time difference between when the last occupant exits the corridor and when the first occupant has walked 2.4 m into the corridor, in the same way as in the experiment.

The occupant density is calculated in two zones in front of the end opening. Both zones have an area of 2.88 m^2 each and the exact positions are shown in Figure 7. The density is calculated each second. The calculations are made by comparing the times of which occupants enter and leave the zones and thus specifying the number of occupants that are in the zones at a specific time. The density is only calculated when flows are considered to be stable.

4.1.2 Results

The results from the simulations of Scenario B-E with *default settings* are presented in Table 16, Table 17 and Table 18 below. Table 16 shows a comparison between the movement time means from the simulations and from the experiment. Table 17 shows a comparison of the occupant flow means. Table 18 shows a comparison of the occupant density in Zone 1 and 2.

Table 16. Movement times from Scenario B-E with *default settings.*

Scenario	Simulation Movement Time Mean (s)	Experimental Movement Time Mean (s)	Time Difference (s)	Time Difference (%)	Number of Simulations
B	75	43	32	74	19
C	72	37	35	95	15
D	60	31	29	94	15
E	51	28	23	82	10

Table 17. Flows from Scenario B-E with *default settings.*

Scenario	Simulation Flow Mean (p/s)	Experimental Flow Mean (p/s)	Flow Difference (p/s)	Flow Difference (%)	Number of Simulations
B	0.6	1.1	-0.5	-45	19
C	0.6	1.3	-0.7	-54	15
D	0.8	1.6	-0.8	-50	15
E	0.9	1.8	-0.9	-50	10

Table 18. Densities from Scenario B-E with *default settings.*

Scenario	Zone	Simulation Density Mean (p/m^2)	Experimental Density Mean (p/m^2)	Density Difference (p/m^2)	Density Difference (%)	Number of Simulations
B	1	1.0	1.8	-0.8	-44	19
C	1	0.9	2.0	-1.1	-55	15
D	1	1.0	1.9	-0.9	-47	15
E	1	0.8	1.0	-0.2	-20	10
B	2	1.8	1.8	0	0	19
C	2	1.8	1.8	0	0	15
D	2	1.4	1.7	-0.3	-18	15
E	2	0.7	1.1	-0.4	-36	10

Table 19, Table 20 and Table 21 below show the corresponding results with *specified settings.*

Table 19. Movement times from Scenario B-E with *specified settings.*

Scenario	Simulation Movement Time Mean (s)	Experimental Movement Time Mean (s)	Time Difference (s)	Time Difference (%)	Number of Simulations
B	41	43	-2	-5	11
C	41	37	4	11	10
D	36	31	5	16	13
E	27	28	-1	-4	10

Table 20. Flows from Scenario B-E with *specified settings.*

Scenario	Simulation Flow Mean (p/s)	Experimental Flow Mean (p/s)	Flow Difference (p/s)	Flow Difference (%)	Number of Simulations
B	1.2	1.1	0.1	9	11
C	1.2	1.3	-0.1	-7	10
D	1.4	1.6	-0.2	-13	13
E	1.9	1.8	0.1	6	10

Table 21. Densities from Scenario B-E with *specified settings.*

Scenario	Zone	Simulation Density Mean (p/m^2)	Experimental Density Mean (p/m^2)	Density Difference (p/m^2)	Density Difference (%)	Number of Simulations
B	1	1.2	1.8	-0.6	-33	19
C	1	1.1	2.0	-0.9	-45	15
D	1	1.1	1.9	-0.8	-42	15
E	1	1.2	1.0	0.2	20	10
B	2	2.4	1.8	0.6	33	19
C	2	2.3	1.8	0.5	28	15
D	2	2.0	1.7	0.3	18	15
E	2	1.0	1.1	-0.1	-9	10

The time intervals of when the flows were considered to be stable in the simulations are presented in Table 46 and Table 47 in *Appendix C.*

It is also observed that in all performed simulations of Scenario B-D a few occupants move to the corners at the end opening before exiting the corridor. These occupants idle in the corners for ~1-20 seconds and partially block other occupants that are trying to exit the corridor, see Figure 37.

Figure 37. Screenshot from *Validation test 1 - Corridor experiment*. A few occupants move to the corners at the end opening and partially block other occupants.

4.1.3 Analysis

The analysis is divided into three separate sections addressing *default input settings, specified input settings* and joint observations for both settings.

4.1.3.1 Default Input Settings

Table 16 shows that the mean movement times from the simulations are ~20-35 s longer than in the experiment. The movement time means for the simulations with *default settings* are thus showing movement times that are 70-95 % longer compared to the experiment. The calculated flow means in the door opening are between 0.6 p/s and 0.9 p/s for the simulations in different scenarios, which is ~50 % lower than the experimental results.

The results presented in Table 18 show that the densities in Zone 1 are ~0.9 p/m^2 for the simulations, which are ~20-55 % lower than the experiment. The densities in Zone 2 are in the range of ~0-35 % lower for the simulations compared to the experiment.

4.1.3.2 Specified Input Settings

The movement time means for the simulations with *specified input settings* are in the range of 27-41 s, which can be compared to the experiment with movement times in the range 28-43 s. The movement time means are between 5 % shorter and ~15 % longer for the simulations compared to the experiment, see Table 19. The flow means from the simulations differ 0.1-0.2 p/s from the experiment, resulting in a percentage difference in the range of ~15 % lower and ~10 % higher than the experimental results.

As seen in Table 21 occupant densities in Zone 1 are 0.6-0.9 p/m^2 lower for the simulations compared to the experiment in Scenario B-D, which means a difference of ~30-45 %. Scenario E on the other hand has a 20 % higher occupant density mean in the simulations than in the experiment with a density in Zone 1 of 1.2 p/m^2. For Scenario B-D, the occupant densities in Zone 2 are 0.6-0.9 p/m^2 higher in the simulations compared to the experiment, which is a difference of ~20-35 %. The occupant density mean from the simulations of Scenario E is 0.1 p/m^2 lower than the experiment, resulting in a 9 % difference.

4.1.3.3 Joint Observations

The simulations with *default settings* as well as with specified settings show a trend where the mean movement times decrease with the scenario progression. Scenario B shows the longest movement time means and Scenario E has the shortest movement time means. The results show a decrease in movement time means with an increased opening width. The same trend is visible for the experimental results. As for the occupant flows, there is a trend for both the experiment and for the simulations with different input settings where the flow increases with the opening width.

Figure 37 shows a phenomenon were occupants get stuck in the corners beside the opening at the end of the corridor. The observations are supported by the measured occupant densities in Zone 1 and 2. In Scenario B-D the densities in Zone 1 are 0.8-1.2 p/m^2 when using the different input settings. The corresponding occupant densities for Zone 2 are between 1.4 and 2.4 p/m^2. The experimental result of occupant density does not show the same trend as the results from the simulations. The measured densities in Zone 1, from the experiment, were in the range of 1.8-2.0 p/m^2 for Scenario B-D. The densities in Zone 2 were in the range of 1.7-1-8 p/m^2 for the same scenarios.

4.2 Validation Test 2 – Classroom Experiment

The second validation test is based on the classroom evacuation experiment by Guo et al. (2012), which is described in section *2.4.2 Classroom Experiment*. Since the participants were blindfolded in six of the 12 trials only the six trials without blindfolds are used.

Validation test 2 – Classroom experiment is performed with two different sets of input settings, named *default* and *specified settings*. When using the *default settings*, the 30 occupants are placed randomly in the rows of seats and the model's standard input settings, including walking speeds, are used.

When using the *specified settings*, all occupants are placed in the exact same starting positions as in the experiment. Additionally, the occupants' routes are specified in detail and the walking speeds are adjusted to fit the occupant demographics.

4.2.1 Simulation Description

The classroom is constructed in Viswalk in accordance with the specified geometry, see Figure 38.

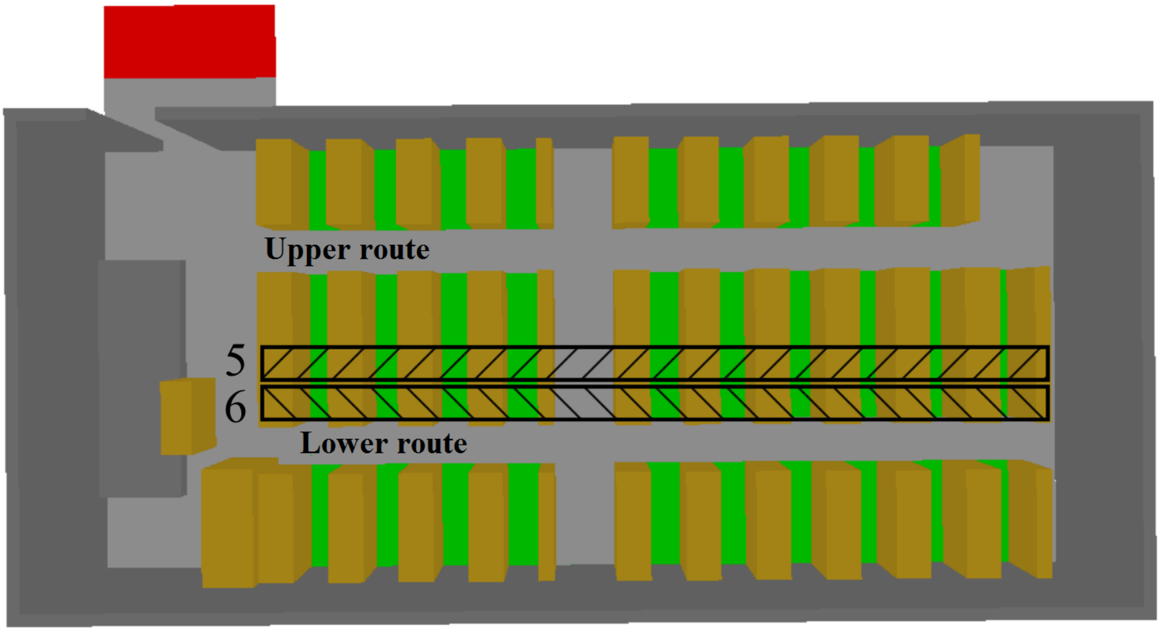

Figure 38. The classrom from *Validation test 2 - Classroom experiment*. Occupants from column 5 and 6 are assigned to the upper or lower route when using the specified settings.

