Modelling Ascending Stair Evacuation

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Abstract
The thesis presents a basic validation study on the use of evacuation models for the simulation of ascending stair evacuation. The validation of the evacuation models is performed against a benchmark experiment consisting of a 50-floor ascending evacuation. The aim is to find which models – depending on the input calibration effort -can provide conforming results against the benchmark experiment regarding total evacuation time and walking speeds at each floor. This is performed by selecting five evacuation models for validation, representing different types of modelling assumptions. These models are then used to simulate ascending evacuation applying default settings and modified settings. The study indicates that models under consideration are not conservative when applying their default settings but models which have the possibility to alter the reducing speed factors per floor generally give better conforming results to the experimental results. The study also shows that the models estimation of the walked distance is a crucial factor.

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MODELLING ASCENDING STAIR EVACUATION

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Disclaimer

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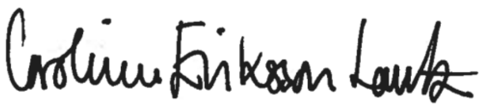

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Summary

Increased urbanisation leads to the construction of more and often complex underground facilities. This is to cope with an increasing demand of transportation facilities. Evacuation from underground facilities may imply that a long vertical distance have to be travelled by stairs in case of an emergency. In case of evacuation in long ascending stairs, it can be assumed that physical fatigue can influence the walking speed negatively.

The purpose of the thesis is to perform a simple validation study of an ascending evacuation scenario in long stairs using a full scale experiment as benchmark. The validation focuses on the total evacuation time and the simulated walking speeds. The objective is to quantify the possible differences in total evacuation time and walking speed between five selected models and a benchmark evacuation experiment.

The models selected for validation are EXIT89, FDS+Evac, Pathfinder, Simulex and STEPS. Three different input configurations are applied to the models to see the possible change in total evacuation time and walking speed per five floors in relation to the degree of user effort in the input calibration phase. The configurations are; default settings, applied reducing speed factors and a modified distribution of the initial walking speed.

The level of decreasing speed per five floors is presented as a factor. The factor is determined by calculating the percental decrease in walking speed every five floors from data given in the benchmark experiment. The factors of reducing speed are used to apply the reduction of speed per five floors to the models for possible better conforming results with the benchmark evacuation experiment.

With default settings all models underestimate the total evacuation time which do not give conservative results. *Simulex* is the model with the better conforming results with default settings with the occupant characteristics 'commuters' and 'HK commuters' (0.8 % and 5.5 % difference) but do not support the application of reducing speed factors. *EXIT89* provide underestimated walking speeds with both available modes, normal and emergency mode (64.0 % and 71.5 % difference). The models with the possibility to apply factors of reducing speed in general show the better conforming results, this is *FDS+Evac* (2.9 % difference), *Pathfinder* (5.6 % difference) and *STEPS* (0.8 % difference). Default walking speed distribution with uniformly distributed reducing speed factors (same speed reducing factor on horizontal parts and stairs) gives the better conforming total evacuation time with the benchmark experiment.

The comparison of walking speed per five floors is performed with FDS+Evac and STEPS. The resulting walking speeds within this study should be seen as an indication that the walking speeds can be estimated near the actual walking speeds, but that they are not absolute. As the models are not deviating much from the total time of evacuation the walking speeds results should be more similar than found. For example STEPS provides the total distance walked for each run with an estimated average distance of 240 m. Comparing this distance to the calculated distance of the benchmark experiment which is 375 m it is more than 30 % difference. This

indicates that of the two parameters walking speed depends on, time and distance, time is the easiest parameter to define while the distance may be difficult to estimate.

The validation study indicates that the vertical distance should be determining for decelerating walking speed and indirectly fatigue. The calculated distance walked within STEPS is roughly 30 % shorter than calculated within the benchmark experiment. Due to the large divergence in walked distance between the two ascending evacuations, the models assumptions affecting the travelled distance should be thoroughly considered when using the model as it will affect walking speed and thus the total evacuation time.

The models validated within this thesis are not recommended for simulation of ascending stair evacuation with their default settings. The models with the possibility to apply reducing speed factors, FDS+Evac, Pathfinder and STEPS, could be used for simulation of approximately 50 floor ascending stair evacuation with considerable user input. To use the models for simulation of other vertical distances further studies should be performed to validate the models reliability.

Sammanfattning

Ökad urbanisering leder till byggandet av fler och ofta komplexa underjordiska anläggningar. Detta för att klara av en ökande efterfrågan på transportmöjligheter i form av exempelvis stationer för tåg och tunnelbana. Evakuering från underjordiska anläggningar kan innebära att personer måste förlyttas en lång vertikal sträcka uppåt via trappor i händelse av en nödsituation. Vid evakuering via långa uppåtgående trappor kan det antas att fysisk trötthet påverkar gånghastigheten negativt.

Syftet med uppsatsen är att utföra en enkel valideringsstudie av ett evakueringsscenario uppför långa trappor med hjälp av ett fullskaligt evakuerinsexperiment som referens. Valideringen fokuserar på den totala evakueringstiden och gånghastigheter. Målet är att kvantifiera de eventuella skillnaderna i total evakueringstid och gånghastighet mellan fem utvalda evakueringsmodeller och en studie av ett evakueringsexperiment.

De modeller som valts ut för validering är EXIT89, FDS + Evac, Pathfinder, Simulex och STEPS. Tre olika konfigurationer tillämpas inom modellerna för att se eventuella förändringar i total evakueringstid och gånghastighet per fem våningar. Nödvändiga förkunskaper, antaganden och inmatning av parametrar och data som krävs av användaren för att ge tillförlitliga resultat gentemot referensexperimentet har tagits hänsyn till. Detta för att bestämma modellernas tillförlitlighet. Desto mindre förkunskaper som krävs för att ge tillförlitliga resultat, desto mer trovärdig är modellen. De tre konfigurationerna är; modellernas standardinställningar, adderade och en modifierad fördelning av den ursprungliga gånghastigheten.

Den minskande hastigheten per fem våningar presenteras som en faktor, reduktionshastighetsfaktor. Koefficienten bestäms genom att beräkna procentuell minskning av gånghastighet var femte våning utifrån data tillgängligt i publikationen av referensexperimentet. Faktorer för minskad gånghastighet används för att tillämpa minskningen av hastigheten per fem våningar i modellerna och på så sätt eventuellt få bättre resultat gentemot referensexperimentet.