The exact size of the platform, the computer workbench and the lectern is not specified in the experiment and their sizes are therefore estimated in the simulations by comparing the setup to a schematic drawing from the experiment. The size of the platform is estimated to 1.1 x 3.2 m and the size of the computer workbench next to the platform is estimated to 0.4 x 0.95 m. The size of the lectern is estimated to 0.65 x 1.5 m.

After exiting the classroom, the occupants move across an area of size 2.35 x 0.85 m before they exit the setup. A measurement area is placed in the door opening to measure each occupant's movement time. The flow through the opening is calculated by dividing the total number of occupants with the total movement time. This is done for the simulation results as well as the experimental results since only the movement time of each occupant is presented in the report by Guo et al. (2012). A mean is then calculated that include the results from all simulations or experimental trials.

In the simulations with *specified settings*, the walking speeds are adjusted to better fit the assumed occupant demographics. In the report by Guo et al. (2012) it is stated that the participants were students, however no further information is given. The *default settings* for walking speeds are recommendations from the *IMO* guidelines for 30-50 year olds. It is more likely with a younger population since they are students. The corridor experiment described in section *2.4.1 Corridor experiment* includes a measurement of the walking speeds for a group of Swedish students and these walking speeds are considered to agree better with the students in the classroom experiment. The same walking speed distributions as in *Validation test 1 – Corridor experiment* are therefore used in the simulations with the *specified settings.*

The exact routes of the participants in column 5 and 6 are not known, se Figure 38. The report only states the number of participants from these columns that walk on each side of the middle section. In the simulations it is assumed that the occupants in column 5 and 6 that are closest to the exit use the upper route shown in Figure 38. The remaining occupants in column 5 and 6 that start in the back of the classroom use the lower route.

The routes are defined by using intermediate destinations on the way to the exit. The intermediate destinations are implemented by creating small areas that the occupants have to walk across before continuing to the exit. The intermediate destinations for the two routes are placed in line with the front row in each route. Additional intermediate destinations are created for a few occupants that tend to get stuck on the corners of the tables because of the narrow space between the rows. Also, the lectern is first created with the size 0.65 x 1.6 m, which results in occupants getting stuck between the lectern and the first bench row. The size of the lectern is therefore adjusted to 0.65 x 1.5 m.

4.2.2 Results

Table 22 and Table 23 show the results from the simulations with *default* and *specified input settings*. Table 22 shows a comparison between the movement time means from the simulations and from the experiment while Table 23 shows a comparison of the occupant flow means.

Table 22. Movement times from *Validation test 2 - Classroom experiment.*

Input Settings	Simulation Movement Time Mean (s)	Experimental Movement Time Mean (s)	Time Difference (s)	Time Difference (%)	Number of Simulations
Default	45.2	25.6	18.9	77	24
Specified	24.4	25.6	-1.2	-5	12

Table 23. Flows from *Validation test 2 - Classroom experiment.*

Input Settings	Simulation Flow Mean (p/s)	Experimental Flow Mean (p/s)	Flow Difference (p/s)	Flow Difference (%)	Number of Simulations
Default	0.67	1.18	-0.51	-43	24
Specified	1.23	1.18	0.05	4	12

Figure 39 and Figure 40 show the proportion of people that have exited the classroom as a function of time with either *default* or *specified settings*. Figure 39 shows the results with *default settings* and Figure 40 shows the results with *specified settings.*

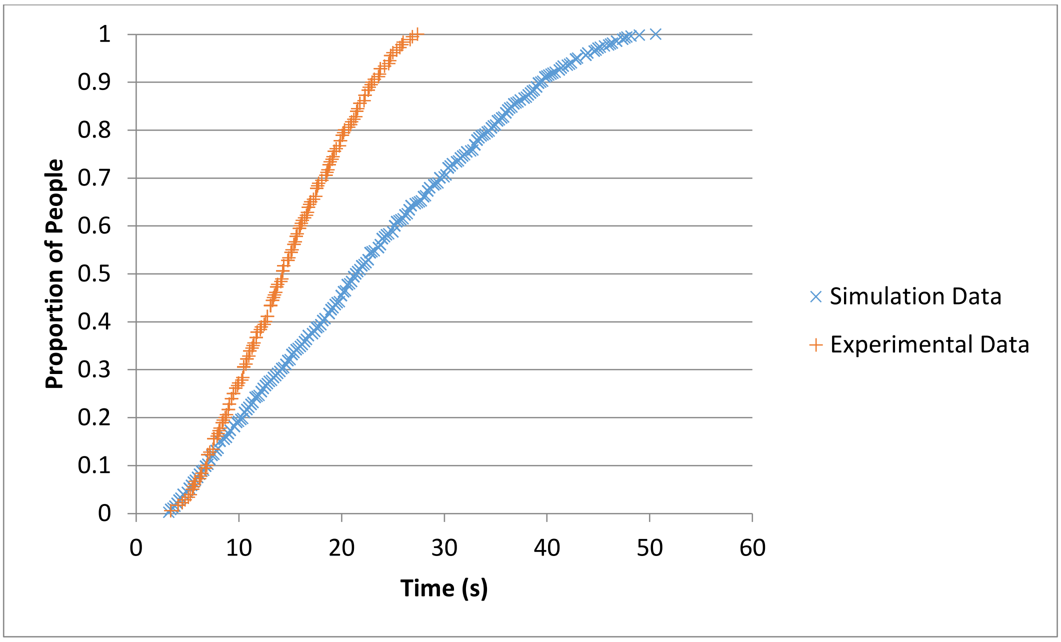

Figure 39. The proportion of people that have exited the classroom as a function of time with *default settings,* compared to the experiment.

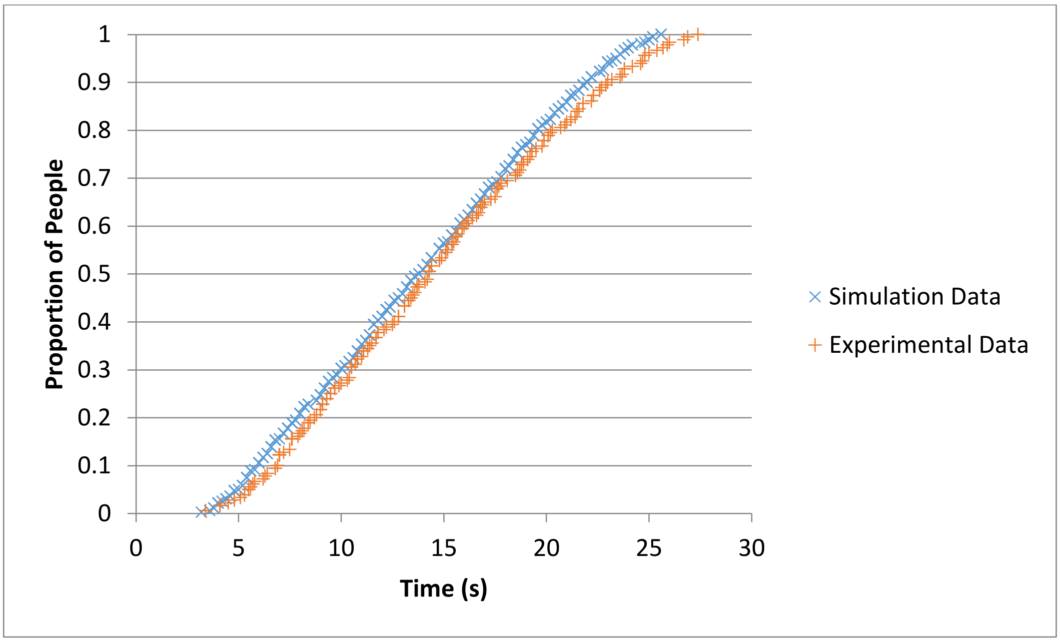

Figure 40. The proportion of people that have exited the classroom as a function of time with *specified settings,* compared to the experiment.

4.2.3 Analysis

When using the *default input settings*, the simulations show that the total movement times from the simulations are ~20 seconds longer than the movement times from the experiment, which is ~75 %. These differences are also seen in Figure 39 where the curve that represents the experimental movement times has a greater incline than the curve that represents the simulation data. When comparing the curves, they seem to match each other for 7-8 seconds before they separate. The differences between the experimental and simulation movement times lead consequently to differences between the occupant flows. The simulation flows when using the *default settings* are ~45 % lower than the experimental flows, which is 0.5 persons per second.

When using the same walking speed distributions as in *Validation test 1 – Corridor experiment* and specifying the starting positions and routes, the movement times from the simulations are reduced from ~45 s to ~24 s, which can be compared to the experimental results of 25.6 s. When comparing the curves in Figure 40, their shapes are similar, which means that about the same number of persons have evacuated the classroom at every certain point in time during the evacuation. The curve from the simulation data is slightly shifted to the left, indicating that the occupants' movement times are shorter in the simulations than in the experiment.

4.3 Validation Test 3 – Theatre Experiment

The third validation test is based on the theatre evacuation experiment at the *AF* facilities in Lund (Frantzich et al., 2007), which is described in section *2.4.3 Theatre Experiment*. Since there is only one trial with documented results, the subsequent analysis of the simulation results is limited.

Validation test 3 is performed with two different sets of input settings, named *default* and *specified settings*. When using the *default settings*, the model's standard input settings are used in the same way as in the prior validation tests. When using the *specified settings*, the occupants' walking speeds are adjusted to fit the specified occupant demographics, see section *4.3.1 Simulation Description.*

4.3.1 Simulation Description

The theatre lobby is constructed in Viswalk with the given measurements, see Figure 41.

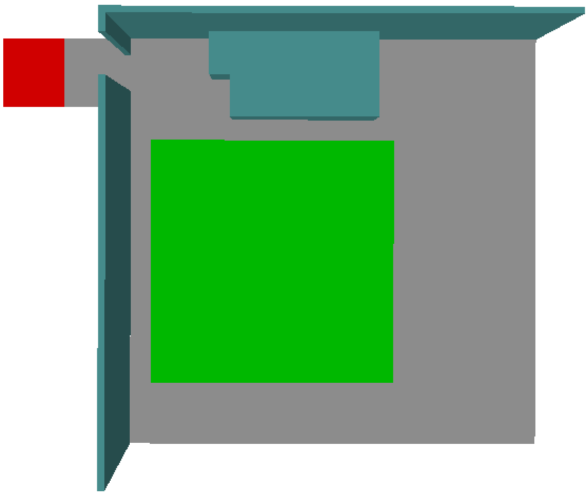

Figure 41. The theatre lobby from *Validation test 3 - Theatre experiment.*

The exact starting points of the occupants are not known and are therefore estimated in the simulations. The size of the starting area is set to 6 x 6 m and the 50 occupants appear randomly within this area. When exiting the lobby, the occupants walk across an area with size 1.5 x 1.7 m before they reach the end area and exit the configuration.

A measurement area is placed in the door opening to measure each occupant's movement time. The flow through the opening is calculated by dividing the total number of occupants with the difference between the time at which the first occupant exits the room and the exit time for the last occupant.

The occupant demographics for this experiment are not described in detail in the report by Frantzich et al. (2007) and they are therefore estimated when using the *specified input settings*. It is known that the occupants' ages varied from ~15-70 years with an emphasis on ~30 years and that there were about the same proportions of males and females. Since this is all information that is provided regarding the occupant demographics it is assumed that the occupants' ages are distributed randomly within the age interval, with an emphasis on ~30 years.

To assign a specific walking speed distribution to the occupants they are divided into three groups for each gender in accordance with the occupant groups used in the *IMO* guidelines; <30 years, 30-50 years and >50 years (International Maritime Organization, 2007). The proportion of occupants in each group is then estimated by dividing the number of years within each group with the total length of the age interval. For example, the proportion of occupants in the <30 years group is calculated by dividing 15 (30-15) with 55 (70-15), which results in 27 % in the first occupant group. This results in 36 % for the second and 36 % for the third occupant group. Since there was an emphasis on ~30 years in the experiment, it is assumed that 30 % belong to the first group, 40 % belong to the second group and 30 % belong to the third group.

It is also known that there were about 50 % males and 50 % females in the experiment which correspond to the occupant groups stated in Table 24 below. The walking speed distribution for each occupant group is uniform and obtained from the recommendations from the *IMO* guidelines (International Maritime Organization, 2007).

Table 24. Occupant demographics used in *Validation test 3 - Theatre experiment*. The walking speeds are obtained from the recommendations from the International Maritime Organization (2007).

Occupant Group	Walking Speed Minimum (m/s)	Walking Speed Maximum (m/s)	Proportion (%)
Females <30 years	0.93	1.55	15
Females 30-50 years	0.71	1.19	20
Females >50 years	0.56	0.94	15
Males <30 years	1.11	1.85	15
Males 30-50 years	0.97	1.62	20
Males >50 years	0.84	1.4	15

4.3.2 Results

Table 25 and Table 26 show the results from the simulations with *default* and *specified input settings.* Table 25 shows a comparison between the movement time means from the simulations and from the experiment while Table 26 shows a comparison of the occupant flow means.

Table 25. Movement times from *Validation test 3 - Theatre experiment.*

Input Settings	Simulation Movement Time Mean (s)	Experimental Movement Time Mean (s)	Time Difference (s)	Time Difference (%)	Number of Simulations
Default	46	41	5	12	10
Specified	43	41	2	5	10

Table 26. Flows from *Validation test 3 - Theatre experiment.*

Input Settings	Simulation Flow Mean (p/s)	Experimental Flow Mean (p/s)	Flow Difference (p/s)	Flow Difference (%)	Number of Simulations
Default	1.09	1.25	-0.16	-13	10
Specified	1.17	1.25	-0.08	-6	10

4.3.3 Analysis

The simulations with *default input settings* have the longest movement time mean of 46 s and show a movement time that is 12 % longer than the experimental movement time. The flow mean of the simulations with *default settings* is 13 % lower than the measured flow in the experiment.

The results from the simulations with *specified settings* show a movement time mean of 43 s which is 5 % longer than the experiment. There is a 6 % lower flow mean in the specified simulations compared to the experimental results. The movement time means from the simulations are longer than the experimental results for both settings. Flow means of the simulations are all lower than in the experiment, which is a direct consequence of the movement times being longer in the simulations compared to the experiment.

4.4 Validation Test 4 – Stair Experiment

The fourth validation test focuses on vertical movement and is based on the stair experiment at the *AF* facilities in Lund (Frantzich et al., 2007), described in section *2.4.4 Stair Experiment*. The test includes movement times and flows of pedestrians moving down stairs.

The validation test is divided into three scenarios; Scenario A, B and C with different input settings. In Scenario A, the model's *default input settings* are used, which means that the walking speeds that are used are the model's default values. Scenario B is performed with modified horizontal walking speeds to agree better with the occupant demographics from the experiment. Scenario C is performed with the same input settings as Scenario B but it also includes specified stair walking speeds.

4.4.1 Simulation Description

The geometry of the test is created in Viswalk as shown in Figure 42.

Figure 42. The geometry used in *Validation test 4 - Stair experiment.*

The dimension of the starting level is 10 x 10 m and the occupants appear randomly within this area. Since there are two trials with 61 and 91 occupants, simulations are performed with both 61 and 91 occupants for each scenario with different input settings described above. The bottom level is the same size as the starting level and the occupants exit the setup after they have walked across the bottom level, see Figure 42.

The size of the stair is 2.25 x 4.0 m (width x length) with a 26 degree slope, which matches the stair from the experiment. The user cannot specify handrails in Viswalk and the width of the stair is therefore defined as the width between the handrails, which is 2.25 m.

A measurement area is created as a 2.1 m long section on the stair to measure the movement time in the same way as in the experiment. The movement time is defined as the time difference between when the first and the last occupant enters the measurement area. The flow down the stair is calculated by dividing the total number of occupants with the movement time.

The experiments used as benchmarks for *Validation test 3 – Theatre experiment* and *Validation test 4 – Stair experiment* were performed in the same building, but with four years between the experiments. The participants are therefore not the same in these experiments but according to Frantzich et al. (2007) the occupant demographics were similar. When simulating Scenario B and C it is therefore assumed that the occupants' walking speed distributions are the same as in *Validation test 3 – Theatre experiment*, see section *4.3.1 Simulation description*.

In Scenario C, the walking speeds on the stair are modified by assigning specific walking speed distributions to all occupants as they move on the stair. These walking speed distributions are obtained from the recommendations from the *IMO* guidelines, see Table 27 below (International Maritime Organization, 2007). The proportions of occupants in each group are the same as in Scenario B. Each occupant group is applied as a uniform distribution with the minimum and maximum walking speeds presented in Table 27 below.

Table 27. Occupant demographics used in *Validation test 4 - Stair experiment.* The walking speeds are obtained from the recommendations from the International Maritime Organization (2007).

Occupant Group	Stair Walking Speed Minimum (m/s)	Stair Walking Speed Maximum (m/s)	Proportion (%)
Females <30 years	0.56	0.94	15
Females 30-50 years	0.49	0.81	20
Females >50 years	0.45	0.75	15
Males <30 years	0.76	1.26	15
Males 30-50 years	0.64	1.07	20
Males >50 years	0.5	0.84	15

4.4.2 Results

The results from the simulations are shown in Table 28 and Table 29 below. Table 28 shows the movement time means from the simulations compared to the experiment while Table 29 shows the occupant stair flows.

Table 28.Movement times from *Validation test 4 - Stair experiment.*

Scenario	Number of Occupants	Simulation Movement Time Mean (s)	Experimental Movement Time Mean (s)	Movement Time Difference (s)	Movement Time Difference (%)	Number of Simulations
A	61	42	52	-10	-19	10
B	61	44	52	-8	-15	12
C	61	51	52	-1	-2	12
A	91	57	83	-26	-32	12
B	91	61	83	-22	-27	13
C	91	72	83	-11	-13	12

Table 29. Flows from *Validation test 4 - Stair experiment.*

Scenario	Number of Occupants	Simulation Flow Mean (p/s)	Experimental Flow Mean (p/s)	Flow Difference (p/s)	Flow Difference (%)	Number of Simulations
A	61	1.47	1.17	0.30	26	10
B	61	1.40	1.17	0.23	20	12
C	61	1.19	1.17	0.02	2	12
A	91	1.61	1.11	0.50	45	12
B	91	1.51	1.11	0.40	36	13
C	91	1.27	1.11	0.16	14	12

When performing the simulations it is observed that the occupants want to keep a certain distance from the sides in the middle section of the stair. This is not observed in the beginning and end of the stair but only in the middle section. An attempt to illustrate this phenomenon is shown in Figure 43 below.