Med standardinställningarna underskattar samtliga modeller den totala utrymningstiden vilket inte ger konservativa resultat. *Simulex* ger bättre överensstämmande resultat med standardinställningarna och med personegenskaper valda till "commuter" (pendlare) och "HK commuter" (Hong Kong pendlare) vilket ger 0.8 % och 5.5 % skillnad. Simulex stöder dock inte tillämpning av reduktionshastighetsfaktorer. *EXIT89* underskattar totala evakueringstiden med båda tillgängliga inställningar, normal och nödläge (64.0 % och 71.5 % skillnad). Modellerna med möjlighet att tillämpa faktorer för att minska hastigheten visar i allmänhet bättre överensstämmande resultat, dessa modeller är *FDS + Evac* (2.9 % skillnad), *Pathfinder* (5.6 % skillnad) och *STEPS* (0.8 % skillnad). Standardfördelningen för gånghastighet med jämnt fördelade reduktionshastighetsfaktorer (samma hastighetsreducerande faktor på horisontella plan och i trappor) överensstämmer bättre med total evakuering tid gentemot referensexperimentet.

Jämförelsen av gånghastighet per fem våningar är gjord för FDS + Evac och STEPS. Gånghastigheter funna i denna studie kan ses som en indikation på att gånghastigheter kan uppskattas nära den faktiska gånghastigheten, men att de inte är absoluta. Eftersom modellerna

inte avviker mycket från den totala evakueringstiden bör resultaten för gånghastigheterna vara bättre överrensstämmande än vad som konstaterats i denna studie. STEPS beräknar till exempel den totala gångsträckan till ca 240 m. Denna sträcka kan jämföras med den beräknade sträckan i referensexperiment som är beräknad till 375 m, vilket är mer än 30 % skillnad. Detta indikerar att av de två parametrar gånghastigheten beror på, tid och sträcka, är tid den parametern som är lättast att definiera medan sträckan kan vara betydligt svårare att uppskatta.

Denna valideringsstudie visar att det vertikala avståndet bör vara avgörande för reduktionshastighetsfaktorer och indirekt tillämpning av fysisk trötthet vid gång uppfär trappor. Den beräknade sträckan inom STEPS är ungefär 30 % kortare än beräknat inom referensexperimentet. På grund av den stora skillnaden i uppmätt sträcka mellan de två evakueringarna bör antaganden inom modellerna som påverkar sträckan noga övervägas vid användande av modellen. Detta eftersom antagandena påverkar sträcka och gånghastighet och därmed den totala evakueringstiden.

Modellerna som validerats i denna avhandling rekommenderas inte för simulering av uppåtgående evakuering 50 våningar via trappa med standardinställningar. Modellerna med möjlighet att tillämpa reduktionshastighetsfaktorer, FDS + Evac, Pathfinder och STEPS, kan användas för simulering av evakuering uppför trappor cirka 50 våningar men där betydande förkunskaper krävs hos användaren. För att använda modellerna för simulering av andra vertikala sträckor bör studier utföras för att validera modellernas tillförlitlighet och för att fastställa hur reduktionshastighetsfaktorer beror av trappans vertikala sträcka.

Acronyms

BRE — *Building Research Establishment:* an UK independent and impartial, research-based consultancy, testing and training organisation in the built environment and associated industries.

CFAST — *Consolidated Model of Fire and Smoke Transport*: a two-zone fire model used to calculate the evolving distribution of smoke, fire gases and temperature throughout compartments of a building during a fire.

FDS — *Fire Dynamics Simulators:* a computational fluid dynamics model of fire-driven fluid flow with an emphasis on smoke and heat transport from fires.

FDS+Evac — The evacuation simulation module for Fire Dynamics Simulator. The programme model the movement of people in evacuation situations.

SFPE — *Society of Fire Protection Engineers:* a global professional society representing those practicing the field of fire protection engineering.

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1. INTRODUCTION

Increased urbanisation leads to the construction of more and often complex underground facilities. This is to cope with an increasing demand of transportation facilities. With a large number of passengers travelling underground train stations, the complexity of safe evacuations is greater and the demand for understanding effectiveness of ascending evacuation in these types of facilities increases. Evacuation from underground facilities may imply that a long vertical distance have to be travelled by stairs in case of an emergency. For evacuation in ascending long stairs it can be assumed that physical fatigue can influence the walking speed negatively and also affect the behaviour of the occupants evacuating. The current knowledge of ascending evacuation by stairs is limited and has been given little attention in research (Norén, et al., 2014). As a result a research project was initiated in 2013 in Sweden by Lund University, Briab – Brand & Riskingenjörerna AB and DeBrand Sverige AB. The purpose of this project is to study the potential effects of fatigue and physical exhaustion on the walking speed and behaviour. This knowledge is intended to increase the reliability of future evacuation assessments.

When designing the evacuation of facilities, evacuation models can be used within the context of a performance-based design approach (Society of Fire Protection Engineers, 2007). These models are developed with different assumptions which affect its appropriateness in simulating ascending stair evacuation. Similar to the knowledge in evacuation walking speeds that is often based on studies on descending evacuation, stair movement in evacuation models is generally represented using data-sets retrieved from descending evacuation.

This thesis is aiming to do a basic validation study of a set of evacuation models for ascending stair evacuation. The aim is to increase the understanding within the ascending evacuation modelling area and get an indication on how accurately the models can simulate walking speed in long stairs. To be able to model ascending stair evacuation properly and produce conservative results it is important to account for i.e. reduction of speed due to fatigue.

A publication studying walking speeds in long ascending stairs was published by Choi, Galea and Hong in 2014. This study will be used as benchmark data when comparing the evacuation models ability and correctness to simulate appropriate walking speeds.

This thesis is the final part of the International Master of Science in Fire Safety Engineering. It is written at Lund University with supervision from Enrico Ronchi, associate senior lecturer at the Department of Fire Safety Engineering at Lund University and external supervision from Johan Norén, technical director at Briab – Brand & Riskingenjörerna AB.

1.1. Purpose and objectives

The purpose of the thesis is to perform a limited validation study of an ascending evacuation scenario in long stairs using a full scale experiment as benchmark. The validation focuses on the total time of evacuation and the walking speed. The overall purpose is to get an initial understanding of the current limitations of modelling the total ascending evacuation movement in long stairs, and the models ability to simulate or predict the walking speed and thus the influence of fatigue on the walking speed.