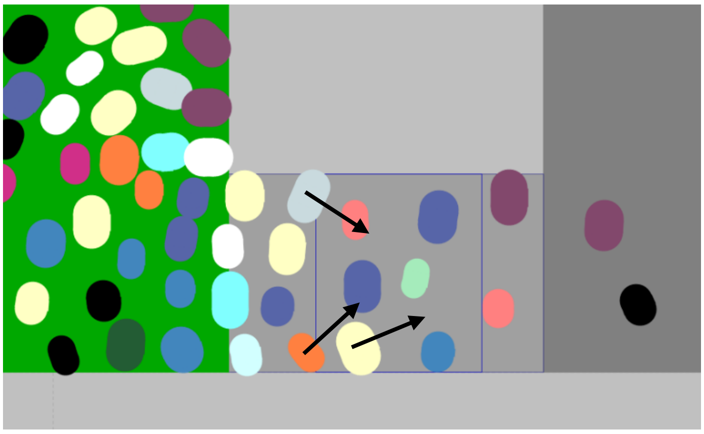

Figure 43. The occupants marked with arrows are trying to keep a distance to the walls.

The three occupants marked with arrows are turning toward the center of the stair as they have walked a few meters on the stair. As occupants have passed the middle section, they tend to diverge and walk closer to the sides of the stair before they reach the lower level. When reaching the lower level, they once again turn away from the sides and keep a certain distance to the sides. This phenomenon is discussed in chapter *5 Discussion.*

4.4.3 Analysis

The results show that the movement times from Scenario A and B with 61 occupants are ~10 s shorter than in the experiment, which is 15-19 %. The movement time from Scenario C with 61 occupants is 51 s which is 1 s shorter than in the experiment. The movement time differences are larger for all scenarios when instead using 91 occupants and the time is 13 % shorter for Scenario C and ~30 % shorter for Scenario A and B compared to the experiment.

The resulting flows show the same trend as the movement times, where Scenario A and B show larger flow differences than Scenario C. With 61 occupants, the flows from Scenario A and B are ~0.2-0.3 p/s higher than in the experiment, which is 20-26 %. For Scenario C using 61 occupants, the flow is 2 % higher than in the experiment. The flows with 91 occupants in Scenario A and B are 0.4-0.5 p/s larger than in the experiment, which is 36-45 %. With 91 occupants in Scenario C, the flow is 14 % larger than in the experiment.

The phenomenon illustrated in Figure 43 above could have an impact on the resulting movement times of the occupants since it affects their trajectories on the stair. The occupants are moving closer to the sides in the beginning and end of the stair which could affect the total movement times since the resulting densities in these zones are increased. To analyse the possible impact of the observed phenomenon a simple setup is created in Viswalk, see Figure 44.

Figure 44. Setup when analysing the impact of the observed stair phenomenon.

A stair with size 2 x 3 m (width x length) combines two levels with 1 m vertical distance. 30 occupants are placed at the starting level with size 2 x 5 m and their movement times down the stair are measured with a measurement area on the stair. The results from this scenario are compared to a similar scenario where the stair instead is replaced by a corridor with the same width and length. The default occupant demographics are used with a walking speed of 1 m/s. The total movement time is defined as the time it takes for all occupants to reach the end destination of the setup. The results from these two scenarios are presented in Table 30 below and the complete results are presented in Table 48 and Table 49 in *Appendix C.*

Table 30. Movement times when analysing the impact of the observed stair phenomenon.

Scenario	Movement Time Mean (s)	Number of Simulations
Stair	22.6	10
Corridor	25.0	10

The results show that movement time mean is ~2.4 s shorter for the stair scenario compared to the corridor scenario, which is about 10 %. These results are discussed in chapter *5 Discussion.*

4.5 Uncertainty Analysis

The following section is addressing the uncertainties associated with the validation tests, based on the four types of uncertainties described in section *2.3.3 Uncertainties in Evacuation Modelling*. As the various uncertainties have been addressed, uncertainties that are believed to have large impacts on the results are evaluated by performing sensitivity analyses.

4.5.1 Model Input Uncertainty

The model input uncertainties are introduced by assuming the input parameter values when performing simulations in Viswalk. In all validation tests, some assumptions are made concerning the occupant demographics, e.g. walking speeds, gender, body size, etc. The occupant demographics are described in detail in *Validation test 1 – Corridor experiment*, where walking speed distributions, age and gender are presented. The other validation tests do not have as detailed information, thus requiring assumptions to be made when performing simulations. When occupant demographics are only described with for example age and gender, their walking speeds have to be assumed. The *IMO* guidelines provide suggestions for walking speeds for certain occupant demographic groups.

However, there are uncertainties present when using these suggested values, since they may not match the actual population from the experiment. To study how the occupant demographic assumptions affect the resulting movement times and flows, two sensitivity analyses are performed in section *4.5.5.3 Sensitivity analysis 3 – Walking speeds* and *4.5.5.4 Sensitivity analysis 4 – Body sizes* below. One of the analyses focuses on walking speeds while the other focuses on body sizes.

Another source of potential uncertainties is the geometric descriptions from the experiments. The geometries are overall described in detail but there are some room for interpretations. For example, the exact size and location of the starting areas in *Validation test 3 – Theatre experiment* and *Validation test 4 – Stair experiment* are not specified in the experiments and are therefore assumed in the simulations. The starting positions of the occupants may influence flows and movement times and are therefore evaluated with a sensitivity analysis in section *4.5.5.2 Sensitivity analysis 2 – Starting positions* below.

4.5.2 Measurement Uncertainty

There are several uncertainties associated with the experiments that are used as benchmarks for the validation tests. For example, there are uncertainties with the technique and equipment used for documentation and processing of data from the experiments. Measurements depend on the calibration of equipment and how the researcher performs the measurements. Additionally, to simplify the results, the data is often processed and interpreted before being published. The impacts of these uncertainties are not clarified in the experiments and their magnitude can therefore not be determined. Overall, the selected experiments provide relatively detailed descriptions of the methods used for documenting and processing the results, along with the specific conditions of each experiment. This is an attempt to reduce the uncertainties associated with the experimental results.

An example of an uncertainty caused by the research method is the flow calculations used as benchmarks for *Validation test 1 – Corridor experiment*. The researchers calculated the flow in a time interval when they deemed the flow to be steady, and excluded unsteady flows from the beginning and end of the measurements. A different assumption for this calculation may lead to different flows. When implementing the same method for the simulation results, these uncertainties are present when the lengths of the time intervals are chosen. To analyse the impact of the uncertainties surrounding the lengths of the time intervals from the simulations a sensitivity analysis is performed in section *4.5.5.1 Sensitivity analyses* below. The sensitivity analysis is performed by changing the lengths of the time intervals and studying how the resulting flows are affected.

There are also uncertainties associated with the extent of information that is given to the participants in the experiments. There may be differences in the participants' behaviours as a result of how well informed they are about the experiments and the objective of the study. For example, if the participants know that the objective of the experiment is to measure their walking speeds, this may lead to unwanted adjustments of their speeds. Experiments are chosen that include both informed and uninformed participants to try to take these uncertainties into account. It should also be noted that participants in the validation experiments may adjust their behaviour when participating in several trials from the same experiment.

4.5.3 Intrinsic Uncertainty

Uncertainties associated with the model's formulations of mathematical and physical relationships are more difficult to determine than the model input uncertainties and measurement uncertainties (Hamins & McGrattan, 2007). One example of an intrinsic uncertainty that may affect the results in the validation tests is the size of the area around each occupant in which the occupant gets affected by other occupants. Another intrinsic uncertainty that can affect the results is the use of the social force model, which partially reproduces the social conventions that real life experiments contain. The uncertainties in this category are however not covered in more extent due to the difficulty to measure their impact on the results and the limited scope of the thesis.

4.5.4 Behavioural Uncertainty

Generally, the number of trials in the experiments is limited. This affects the analyses and conclusions that can be made when comparing the experiments to simulations. A large number of trials will enable an evaluation of the possible range of the results to be made, since the results are not only point estimates of the studied factors. If only experiments with single trials are used, it is impossible to know if the obtained results are representative for the possible outcomes. Even with constant parameters such as the building geometry and occupant demographics, there may still be fluctuations in the results due to behavioural uncertainties. Aspects of behavioural uncertainties are described in section *2.3.3 Uncertainties in Evacuation Modelling* and are associated with the fact that the same occupants may behave differently if the exact same evacuation scenario is repeated. The experiments used as benchmarks for the validation tests include single trial as well as multiple trial experiments. The results from the single trial experiment are more uncertain and the conclusions have to be adapted accordingly. The impact of behavioural uncertainties are discussed in section *5.2.1 Uncertainties.*

4.5.5 Sensitivity Analyses

In the following section, four sensitivity analyses are performed to evaluate the impact of the time interval lengths, starting positions, walking speeds and body sizes on the results from the validation. The analyses are delimited to these four uncertainties and there are other uncertainties that may affect the results that are not analysed further.

4.5.5.1 Sensitivity Analysis 1 – Time Interval Lengths

The first sensitivity analysis focuses on how the occupant flow calculations depend on the choice of time interval lengths in *Validation test 1 – Corridor experiment*. The simulations with *specified input settings* provide results that better match the results from the experiments, compared to the simulations with *default settings*. The simulations with *specified settings* are therefore used in the sensitivity analysis.

To analyse the impact of the lengths of the time intervals, both an increase and a decrease of the intervals are tested. Firstly, the time intervals are increased with 10 s, which is distributed as 5 s in the lower bound and 5 s in the upper bound of each interval. The flow is calculated for the increased time interval lengths to enable a comparison with the flow obtained with the original time intervals. Secondly, the original time interval lengths are decreased with 10 s, to analyse how the occupant flow calculation results differ with a shorter time interval. The original time interval is decreased with 5 s in the lower bound and 5 s in the upper bound.

Table 31 and Table 32 show the calculated flows with modified time interval lengths as well as the difference between flows obtained with the different time intervals.

Table 31. Sensitivity analysis of the time interval lengths from *Validaton test 1 - Corridor experiment.* The intervals are increased with 5 s in the beginning and 5 s at the end of each interval.