The objective of this thesis is to select five evacuation models, based on a review and evaluation of ten models which are considered amongst the most well-known and used. The objective is then to quantify the possible differences in total evacuation time and walking speed between the selected models and the benchmark evacuation experiment. Other than quantifying the models possible differences from the benchmark experiment, the objective is to provide a basic comparison of the possibility to model the total evacuation and walking speed between the validated models.

The thesis is intended for those interested in how a selection of currently available evacuation models simulate the whole evacuation process and walking speed of long ascending stairs.

1.2. Background

Two recognised sources regarding evacuation and walking speeds are among others Fruin and Predtechenskii & Milinskii, who both published their research in the 70ies. Fruin published 'Pedestrian Planning and Design' (1971) and Predtechenskii & Milinskii published 'Planning for foot traffic flow in buildings' (1978).

Existing research regarding stair evacuation is mainly focusing on descending evacuation from buildings above ground (Kuligowski, et al., 2014). Research on ascending stair evacuation is limited, and in particular research regarding longer distances (Kretz, et al., 2008). Due to this, knowledge in ascending stair evacuation is commonly retrieved from descending stair evacuation and the publications of Fruin and Predtechenskii and Milinskii.

It is expected that the workload to ascend a long stair would be greater than to ascend a short stair, and increase the longer the ascending is. Thus it is assumed that the behaviour of the occupants will differ. The effect of fatigue has been identified during evacuation in long ascending stairs and studies have showed that reduced walking speeds may be the effect of physical fatigue. When and to what extent physical fatigue can affect the walking speed is however not determined (Norén, et al., 2014). As a result of the scarcity of data on ascending stair evacuation a two year research project was initiated in Sweden in 2013 and the final report will be published in September 2015.

Within the research field that in general have scarcely available data, publications are increasing. Beyond the Swedish research project, Choi, Galea and Hong published a study in 2013 (Choi, et al., 2014) with data on a full scale experiment in ascending stairs which is an opportunity for a benchmark for comparison of walking speeds and total evacuation time. The report will be used as a benchmark experiment for validation of evacuation models within this thesis.

1.3. Limitations

The limitations of the project are as follows.

Solely the ascending direction is considered. The movement on stairs is solely ascending i.e. no counter-flows are considered nor walking in descending direction or merging flows.

The results of individual total evacuation times and walking speed every five floors are considered within the validation study.

An evaluation of ten models, with information from relevant sources (Ronchi & Kinsey, 2011), who are considered among the most commonly used is the basis for the selection of the five models to be validated against the benchmark experiment. The criteria when choosing which evacuation models to use are accessibility of the software, its model structure and available time within the project.

The case study includes only one individual participating at a time. Thus the case of evacuation has a constant low density. Density can figure as a defining factor of the calculated impeded walking speed in some evacuation models. This results in calculations in which only the unimpeded walking speeds are considered (i.e., density is not a limiting factor).

Geometry cannot always be represented in evacuation models exactly as in the full scale experiment. The geometry is sometimes modified in line with the assumptions of the model in terms of space representation. When possible, the same configuration as in the full scale experiment will be used when representing the geometry in evacuation models.

The data available from the benchmark experiment are solely from the published report (Choi, et al., 2014). Despite being a primary source the data available within the report is mainly presented as average values and thus no exact values are available. The data used for calculation of walking speed etc. are visual estimates from graphs within the report.

The validation is performed against a single benchmark study. Having limited experimental data is common regarding human behaviour in fire and no exception in this case (Ronchi, et al., 2013). Access to one evacuation experiment will represent only one example of a distribution of outcomes that might occur during this specific case.

The collection of evacuation experimental data may contribute to subsequent uncertainty given the techniques adopted to collect the data (Ronchi, et al., 2013).

In the present work, the number of multiple runs for each modelled scenario is depending on the convergence of results of total evacuation time based on an acceptance criterion of 5 % of ten consecutive runs.

All possible scenarios given the available properties within each model are not simulated. The consecutive modelled scenarios are selected on assumptions which aim to rationally cover the scenarios concerned within the thesis and that are available, and within the properties of each model.

2. THEORY

This part explains some of the current theories used in evacuation models. It presents a set of information which is selected to explain the necessary background in evacuation modelling to the reader. First there is a brief description of the different ways models can be followed by methods for validation of evacuation models. The different assumptions for space representation in evacuation models are presented as well as how the perspective of the model, global or local perspective, affects the modelling. How route choice is solved is described briefly and last, which behaviours and movement models to represent walking speeds can affect evacuation results.

2.1. Model availability

Models may be designed for a specific set of infrastructures. When deciding on which model to use for a scenario the models with an aligning purpose can preferably be selected amongst.

An easily available model may be used more often or have a wider range of users. The availability of models is an element which affects the selection of models for validation within this study despite it being undesirable.

Evacuation models are available to the public in three different ways. A few models are freely available, other models are proprietary and used only on a consultancy basis while the majority of models are available against a fee, either at a yearly rate or a one-time fee (Kuligowski, et al., 2014).

The model sources are either open source or closed source. The open source models provide the complete set of equations and assumptions of the model while the closed source does not.

2.2. Model validation methods

The model validation will be a quantitative comparison with an evacuation experimental study of a 50 floor residential building. The described model assessment is used to evaluate the evacuation models quantitative predictive capabilities in this specific evacuation scenario. By knowing the total evacuation time, average walking speed and walking speed at every five floors the assessment of the models for this specific scenario is possible. The validation will be performed by applying the methodology of blind calculations and later the method of open calculations (Lord, et al., 2005).

The input required for blind calculations are basic descriptions of the modelled scenario including information on the geometry of the structure and the type of structure. Other details necessary to simulate the scenario are up to the user to define. This will illustrate the comparability of models with their default settings and also test the model user's ability to use appropriate input data.

In an open calculation the required input description is more extensive. Descriptions on the geometry of the structure, occupant characteristics and numerical constants specific to the model and data from the benchmark evacuation study. Data on walking speeds and total time evacuation from the benchmark study is used to define factors applied within the scenarios to be modelled.

2.3. Model space representation

The way in which the evacuation model represents the geometry of a structure can have significant influence on the results of evacuation modelling (Lord, et al., 2005). The structures available amongst the models today are coarse network, fine network, continuous or hybrid models (Nilsson, 2007; Chooramun, et al., 2010). Differences in the representation of the geometry of coarse-, fine network and continuous models are shown in Figure 1. The hybrid models are at an initial stage of research and yet not applied and will not be further described.