Scenario	Increased Interval (s)	Original Interval (s)	Flow With Increased Interval (p/s)	Flow With Original Interval (p/s)	Difference (p/s)	Difference (%)
B	5-45	10-40	1.04	1.21	-0.17	-14
C	5-45	10-40	1.04	1.20	-0.16	-13
D	5-40	10-35	1.19	1.42	-0.23	-16
E	5-35	10-30	1.40	1.88	-0.48	-26

Table 32. Sensitivity analysis of the time interval lengths from *Validaton test 1 - Corridor experiment.* The intervals are decreased with 5 s in the beginning and 5 s at the end of each interval.

Scenario	Decreased Interval (s)	Original Interval (s)	Flow With Decreased Interval (p/s)	Flow With Original Interval (p/s)	Difference (p/s)	Difference (%)
B	15-35	10-40	1.29	1.21	0.08	7
C	15-35	10-40	1.20	1.20	0.00	0
D	15-30	10-35	1.53	1.42	0.11	8
E	15-25	10-30	2.19	1.88	0.31	17

The results from the sensitivity analysis show that the increased time intervals have varying impacts in each scenario, ranging from a decrease in flow of 13-26 %. The greatest difference in flows is obtained when the time interval is increased in Scenario E, which decreases the flow from 1.88 p/s to 1.40 p/s. Scenario E does also have the shortest time interval length to begin with, calculated within 10-30 s in the simulation.

Results from the calculations with the decreased time interval lengths show that the flows are increasing with 0-17 % compared to the original time interval. It can be observed that the flow difference is greater with the increase of the time intervals compared to the decrease of the intervals. The results are discussed in chapter *5 Discussion.*

4.5.5.2 Sensitivity Analysis 2 – Starting Positions

The second sensitivity analysis is performed using *Validation test 2 – Classroom experiment* and the analysis consists of two different scenarios, Scenario A and B. In Scenario A, the impact of the starting area size is studied by increasing its size from 6 x 6 m to 9 x 7 m, see Figure 45.

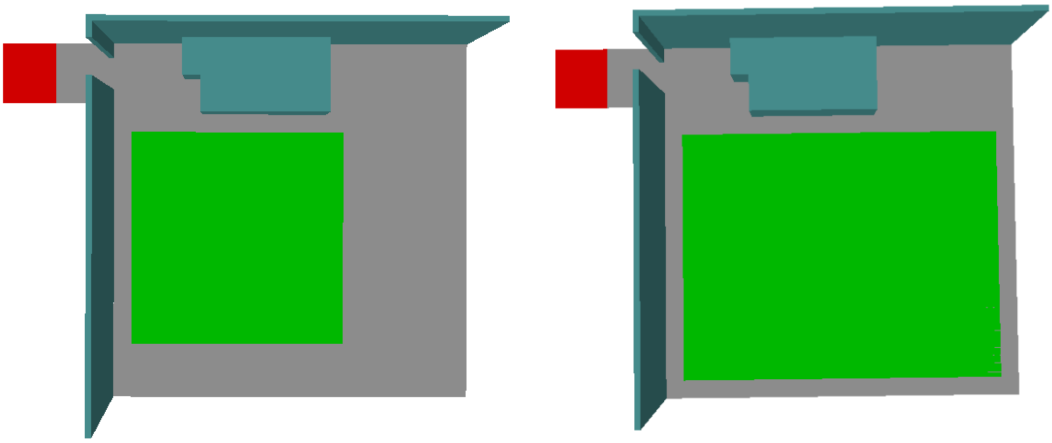

Figure 45. The size of the starting area in *Validation test 3 - Theatre experiment* is increased.

The starting positions of the occupants are thereby distributed on a larger area which means that the initial occupant density is decreased.

In Scenario B, the impact of the location of the starting area is studied by placing the area further away from the exit, see Figure 46. The original starting area size of 6 x 6 m is used and the area is moved 3 m to the right and 1 m down compared to the original position.

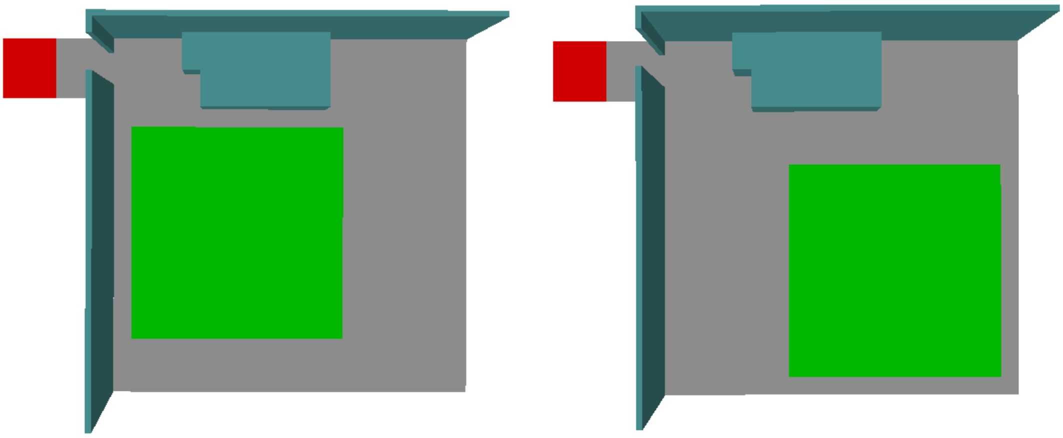

Figure 46. The starting area in *Validation test 3 - Theatre experiment* is moved further away from the exit.

A total of 10 simulations are performed with each scenario and the results are presented in Table 33 below.

Table 33. Results from *Sensitivity analysis 2 - Starting positions.*

Scenario	Starting Area Size (m)	Spawn Area Location	Flow Mean (p/s)	Original Flow Mean (p/s)	Flow Difference (%)
A	9 x 7	Original	1.17	1.17	0
B	6 x 6	Opposite corner	1.18	1.17	1

The results show that changing the size of the starting area from 6 x 6 m to 9 x 7 m results in the same flow mean through the opening as in the original validation test. The new location of the starting area yields a flow mean that is 1 % higher than the original flow mean. The results are discussed in chapter *5 Discussion.*

4.5.5.3 Sensitivity Analysis 3 – Walking Speeds

The impact of the assumed walking speeds are analysed by performing *Validation test 2 – Classroom experiment* with modified walking speeds and comparing the results to the validation test results. This is done by decreasing the minimum and maximum values for the walking speed distributions that are used with 25 %. For example, the uniform walking speed distribution from 1.0 to 1.1 m/s is modified to 0.75-0.825 m/s and this is done for all walking speed distributions used in the validation test with specified input settings. The results from the sensitivity analysis are presented inTable 34 and Table 35 below.

Table 34. Movement times from *Sensitivity analysis 3 - Walking speeds.*

Movement Time Mean, Reduced Speeds (s)	Movement Time Mean, Original Speeds (s)	Time Difference (s)	Time Difference (%)	Number of Simulations
35.6	24.4	11.2	46	12

Table 35. Flows from *Sensitivity analysis 3 - Walking speeds.*

Flow Mean, Reduced Speeds (p/s)	Flow Mean, Original Speeds (p/s)	Flow Difference (p/s)	Flow Difference (%)	Number of Simulations
0.85	1.23	-0.38	-31	12

As seen in Table 34, when decreasing the walking speeds in *Validation test 2 – Classroom experiment*, the movement time mean increases from ~24 to ~36 s, which is just below 50 %. The mean flow through the door opening decreases from ~1.2 to 0.85 p/s which is about 30 %.

4.5.5.4 Sensitivity Analysis 4 – Body Sizes

Validation test 3 – Theatre lobby is used to analyse the impact of the assumptions of the occupants' body sizes. The simulations with *specified input settings* are used in the comparison because the results from these simulations are closest to the experimental results.

Viswalk provides default compositions of occupants which have a default ratio of 50 % men and 50 % women. Each group with either men or women consists of four occupant types that have different height, shoulder width and step length. As occupants are simulated there is an equal probability for the occupant to be assigned to any of the four occupant types. There is also a predefined variance of the occupant body preferences, which is applied as the occupants are simulated.

As the body sizes of the default occupant types are similar, occupant groups representing boys and girls are used in the sensitivity analysis. This is motivated by the distinct difference between children's and adult's body sizes, which should result in an estimation of the maximum impact of the body size uncertainties.

The groups with boys and girls consist of four different occupant types with varying shoulder width. The mean shoulder width for the children occupant types are approximately 20 % smaller than the mean shoulder width of the adult occupant types. Simulations are performed with all default parameters except the shoulder width, step length and height of the occupants. The results are presented in Table 36 below.

Table 36. Results from *Sensitivity analysis 4 - Body sizes.*

Results	Original Values	Values With Decreased Shoulder Width	Difference	Difference (%)
Movement Time Mean (s)	43	32	-11	-26
Flow Mean (p/s)	1.17	1.59	0.40	36

The results from the sensitivity analysis show that the movement time mean decreases with 26 % with a decreased shoulder width of 20 %. The flow mean with the decreased shoulder width is 1.59 p/s, which is an increase of 36 %.

5 Discussion

The following chapter contains a discussion about the verification and validation of Viswalk along with the method that is used and the role of evacuation modelling in the risk management process.

5.1 Verification

The results from the verification tests correspond with the expected results. For *Verification test 2.1 – Speed in a Corridor* and *Verification test 2.2 – Speed on Stairs*, the results show deviations from the expected results with up to 0.2 s. These deviations are however within the margin of error described in section *3.2.4 Analysis*. From an evacuation modelling perspective, variations in this magnitude do not have a considerable impact on the resulting movement times as there usually are larger uncertainties involved.

The maximum flow rate in *Verification test 5.2 – Maximum flow rates* corresponds with the experimental data presented in section *3.10.1.1 Test Modifications*, that suggests a flow rate of 1.25-2.0 p/m/s. The obtained maximum flow rate of 1.8 p/m/s is in the higher region of the interval, which should also be expected since the flow rates from the experiments are not maximum values but average values over a certain time.