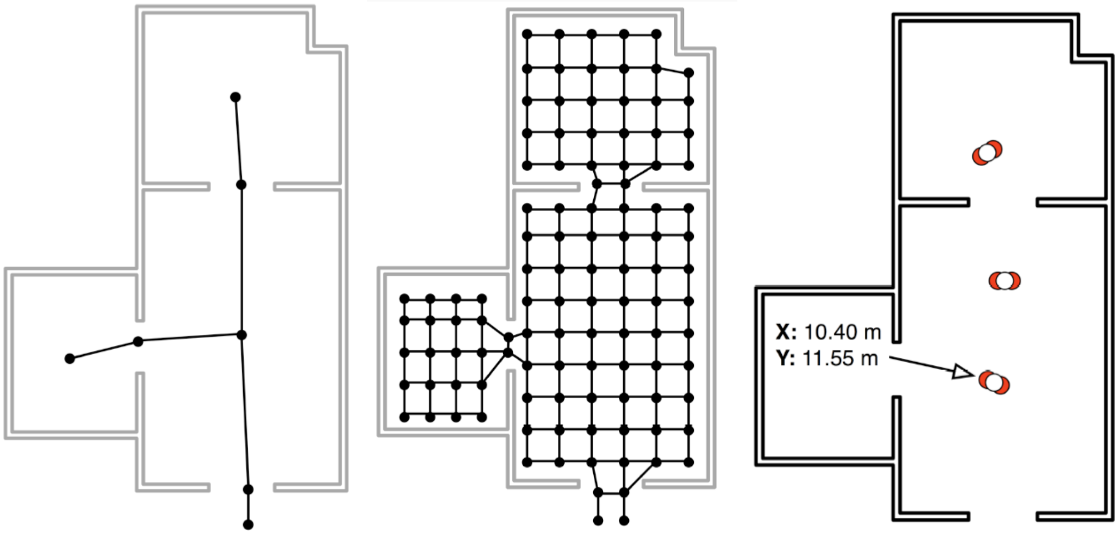

Figure 1. The same geometry rendered in (from left) a coarse network, fine network model and a continuous model, taken from Nilsson (2014) with permission.

2.3.1. Coarse network

Coarse network models represent the building's floor space with a network of nodes and arcs (see Figure 2). The occupants move between the nodes which are connected via links. Depending on the model or the user settings the capacity of each node can be restricted or non-restricted. The way stairs and doorways can be defined also depending on the model. In some models, they can either be defined directly while in other models they can be simulated by restricting the flow in these sections.

Advantages of coarse network models are that they generally have a lower computational cost and require less computational power than other models using different space representations. They are simpler to use but can be very user dependent. Coarse network models generally use more elementary calculations and are often deterministic (Nilsson, 2007).

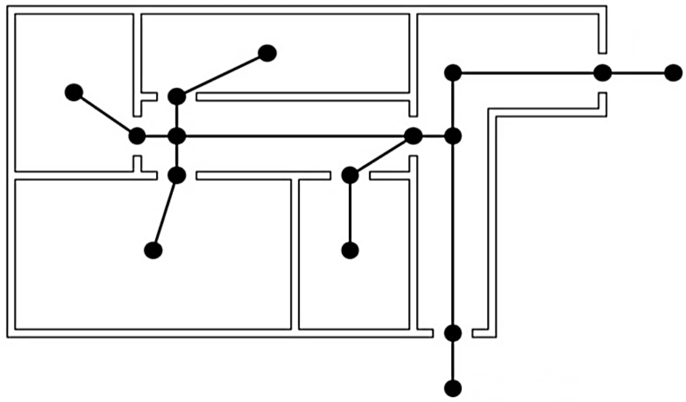

Figure 2. Example of a node network in a coarse network model, taken from Nilsson (2007) with permission.

2.3.2. Fine network

Fine network models represent the geometry with a grid consisting of uniform cells with one occupant per cell. The unoccupied cells surrounding the occupants' cell are the possible directions of movement. This is applied in the Moore neighbourhood assumption for instance which gives the occupant eight possible directions of movement. The cells admit an improved tracking of the occupant's location compared to coarse network models. Cell size can be used to alter the density in some models.

The occupants are represented as individual entities with the possibility to simulate local and global behavioural factors (Kuligowski, et al., 2014).

Stairs, doorways and elevators are used as connections between rooms and floors, and are functions available within the model. The way the geometry is constructed depends on the model. One way is that the cells in contact with walls or other obstacles are blocked.

Advantages of fine network models are that they are relatively quick to use and generally require less computational power. The disadvantage is that within fine network models the results often are depending on the assumptions regarding the grid (Nilsson, 2014).

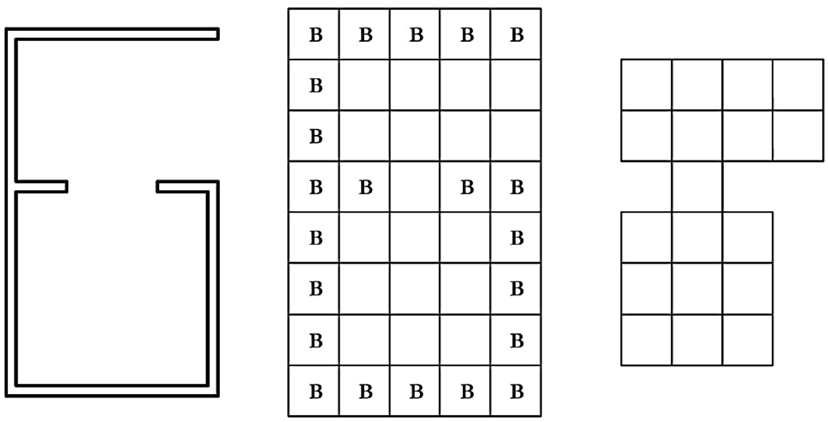

Figure 3. A room with examples of two ways fine network models create the geometry, by blocked cells (B) or without the cells, taken from Nilsson (2007) with permission.

2.3.3. Continuous

Continuous models represent the geometry in terms of coordinates where the agents can move in directions in a coordinate system. The differences in model structures are shown in Figure 1. The flexibility to simulate properties that otherwise may be sensitive to the occupants' locations is one of the important benefits of continuous models. Subsequently, models where walking speed depends on density a more precise position of the agents will provide a more accurate walking speed. Behavioural properties which depend on the accuracy of the location of the agent will also be improved.

Continuous models have the advantages of being more realistic and less user dependent than course- and fine network models. Subsequently disadvantages arise. Being more realistic come at a higher computational cost and being less user dependent means the models is more depending on its programming.