In the context of the above mentioned experimental results, the flow rate 1.33 p/m/s is in the lower region of the interval. No information has been found regarding exactly why this flow rate is a recommended threshold for evacuation modelling. It could be due to the fact that a rather low flow rate yields longer evacuation times and thereby values that could be seen as conservative from a perspective of building evacuation modelling. It should however be mentioned that several of the experiments stated above were performed with good conditions such as informed able-bodied participants and no smoke which could result in higher flow rates.

When using Viswalk for evacuation analyses, it is important for the user to be aware of that non-conservative evacuation times can be obtained if the default flow rates are used, so that it can be taken into account by the user. Many other evacuation models produce default flow rates that are lower so that the resulting evacuation times are conservative from an evacuation modelling perspective. If the user is not aware of that Viswalk can produce non-conservative evacuation times, it may lead to that the total evacuation times are underestimated which may result in for example misleading conclusions about the building’s fire safety.

The user cannot directly specify maximum flow rates through openings in Viswalk, which can be a drawback from a building evacuation analysis point of view since the building regulations in many countries specify flow rates that should be used for evacuation modelling. However, it is possible to modify the occupant flow rate indirectly by adjusting specific parameters in the model. For example, the occupants’ behaviours in or close to a door opening can be modified by adjusting parameters in the social force model. It is also possible to adjust the occupants’ walking speeds close to an opening to decrease or increase the occupant flow through the opening. Since it is possible to adjust the flow indirectly by parameter calibration or by for example using conservative walking speeds, the fact that the user cannot specify a certain flow rate is not considered to limit the use of the model, atleast not for an experienced user. It may however increase the time it takes to prepare the model for a simulation.

5.2 Validation

The validation tests show that the simulations with *default settings* generate results that differ more from the experimental results than the simulations with *specified settings*. This is expected since the occupant demographics with *specified settings* are adjusted to fit the populations in the experiments. When studying the movement times, the *default settings* yield times that are up to 95 % longer than in the experiments, which can be compared to the simulations with *specified settings* that show smaller deviations, with movement times that differ less than 16 % from the experiments. The same trend can be seen when studying the occupant flows. The exception is *Validation test 3 – Theatre experiment* where the results from the simulations with *default settings* have a better agreement with the experiment than the other validation tests, with 12 % longer movement times for the simulations.

In the experiment used in *Validation test 3 – Theatre experiment*, the participants are 15-70 years old and their walking speeds are therefore in a wide range. In the simulations with *default settings*, the default walking speeds vary from 0.71-1.62 m/s, which is for a population of 30-50 year olds. The better agreement in *Validation test 3 – Theatre experiment* between the experiment and the simulations with *default settings* can be explained by that the walking speeds of the participants in the experiment and the default walking speeds are similar, and both are in a wide range. The simulations with *specified settings* provide walking speeds in the range of 0.56-1.85 m/s, which also includes <30 year olds and >50 year olds. The resulting movement times from the simulations with *specified settings* are 5 % longer than in the experiment, which is a smaller deviation than in the simulations with *default settings*. A probable reason is that the participants' walking speeds from the experiment correspond better with the adjusted walking speeds in the simulations with *specified settings* than with *default settings*. However, since the experiment includes one single trial it should be mentioned that the results involve uncertainties due to the limited amount of data. The single trial can represent any value in a range of possible outcomes, which makes it more difficult to make conclusions from the results compared to *Validation test 1 – Corridor experiment* and *Validation test 2 – Classroom experiment,* that contain multiple trials.

When examining the densities in *Validation test 1 – Corridor experiment*, it is noted that the densities differ with up to 55 % with the *default settings* and up to 45 % with the *specified settings* compared to the experiment. The densities in Zone 1 are lower in the simulations than expected and Zone 2 shows densities that are higher than in the experiment. This can be explained by the phenomenon shown in Figure 37, which suggests that the occupants form a line that is wider close to the opening compared to the line further back in the corridor. It is also noted that occupants get stuck beside the opening which further increases the density in this area. The results from the experiment show that the densities in the two zones are similar, with density differences of 0.2 p/m/s or less. The similar densities indicate that the width of the line was more uniform in the experiment than in the simulations. Despite line formation differences, the occupant flows and movement times deviate less than 16 % from the experimental results. The line formation and densities may be important in some scenarios, when not only evacuation times and flows are studied, but other results as well. When studying the densities it is important for the user to be aware of that they may differ from real life scenarios so that it can be taken into account. The densities may be important for example when performing toxicity assessments to analyse the occupants' exposure to smoke and the deviating densities can therefore limit the use of the model in some cases. The densities are also important when for example studying congestion in a building and the design and placement of exits and evacuation routes.

Validation test 2 – Classroom experiment is the only test where it is possible to compare evacuation time curves, since the experiment includes each individual's movement time. This enables an analysis of the entire evacuation process and it is not restricted to the total movement time. With the *default settings* the movement times are 77 % longer in the simulations compared to the experiment, which can be a result of the different occupant demographics. Viswalk uses a population of 30-50 year olds, which is not likely to correspond with a group of students. The occupant demographics involve walking speeds and these should be faster for a younger population. In the simulations with *specified settings*, the movement times are 5 % shorter than in the experiment, which shows that Viswalk can reproduce more accurate results for the specific setup, when the assumptions about occupant demographics are adjusted to the studied population.

An interesting observation in *Validation test 2 – Classroom experiment* is that the occupants tend to get stuck in the narrow areas between the benches and next to the opening. Overall this trend is clearer when the occupant walking speeds are lower. This could be explained by the social force model used, where low walking speeds yield weaker forces that act on the occupants, which makes forces from obstacles have a greater impact on the occupants. This phenomenon is important to be aware of as a user, especially when performing simulations of confined spaces.

Validation test 4 – Stair experiment shows, like *Validation test 3 – Theatre experiment*, that the difference between *default* and *specified settings* is smaller than in the other two validation tests. As the populations in test 3 and 4 are similar, the *default settings* should correspond with the actual population, and the difference should therefore be smaller than in the other two validation tests. However, the simulations show up to 45 % higher flows than in the experiments and this can be explained by the default walking speeds on stairs used in Viswalk. The model uses the same walking speeds measured along the incline of the stair as the horizontal walking speeds. When compared to the walking speed recommendations from the *IMO* guidelines, this assumption seems to overestimate the occupants' walking speeds on stairs. When changing the walking speeds on the stair to the recommendations from the *IMO* guidelines, the resulting flow agrees better with the experimental flow, with 2 % and 14 % higher flows. This suggests that the default walking speeds on stairs overestimate the flow compared to the experiment. It should be noted that the evaluated version of Viswalk has the same walking speed up and down the same stair, which does not agree with the *IMO* guidelines that suggests a lower walking speed upwards compared to downwards.

A phenomenon that is noticed in *Validation test 4 – Stair experiment* is that the occupants do not seem to keep a distance to the walls in the beginning and end of the stair. This leads to an irregular walking behaviour on the stair, which may influence the resulting movement times. The analysis in section *4.4.3 Analysis* indicates that this phenomenon can affect the resulting movement times up to about 10 % for a short stair. As the irregularity is found in the beginning and end of the stair, there should be a decreased impact on the resulting movement times with an increase in stair length. This irregularity could however have a larger impact in more complex scenarios with multiple stairs, such as a high-rise building. It should however be noted that the model allows for adjustments of the occupants' behaviours on stairs. For example, the impact of the sides of the stair can be removed so that the occupants walk close to the sides along the whole stair. This adjustment along with a decrease of the stair width could remove the effect of the studied phenomenon, but this requires calibration effort from the user. The conclusion is that the phenomenon may have an impact on the results if the user is unaware of the problem, but it is possible for the more experienced user to work around it.

5.2.1 Uncertainties

The results from the uncertainty analysis show that a decrease of occupant walking speeds with 25 % increases the movement times with 46 % in the evaluated scenario. Even with substantial congestion early in the evacuation process, the walking speed is an important parameter, which is unexpected since the walking speeds are restrained by the ambient occupants when there is congestion. This can be explained by Viswalk's use of the social force model, where the assigned walking speeds affect the forces that act on each occupant. High assigned walking speeds leads to a stronger motivation to reach the end destination, which speeds up the evacuation process. The walking speeds used in the simulations are adjusted to match the populations from the experiments in an attempt to reduce the uncertainties associated with the impact of the assigned walking speeds.

In three of the experiments, there are no measurements of the occupants' walking speeds and it is therefore difficult to make conclusions of the magnitude of the uncertainties involved in the walking speeds. In these experiments, the results from the simulations with *specified settings* do however better match the experimental results, which indicate that the walking speeds can be adjusted in order to improve the agreement between the results.

The method for calculating the flows in *Validation test 1 – Corridor experiment* yields uncertainties as the length of the time interval is user dependent. In the sensitivity analysis, the lengths are varied in a realistic but wide range to estimate the maximum magnitude of these uncertainties, which result in 0-17 % differences in seven of the eight evaluated setups. One of the evaluated setups show a 26 % decreased flow with an increase of the time interval length. This can be explained by the short movement time of the scenario, which means that the increase of 10 s is a major change. The flows are lower in the beginning and end of the simulations and higher inbetween which show a distinct trend of when the flows are steady. The sensitivity analysis is performed to evaluate the largest impact that the time interval lengths can have on the resulting flows, and these uncertainties are likely to have smaller impacts since the trends of the flows are clear.

The impact of the starting positions is 0-1 % in the sensitivity analysis of *Validation test 3 – Theatre experiment*. This can be a result of congestion early in the evacuation process, which means that the occupants' exact starting positions are of less importance. *Validation test 3 – Theatre experiment* is the test where the occupants' starting positions are the most uncertain of the validation tests. Since the starting positions prove to have an impact of 0-1 % on the results in this test, the impacts should be smaller in the other tests where the starting positions are better described and there is congestion early in the evacuation process. The uncertainties associated with the starting positions are therefore considered to have similar or smaller impacts on the results in the other tests.