2.4. Model and occupant perspective

The model can have two different perspectives of the occupants and vice-versa, the occupants can have two different perspectives of the model (Kuligowski, et al., 2010). The perspectives are described here.

2.4.1. Model perspective

The model can view the occupants globally or individually. Viewing the occupants globally imply that the occupants are seen as a homogeneous group moving towards the exits. No distinction between each individual is made. An individual view of the occupants implies that the model tracks each individual during the simulation and provides information such as the position of the individual until the completion of the simulation.

The individual perspective of the occupants is more detailed then the global view. However it depends on the aim of the simulation which perspective is the most suitable. If not interested in the positioning of the individuals during the simulation the global view is sufficient (Kuligowski, 2005).

2.4.2. Occupant perspective

The occupants have two possible perspectives of the model, as the model perspectives, global and individual perspective.

With a global view the individual can recognise the shortest path from its current location to the final exit. This view is representative of individuals familiar with the premises. An individual view implies that the occupants are aware of the exit visible, given information at the floor or from personal experience.

With the shortest path option enabled in a global perspective the occupant will chose the shortest path to the final exit. With an individual perspective the shortest path to the exit of the room is chosen, despite it may be a longer route to the final exit (Kuligowski, 2005).

2.5. Behaviour

Given the scope of the project, behaviour and decision making are not included in the study. Despite models generally simulate walking speed and behavioural aspects, only the walking speed is considered. The settings regarding behaviour are based on the default settings of the models, e.g. on the people movement sub-model such as the social force model (Helbing & Molnár, 1995), steering behaviours (Reynolds, 1999), etc. Additional behavioural issues are not considered (e.g. social interactions, etc.).

2.6. Walking speed

Walking speed can be calculated in various ways. One of the main approaches is to set a base speed. The base speed can be set in terms of a distribution of a fixed value. The base speed is generally the unimpeded walking speed adapted after the person type. Depending on the scenario the speed is then modified in relation to inclination, density, obstacles, etc. A factor that affects ascending walking speed can often be set to influence the speed positively or negatively. The factors are implemented differently within the models.

3. METHODOLOGY

Ten of the most commonly used evacuation models within the fire safety industry are evaluated and five are chosen to be validated against the full-scale evacuation experiment (Ronchi & Kinsey, 2011).

The evaluation of the ten models is the basis for the decision of which five models are selected for simulation of the full-scale experiment.

The validation will be performed by testing the models correctness of evacuation in ascending stairs against the full-scale experiment. The defining measures are the total time of evacuation, average walking speed over the whole evacuation and walking speed measured at every five floors. The methodology applied is initially to perform blind calculations and later open calculations are performed to evaluate the predictive capabilities of the models with a higher level of input calibration effort.

3.1. Sources

Online search engines as well as information from the supervisors are used. Information on the evacuation models are primarily based on the documentation provided by the model developers. The information studied includes mainly scientific articles and publications and are both primary and secondary sources.

Search keywords used in the literature review are walking speed in stairs, speed up stairs, upward walking speed, stair evacuation, ascending evacuation and ascending stair evacuation.

3.2. Evacuation model review

There are over 60 available evacuation models on the market today (Evacmod.net, 2015). To be able to perform a small validation study within the available time period of the thesis, five models will be studied. The 60 available models will be narrowed down to ten to be reviewed and later to five models for the validation study.

The ten selected models are models of which the writer have heard, but have little knowledge. The ten models are assumed to represent the majority of properties available amongst today's evacuation models. The ten selected models will be reviewed and a coarse description of basic properties together with information on walking speed is summarised.

Based on the information retrieved in the model review, five models are selected for the validation study.

3.3. Evacuation model selection

An online survey about the use of evacuation models and their application fields was carried out in 2011 where users of evacuation models within the fire safety industry were the target group of responders (Ronchi & Kinsey, 2011). The results of the survey are partially the basis for the selection of evacuation models to be reviewed. Other factors counting when selecting the models for revive is the authors previous knowledge of the models. Preferably known models are chosen and the models should be representative of the majority of model properties available today.

When selecting the five models for validation the criteria are to preferably have models which are widely used, open sources models, have full model availability and a representation of all model structures.

3.4. Model validation method

The model validation will be a comparison with an evacuation experiment of a 50-floor residential building. The described assessment of the models is used to evaluate their quantitative predictability of use in this specific case of evacuation. By knowing the total evacuation time, average walking speed and walking speed at every five floors, the assessment of the models for this specific scenario is possible. The validation will be performed by applying the methodology of blind calculations and later the method of open calculations (Lord, et al., 2005). The blind calculation will be performed to compare the results of total evacuation time of the different models with default properties applied, against the experiment. The open calculations will be performed to test the impact of a more sophisticated input calibration effort and different configurations of the models properties. In addition to the total evacuation time the open calculations will be compared against the walking speed at every five floors. The input in the open calculations may be altered for the achievement of a better fit between the experimental observations and the data implemented in the models.

3.5. Modelling scenarios

Initially, when possible, the default configuration of the experiment is represented within the models. The default configurations are used for the blind calculations. In a second stage the possibility to model the total evacuation time and walking speeds that correspond to the decrease in walking speed at every five floors within the full-scale experiment is evaluated with a higher level of sophistication of input calibration (open calculations). To model the decrease in walking speed a set of factors corresponding to the decrease in walking speed are used. The walking speeds were measured within the benchmark experiment.

3.6. Uncertainty and convergence of results

Uncertainty modelling, in the fire safety engineering community in general, can be classified into three components. These are model input uncertainty, measurement uncertainty and intrinsic uncertainty (Hamins & McGrattan, 2007). Model input uncertainty is the uncertainty associated with parameters obtained from experiments the model assumptions are derived from. Measurement uncertainty is associated with the uncertainty of data collection techniques for experimental measurements. Intrinsic uncertainty is associated with the mathematical and physical assumptions of which the model is based on (Ronchi, et al., 2013). These uncertainties will not be further analysed but considered within the final results.

In evacuation modelling, an additional component of uncertainty is generally taken into consideration, namely behavioural uncertainty (Ronchi, et al., 2013). Behavioural uncertainty derives from the use of random sampling in the definition of modelling input (e.g. a Monte Carlo approach). Different methods are today available to study behavioural uncertainty, such as the method by Ronchi et al (Ronchi, et al., 2013) or the method by Lovreglio et al. (Lovreglio, et al., 2014).

Within the scope of this work the modelling behavioural uncertainty is studied in terms of convergence based acceptance criteria. The measured parameter is the total evacuation time (TET). The procedure is as follows.

The convergence measure is calculated using the total evacuation time (TET) (Ronchi, et al., 2013). TET_j corresponds to the total evacuation time of the *j*th run out of a total of *n* runs. The consecutive mean TET is TET_{avi} is the series of values converging to the expected mean TET. The arithmetic average of run j is denoted TET_{avj}. The convergence of two consecutive mean TETs, TET_{avj}, expressed in percentage, is obtained by calculating TET_{convj} according to equation 1.

$$TET_{convj} = \frac{TET_{avj} - TET_{avj-1}}{TET_{avj}} \qquad \text{(eq. 1)}$$

The final converged TET towards the expected mean TET of *n* number of runs is TET_{convj}. It is denoted $TET_{convFIN}$ and is calculated according to equation 2.

$$TET_{convFIN} = \frac{TET_{avp} - TET_{avp-1}}{TET_{avp}} \qquad \text{(eq. 2)}$$

Where p is $p = (n-1)TET_{convj}$.

In the present work, the assumption is that $TET_{convFIN}$ is reached when ten consecutive results diverge less than 5 % or at a minimum number of 20 runs.

4. BENCHMARK EXPERIMENT

The comparative study is between the results produced by a set of evacuation models and a full scale experiment. The full scale experiment is a study where ascending and descending walking speeds are measured in a high-rise building in South Korea (Choi, et al., 2013). The results from the ascending walking speeds will be considered.

4.1. Experimental method

The experiment was performed in the staircase of a 50 storey high-rise building. The horizontal walking speed of the participants was measured as they entered a corridor in the experimental building. The participants were unaware of this measurement.

One participant was studied at a time so they were walking throughout the stair during the experiment. The participants were recorded with video footage at each floor landing. The arrival time at each floor was considered when the participant stepped onto the floor landing. The trials consisted of two phases. The participants initially ascended the 50 floors and had at least a two hour rest before taking on the second part, descending the same route.

4.2. Geometry

The stairs connecting two floors consist of two flights of stairs with a half landing in between where all floors are identical. The geometry of the benchmark study is as follows.

Each of the stairs has nine treads with the riser being 0.172 m high, the tread 0.270 m deep and an inclination of 32.5°. The height between each floor is 3.100 m and the horizontal length of the stairs is 2.160 m with a clear width of the stairs of 1.530 m, as in Figure 4.

The length of the route the participants walk on each half flight is calculated by estimating the radius of the semicircle they are assumed to walk. The assumed route the participants walk is a virtual observation and is the basis for calculation of the distance walked. With a radius of 0.510 m half of the perimeter is $\pi r = \pi \cdot 0.510 = 1.602\,m$ and the inclined travel distance is $horizontal\ distance \cdot \sec\theta = 2.160 \cdot \sec 32.5° = 2.561\,m$. This gives a total travel distance of one floor of $2(1.602 + 2.561) = 8.33\,m$. However the total distance within the benchmark study is the sole horizontal distance, the longer vertical inclination is not considered, and thus the walking distance of a floor is defined as 7.51 m.

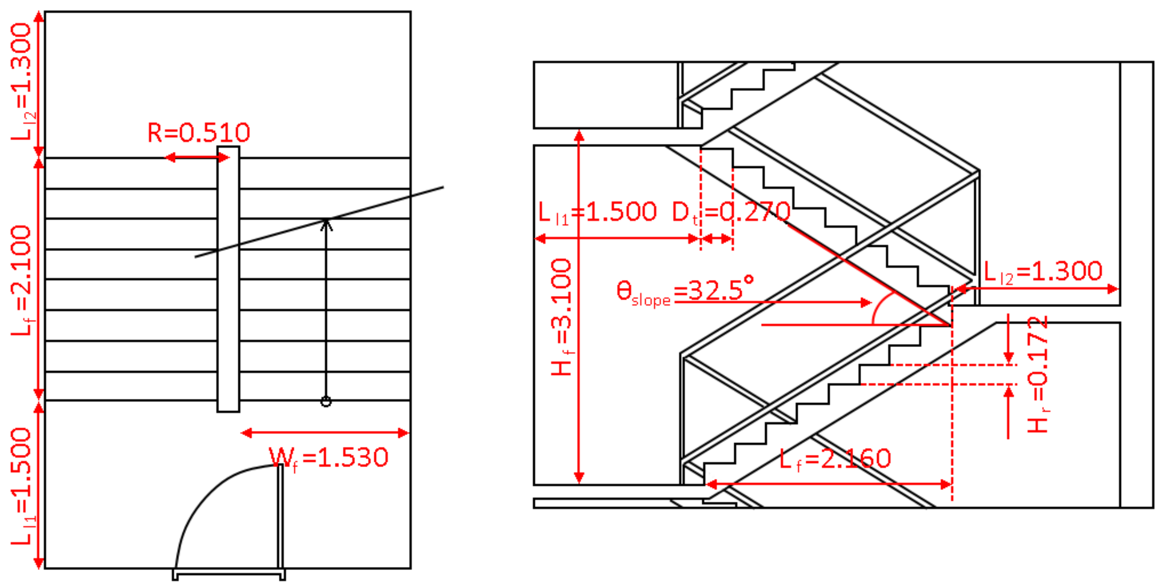

Figure 4. Geometry layout of the full scale experiment. Left: top view, right: side view. Image re-drawn based on Choi et al. (2014).

4.3. Participants

There were 60 participants within the experiment. Out of the 60 participants 30 were women and 30 were men. The age varied between 20 to 28 years with an average age of 23.4 years.

As only one participant is active throughout the simulation no settings regarding a group or population is required. The occupants' person type is kept as default or chosen to be "adult" as this setting is available within all models. The walking speeds of the occupants are altered according to the steps in section 3.4.

4.4. Benchmark experimental data

The average total evacuation time of the benchmark experiment is 730 s, 12.2 min. The average total evacuation time is the average of the average female (832 s, 13.9 min) and male ascending speeds (629 s, 10.5 min).