The sensitivity analysis of body size in *Validation test 3 – Theatre experiment* is performed as an extreme case where simulations with an adult occupant group are compared to simulations with a children occupant group. This is done to get an idea of the range of the uncertainties and their impact on the results. The analysis shows a 26 % decrease of the movement times with a decreased shoulder width of 20 %, which is an extreme case. As the experiments mainly involve adults, the uncertainties associated with the body size assumptions should be smaller than the sensitivity analysis demonstrates. Therefore, these uncertainties are likely to impact the results with less than 26 %.

A type of uncertainty that is not covered in the sensitivity analyses is behavioural uncertainty, i.e. the fact that the occupants could behave differently in a similar situation. The behavioural uncertainty is handled by using probability distributions for input parameters and by performing multiple runs of each scenario in the validation tests, combined with calculating the convergence measure. The convergence measure is below 1 % for at least five consecutive runs for each scenario which means that the latest run affected the movement time mean with less than 1 %. Since the behavioural uncertainties are addressed directly in each scenario, the uncertainty analysis focuses mainly on other types of uncertainties, such as model input uncertainties. However, there are also behavioural uncertaintes involved with the performed experiments, but these uncertaintes are more difficult to analyse since only one of the four experiments includes multiple trials, where the results are presented for each trial.

The discussion above does however only apply to the behavioural uncertainties involved in the specific validation tests that are performed. It should be noted that for more complex scenarios with pre-evacuation time distributions the behavioural uncertainties may have larger impacts on the results. Additionally, when studying the entire evacuation process instead of the movement time means, the convergence method used may be insufficient. In such cases it is appropriate to use a more advanced method for handling behavioural uncertainties, see for example Ronchi et al. (2014).

5.3 Method Used

As mentioned in the literature study, there is no generally accepted method for verification and validation of building evacuation models. It is instead up to the model evaluator to decide how the verification and validation process is performed. The *NIST* procedure that is used in the verification phase leaves room for interpretations and assumptions to be made along with adjustments to fit the tested model. This verification method is however the one that is most up to date out of the three identified methods and it is developed by researchers within the building evacuation modelling field. It evaluates the main core components of evacuation models and is therefore considered to be the most comprehensive. Generally, the verification tests are suitable for the evaluated model and only minor adjustments are needed. However, as discussed above, the recommended maximum flow rate threshold in *Verification test 5.2 – Maximum flow rates* is more appropriate to use for evacuation models that yield conservative values rather than realistic values.

The validation method that is used does not follow a specific guideline since there are no such guidelines for validation of building evacuation models. The method used is partly based on previous validations of other evacuation models but is adapted to fit the aim and objective of the thesis. The focus of the validation is horizontal and vertical movement which are important aspects of evacuation modelling. However, to completely validate a model, other aspects have to be evaluated as well, for example route choice and pre-evacuation times. Furthermore, this should include full-scale experiments so that the entire evacuation process can be evaluated. A continued validation can also be performed by validating Viswalk against other evacuation models that have already been evaluated. This makes it possible to evaluate other aspects of the model for many different scenarios. However, it should be noted that the validation of these models involves limitations due to the limited amount of experimental data that can be used as benchmarks.

The lack of well documented evacuation experiments limits the possible validation tests that can be performed. Ideally, a large number of trials using the same experimental setup with detailed descriptions of the participants' demographics are desired to perform a complete validation. This is an important limitation of the validation and restricts the conclusions that can be made since it affects the surrounding uncertainties.

5.4 Evacuation Modelling as a Part of the Risk Management Process

Evacuation modelling is an important part of the risk management process when evaluating the fire protection design of buildings. Evacuation models can be used in several phases of the risk management process, for example in the risk identification phase where early estimates of pedestrian flows may be necessary and to determine where bottlenecks may occur. Another phase in the risk management process in which evacuation modelling is relevant is when analysing the consequences of specific events. The results can then be used as a basis when determining if a certain design of a building leads to an acceptable level of risk.

One of the most essential aspects of building evacuation models used for risk assessment is the knowledge of how the model relates to real life situations. Thus, it is important to know how the model performs in relation to basic mathematical assumptions and real life experiments, which is where the verification and validation comes in. The verification and validation along with sensitivity analyses give the model user an insight of the model's performance. The model user can utilize the verification and validation to know in which situations the evacuation model is suitable to be used and how reliable the results are. Without verification and validation, the use of the results from an evacuation model is very limited. The verification and validation of Viswalk contributes to the use of more advanced simulation models in risk assessments which is important as buildings become more complex.

The sensitivity analyses provide the model user with important information about Viswalk. The user is given an insight to which parameters that may impact the results and how large the uncertainties can be, which is important when using Viswalk as an evacuation model. If the user is aware of the impacts of different parameters it is possible to take this into consideration by trying to reduce the uncertainties associated with these parameters. It is also important to involve uncertainties in evacuation modelling to be able to interpret the results and to determine the reliability of the results.

6 Conclusions

The verification tests show that Viswalk is able to represent the main core components of evacuation models. The model yields results that correspond with the expected results for all 10 verification tests that are performed. It should however be noted that non-conservative flow rates can be obtained if the model's default input settings are used, which is important for the user to be aware of.

From the validation tests it is concluded that the model can predict and reproduce pedestrian movement in a given situation. In simulations with *specified input settings* the movement times deviate with 2-16 % and the flows deviate with 2-14 % from the experiments in all four validation tests. In simulations with *default input settings* the movement times deviate with 12-95 % and the flows deviate with 13-54 %. The validation tests that focus on horizontal movement yield movement times that are longer and flows that are lower, than in the experiments. This can be explained by the default occupant demographic settings in Viswalk which are specific to a certain occupant group (30-50 year olds).

The default stair settings of the model produce occupant flows that are 20-45 % higher than in the experiment in *Validation test 4 – Stair experiment*. A walking speed reduction can be assigned to the stair to obtain results that better agree with the experiment, which makes the model more user dependent. It should also be noted that separate walking speeds up and down the same stair cannot be defined. Another observation is that the occupants do not maintain the intended distance to the side walls in the beginning and end of stairs, which is important for the user to be aware of. This can decrease the movement times for single stairs with up to about 10 % and may have a larger impact in simulations with multiple stairs, such as high-rise buildings.

The results from the uncertainty analysis show that a decrease of occupant walking speeds with 25 % increases the movement times with 46 % in the evaluated scenario. Even with substantial congestion early in the evacuation process, the walking speed is an important parameter for scenarios similar to the ones under consideration.

The movement patterns of the occupants can deviate from real life experiments in certain situations. Occupants sometimes get stuck between close obstacles when given low walking speeds, which should be taken into consideration when simulating confined spaces. It is also observed that some occupants tend to idle beside openings and partially block other occupants that are trying to exit. The results indicate that the line formation is wider and the density is higher close to the opening than in the experiments. This is important for the user to be aware of since the densities are central when performing for example toxicity assessments or when designing exit routes.

Despite the aspects described above, Viswalk provides the user with the ability to adjust parameters and calibrate the model for specific areas. Results that are close to experimental results can be obtained if the user has a good estimation of the occupant demographics and is aware of the limitations of the model.

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Appendix A – Keywords and Hypothesis Testing

Table 37. Keywords used in the literature study.

Search Area	Keywords Used
Risk Management	risk management, risk management process, RSET ASET, risk management evacuation, risk management evacuation model, risk management egress, performance-based analysis, Kaplan Garrick
Viswalk	Viswalk, Vissim, Vissim pedestrian, Vissim pedestrian validation, Vissim pedestrian verification, Vissim evacuation, social force model, social force model evacuation, self-driven particles, dynamic potential
Verification and Validation Methods	evacuation model validation, validation verification evacuation, validation verification egress, IMO evacuation, RiMEA, NIST evacuation, uncertainty evacuation, uncertainty egress, evacuation modelling uncertainty, behavioural uncertainty
Data Identification	evacuation experiment, building evacuation experiment, egress experiment, horizontal movement evacuation, vertical movement evacuation, evacuation stairs

Procedure for Hypothesis Testing

Hypothesis testing is used to assess the reliability of assumptions, or hypotheses, of populations with the help of random samples from the population (Wahlgren & Körner, 2011). Statements about the population can be done by formulating a null hypothesis and then testing if that hypothesis can be rejected or if there is a possibility that it is true. The null hypothesis (H_0) is usually that there is no difference between the properties of the sample and the assumed population. There is typically an alternative hypothesis (H_1) that is true by default if the null hypothesis is rejected, that states that there is in fact a difference. A test is performed with a certain level of significance, denoted α, which is the probability to reject a null hypothesis that is true. Also, there is a probability of not rejecting a false null hypothesis, which is denoted β. The level of significance is generally set to 5 % as long as there is no reason to have a lower probability of rejecting a true null hypothesis (Wahlgren & Körner, 2011). The level of significance was therefore chosen as 5 % for the statistical testing in the verification phase.

The method for hypothesis testing is based on calculating a p-value. The p-value is the probability of receiving a result with at least the obtained difference between the sample and the expected value according to the null hypothesis, given that the null hypothesis is true. This means that a small p-value supports the alternative hypothesis, and a big p-value supports the null hypothesis. The level of significance is the critical value that determines if a given probability is small or big enough to either reject or support a null hypothesis.

There are many different goodness-of-fit tests that can be performed to see if a sample comes from a specific distribution. A well-known test is the Anderson-Darling test, which was used in the thesis to calculate the p-value.