The data used for determining the factors of decreasing walking speed are visual estimations of the presented data of 'Individual male and female ascent stair walk speeds averaged over five floors' in the publication of the benchmark experiment (Choi, et al., 2014). The average walking speed per five floors, starting at floor five, is thus an average between the male and female average walking speeds presented in the mentioned publication. The initial walking speed is assumed to be the average between female and male ascending walking speeds of floor 1-2 derived within the benchmark experiment. These assumptions are made due to the available data within the publication referred to. The initial walking speed is given a speed factor of 1.0 with the speed factor changing every five floors. The estimated numbers as basis for the estimation of the reducing speed factors and the calculated speed factors are presented in Table 1. The resulting average walking speeds are presented in Figure 5.

Table 1. Calculation of decreasing speed factors.

Floors	Estimated average walking speed			Decreasing Speed Factor
	High	Low	Mean	
0-5	1,10	0,80	0,95	1,00
5-10	1,00	0,60	0,80	0,84
10-15	0,70	0,45	0,58	0,61
15-20	0,60	0,45	0,53	0,55
20-25	0,50	0,45	0,48	0,50
25-30	0,50	0,45	0,48	0,50
30-35	0,50	0,45	0,48	0,50
35-40	0,50	0,45	0,48	0,50
40-45	0,50	0,45	0,48	0,50
45-50	0,60	0,45	0,53	0,55

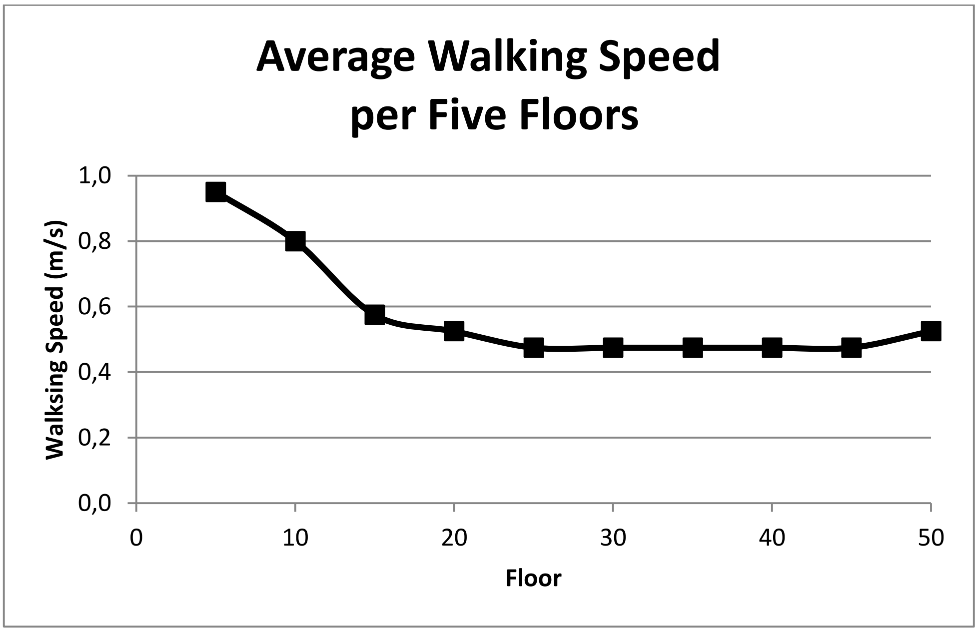

Figure 5. Estimated average walking speed per five floors of the benchmark experiment.

5. MODEL PROPERTIES

The properties of the models evaluated and the models selected for the validation study are compiled in this section. As described earlier the information is a selection of the full model description. The information on the models is concerning the scope of the thesis and includes information, if available, such as; model developers, availability, model structure, model perspective, limitations of the model, validation studies, governing equations and assumptions, walking speeds – calculations, occupants characteristics, distributions, use of fire data, delay times, merging flows, counter flow and smoke impact on humans (toxicity). The information on the models selected for validation is more comprehensive than the information on the models only reviewed. The review is intended to give an insight of the models properties while the models validated are more thoroughly examined to get the sufficient knowledge for performing simulations. The models are presented in alphabetic order.

5.1. EGRESS

EGRESS is developed by ESR Technology. The current model is version 5.4 and is available on consultancy basis. The model is a fine network model with a hexagonal grid.

The model has been designed to model evacuation from relatively large geometries. A selection of geometries where EGRESS is suitable according to its developers includes shopping malls, schools, sport stadiums and airports. High-rise buildings or vertical geometries are not mentioned. The model can simulate thousands of people and many square kilometres, however, the exact numbers are not given.

The route finding algorithm is the shortest path. Walking speed assumptions are based on the work of Predtechenskii and Milinskii and are a function of density. As default the average unimpeded walking speed is 0.9 m/s but it will vary with occupant density. Groups of occupants can be assigned a specific unimpeded walking speed as well as properties affecting their walking speed. The properties will percentally affect the unimpeded walking speed together with the density. Walking speeds and flows on walkways and stairs be manually set but is estimated by an algorithm by default. According to the developers the algorithm allows the model and its code to be used effectively as there are no requirements of the user to estimate or assume reductions in walking speed up and down stairs. EGRESS provides the possibility to impose additional reductions in speed on stairways by assigning slowdown regions. It is suggested that an appropriate slowdown factor is approximately 30%, which is according to the work of Fruin.

Occupants can be assigned itineraries of objectives the occupant will try to reach. The itinerary can be used to model pre-movement, detection and reaction time. EGRESS includes movement through smoke and fire input. The model does not incorporate fire data or merging flows but a collision rule is used. (Ketchell, 2006)

5.2. EXIT 89

EXIT89 is a coarse network model developed by Dr Fahy at the National Fire Protection Association (Fahy, 1994). Its intended use is to model evacuation time from high rise buildings and is considered a research model (Ronchi, 2014). The model is available from its developer.

The model can handle an occupant population of up to 700 people and each floor can have up to 89 nodes/building spaces and a maximum of 10 staircases. Fire input can be retrieved from CFAST (Jones, et al., 2009). The model accounts for occupants travelling up or down stairs (International Organization for Standardization, 2011).

EXIT89 uses a shortest route algorithm or directed paths can be set by the user to move occupants. The occupants have a local perspective of the building and will, once entered a staircase, follow it until its exit and from there find the shortest path towards the final exit. The calculation of total evacuation time is calculated based on the distance travelled to the final exit and the occupants walking speed.

The model handles two different conditions, namely normal and emergency conditions. Three types of occupant characteristics are available. These characteristics will generate different walking speeds. The occupant characteristics are taken from the book 'Planning for foot traffic flow in buildings' by Predtechenskii and Milinskii (1978).