Appendix B – Results From Verification Tests

Table 38. Results from *Verification test 2.1 - Speed in a Corridor.*

Occupant Number	Movement Time (s)	Cumulative Mean (s)	Convergence Measure (%)
1	40.0	40.0	
2	39.8	39.9	0.25
3	39.8	39.87	0.075
4	40.0	39.9	0.075
5	40.0	39.92	0.050
6	39.8	39.9	0.050
7	39.8	39.89	0.025
8	39.8	39.88	0.025
9	40.0	39.89	0.025
10	40.0	39.9	0.025

Table 39. Results from *Verification test 2.2 - Speed on stairs.*

Occupant Number	Direction of Movement	Movement Time (s)	Cumulative Mean (s)	Convergence Measure (%)
1	Upwards	100.0	100.0	
2	Upwards	100.0	100.0	0
3	Upwards	99.8	99.93	0.07
4	Upwards	99.8	99.9	0.03
5	Upwards	99.8	99.88	0.02
6	Upwards	100.0	99.9	0.02
7	Upwards	99.8	99.89	0.01
8	Upwards	100.0	99.9	0.01
9	Upwards	100.2	99.93	0.03
10	Upwards	100.0	99.94	0.01

Table 40. Results from *Verification test 2.2 - Speed on stairs.*

Occupant Number	Direction of Movement	Movement Time (s)	Cumulative Mean (s)	Convergence Measure (%)
11	Downwards	100.0	100.0	
12	Downwards	100.0	100.0	0
13	Downwards	99.8	99.93	0.07
14	Downwards	99.8	99.9	0.03
15	Downwards	99.8	99.88	0.02
16	Downwards	100.0	99.9	0.02
17	Downwards	99.8	99.89	0.01
18	Downwards	100.0	99.9	0.01
19	Downwards	100.2	99.93	0.03
20	Downwards	100.0	99.94	0.01

Table 41. Results from *Verification test 2.8 - Horizontal counter-flows.*

Simulation Number	Number of Occupants in Room 2	Movement Time for the Last Person in Room 1 (s)	Cumulative Mean (s)	Convergence Measure (%)
1	0	100.6	100.6	
2	0	100.6	100.6	0.0
3	0	102.2	101.1	0.5
4	0	102.0	101.4	0.2
5	0	100.6	101.2	0.1
6	0	102.0	101.3	0.1
7	0	102.8	101.5	0.2
8	0	100.2	101.4	0.2
9	0	101.8	101.4	0.0
10	0	102.0	101.5	0.1

Table 42. Results from *Verification test 2.8 - Horizontal counter-flows.*

Simulation Number	Number of Occupants in Room 2	Movement Time for the Last Person in Room 1 (s)	Cumulative Mean (s)	Convergence Measure (%)
1	10	163.6	163.6	
2	10	194.8	179.2	8.7
3	10	116.6	158.3	13.2
4	10	232.0	176.8	10.4
5	10	153.2	172.0	2.7
6	10	157.4	169.6	1.4
7	10	196.4	173.4	2.2
8	10	170.4	173.1	0.2
9	10	139.2	169.3	2.2
10	10	192.4	171.6	1.3

Table 43. Results from *Verification test 2.8 - Horizontal counter-flows.*

Simulation Number	Number of Occupants in Room 2	Movement Time for the Last Person in Room 1 (s)	Cumulative Mean (s)	Convergence Measure (%)
1	50	758.8	758.8	
2	50	578.0	668.4	13.5
3	50	644.8	660.5	1.2
4	50	1389.6	842.8	21.6
5	50	593.2	792.9	6.3
6	50	793.6	793.0	0.0
7	50	1166.0	846.3	6.3
8	50	715.6	830.0	2.0
9	50	586.4	802.9	3.4
10	50	905.0	813.1	1.3

Table 44. Results from *Verification test 2.8 - Horizontal counter-flows.*

Simulation Number	Number of Occupants in Room 2	Movement Time for the Last Person in Room 1 (s)	Cumulative Mean (s)	Convergence Measure (%)
1	100	1318.6	1318.6	
2	100	1097.4	1208.0	9.2
3	100	1507.6	1307.9	7.6
4	100	2266.2	1547.5	15.5
5	100	1595.8	1557.1	0.6
6	100	2711.2	1749.5	11.0
7	100	1328.4	1689.3	3.6
8	100	1485.4	1663.8	1.5
9	100	1371.8	1631.4	2.0
10	100	3761.4	1844.4	11.5
11	100	1377.2	1801.9	2.4
12	100	1415.2	1769.7	1.8
13	100	1792.8	1771.5	0.1
14	100	1973.2	1785.9	0.8
15	100	1165.4	1744.5	2.4

Table 45. Results from *Verification test 5.2 - Maximum flow rates.*

Simulation Number	Maximum Flow Rate (p/m/s)	Cumulative Mean (p/m/s)	Convergence Measure (%)
1	1.80	1.80	
2	1.80	1.80	0.0
3	1.80	1.80	0.0
4	1.60	1.75	2.9
5	1.80	1.76	0.6
6	1.80	1.77	0.4
7	1.60	1.74	1.4
8	1.60	1.73	1.0
9	1.80	1.73	0.5
10	1.80	1.74	0.4
11	1.60	1.73	0.7
12	1.60	1.72	0.6

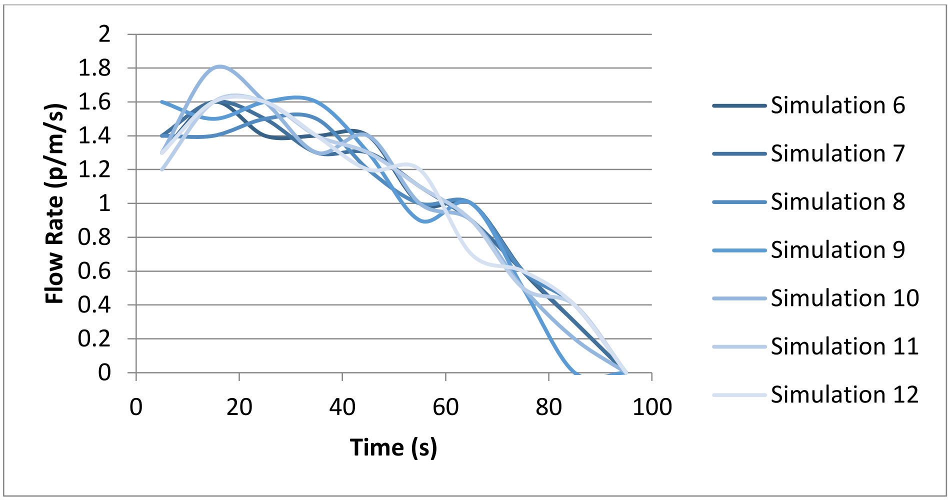

Figure 47. Flow rates from simulation 6-12 in *Verification test 5.2 - Maximum flow rates* with 10 s intervals.

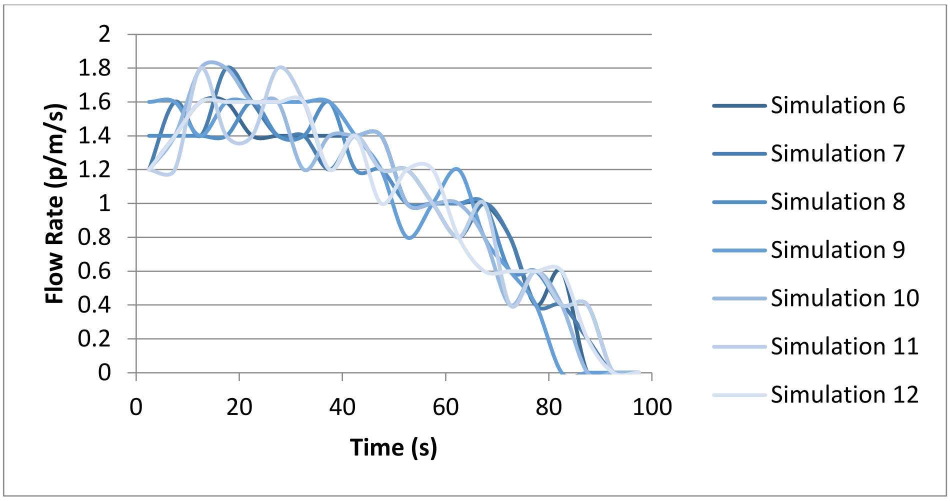

Figure 48. Flow rates from simulation 6-12 in *Verification test 5.2 - Maximum flow rates* with 5 s intervals.

Appendix C – Results From Validation Tests

Table 46. Lengths of the time intervals used in *Validation test 1 - Corridor experiment* with *default settings*. The occupant flow was considered to be stable within these intervals.

Scenario	Stable Flow Start (s)	Stable Flow End (s)
B	15	80
C	15	75
D	15	60
E	15	55

Table 47. Lengths of the time intervals used in *Validation test 1 - Corridor experiment* with *specified settings.* The occupant flow was considered to be stable within these intervals.

Scenario	Stable Flow Start (s)	Stable Flow End (s)
B	10	40
C	10	40
D	10	35
E	10	30

Table 48. Movement times when using a short stair in the analysis of *Validation test 4 – Stair experiment.*

Simulation	Movement Time (s)	Cumulative Mean (s)	Convergence Measure (%)
1	22.20	22.20	
2	22.00	22.10	0.45
3	22.40	22.20	0.45
4	23.00	22.40	0.89
5	23.20	22.56	0.71
6	22.00	22.47	0.42
7	22.80	22.51	0.21
8	22.40	22.50	0.06
9	22.20	22.47	0.15
10	23.60	22.58	0.50

Table 49. Movement times when using a short corridor in the analysis of *Validation test 4 – Stair experiment.*

Simulation	Movement Time (s)	Cumulative Mean (s)	Convergence Measure (%)
1	24.60	24.60	
2	25.00	24.80	0.81
3	24.80	24.80	0.00
4	26.20	25.15	1.39
5	26.00	25.32	0.67
6	25.00	25.27	0.21
7	25.20	25.26	0.04
8	24.00	25.10	0.63
9	23.60	24.93	0.67