EXIT89 calculates walking speed based on the equations of Predtechenskii & Milinskii (1978). Density at building nodes or building spaces together with the occupant characteristics are the steering factors when calculating walking speed. Predtechenskii and Milinskii defined, amongst other, the movement for horizontal paths and ascending stairs. The walking speed calculations are based on crowd densities. The calculations are defined by equations A1-A6 in APPENDIX A.

The maximum possible calculated walking speed under "emergency" conditions is 1.36 m/s and under "normal" conditions 0.91 m/s. The minimum possible calculated walking speeds are 0.18 m/s and 0.15 m/s, respectively.

Other available functions are counter-flows, delay times and reaction to smoke. Human behaviour is not explicitly considered. Delay times for individuals or occupant groups can be applied to simulate detection- and reaction time. Distributions available are log-normal and uniform distributions. The user can set the properties of the distributions and these can be used for simulation of delay times.

It is documented that EXIT89 provides reasonable accurate predictions of the total evacuation time of 6-15 story residential and office buildings. It is also documented that the model may under predict total evacuation times if prior knowledge of the occupant load is not provided and that the model is sensitive to the number of occupants as well as their size (Fahy, 1994).

5.3. FDS+Evac

FDS+Evac is the evacuation module of the Fire Dynamics Simulator (FDS) which combines fire scenario simulations with evacuation simulations. The model is continuous and the version considered is 2.1.1 which is embedded in FDS 5.3.0. The model is developed at VTT Technical Research Centre of Finland and is freely available as FDS.

FDS+Evac is best suited for modelling geometries of buildings with mainly horizontal surfaces and simulations in inclined geometries have not yet been validated. It is recommended that the user not change any of the optional parameters but the occupant characteristics and detection-, reaction- and pre-movement time distributions.

The model has ten available distributions. These are constant speed, uniform, truncated normal, gamma, normal, log-normal, beta, triangular, Weibull, exponential and gumbel all of which can be implemented by the user. The movement algorithm used is the social force model (Helbing & Molnár, 1995) and FDS+Evac does not explicitly simulate merging flows on stairs. Other available functions are counter flow, reaction to smoke and fire data input.

The model has an individual view of the occupants. Occupants are assigned properties such as adult women, adult men, children and elderly. Within each group walking speeds are uniformly distributed within the intervals given in

Table 2. Walking speeds in stairs are manually set. The staircase algorithm is identical for ascending and descending stairs which infer that the speed reduction factors are a user input. The user applies speed reduction parameter, *k*, either for walking up or down stairs.

Table 2. Walking speeds for different occupant types in FDS+Evac (Korhonen & Hostikka, 2009).

Occupant type	Unimpeded walking speed (m/s)	+/-	Lower range	Highest range
Adult	1.3	0.3	1.0	1.6
Male	1.4	0.2	1.2	1.6
Female	1.2	0.2	1.0	1.4
Child	0.9	0.3	0.6	1.2
Elderly	0.8	0.3	0.5	1.1

The walking speeds of the occupants are calculated using the equation of movement within FDS+Evac (i.e. Helbing's social force model). The movement equation is

$$m_i \cdot \frac{d^2 x_i(t)}{dt^2} = f_i(t) + \xi_i(t)$$ (eq. 3)

where:

$x_i(t)$ is the position of the occupant *i* at the time *t*

$f_i(t)$ is the surrounding forces acting on the occupant

m_i is the mass

$\xi_i(t)$ is a small random fluctuation force.

And the walking speed is

$$v_i(t) = \frac{dx_i}{dt}$$ (eq. 4).

(Korhonen & Hostikka, 2009)

5.4. Gridflow

Gridflow is a continuous research model developed at BRE and is available on a consultancy basis. The model has been developed and is able to model design cases today. It can be used for various types of building spaces and elements.

The occupants are represented as individuals and uses distance maps for calculation of distances within the geometry. Both the shortest route option and conditional route are available. The model incorporates pre-movement time which can be given with a distribution or an explicit value. Normal, log-normal and Weibull distributions are available. Counter flow, merging flows and smoke (toxicity) and other factors considered. The default occupant movement is using the shortest route option but specific or random choices can also be specified by the user.

The walking speeds can be set manually to an occupant, a group and a region, or to default values. As default, the walking speeds of the occupants are distributed by normal distribution and are depending on people density. The mean unimpeded walking speed is a distribution with an average walking speed of 1.19 m/s. The unimpeded walking speed can also be assigned a specific value. User defined groups with different properties can be assigned, such as women, men and elderly. Walking speeds can also be assigned regions, such as stairs, to reflect the slower travel speeds through these types of elements. (Bensilum & Purser, n.d.)

5.5. Legion

The model uses a continuous modelling approach and it is developed by Legion Limited. It can model all types of buildings and is available against a fee.

The model can use both the shortest route option and conditional route and has an individual view of the occupants. Counter-flows, smoke and fire data can be simulated.

The walking speeds are depending on the type of occupant/entity and the people density. Different speed profiles are available for application to the occupants. Each occupant has an assigned size and walking speed with possibility to manually set the speed with a maximum walking speed of 1.7 m/s. The walking speed can be altered to represent walking in stairs by adding routing objects or to customise the unimpeded walking speed. Speed can be manually modified for different areas, a drift zone, and is a reduction of speed in percent. (Legion International Limited, 2013)

5.6. MassMotion

MassMotion 6.0 is a continuous model provided by Oasys Software Limited and can be used for mass transit stations, stadiums, airports and schools etc. It is available on a consultancy basis and it costs a fee.

The model has an individual perspective of the occupants, includes delay and pre-movement times, and incorporates counter flows but do not use smoke or fire input.

MassMotion uses a social force model which affects the unimpeded walking speed. The initial walking speeds are depending on the occupant type defined and the distribution can be manually set. The model provides six different distributions; constant, uniform, normal, triangular, log normal and exponential.

Walking speeds on stairs are a percentage of the unimpeded horizontal walking speeds. The reduction in speed is depending on the slope of the stairs and is presented in Table 3. The occupants can be set to choose the shortest route or have global knowledge on the building. The route selection is conditional and depends on the information provided to the occupant.

MassMotion has been validated for stairs and basic pedestrian movement against the data of Fruin (1971). (Oasys Software Limited, 2014)

Table 3. Walking speeds on stairs in MassMotion (Oasys Software Limited, 2014).

Direction of travel	Angle X (degrees)	Percentage of natural speed
Up	27 ≤ X ≤ 32	Interpolated between 42.6 and 37.8
Up	32 < X	37.8
Down	0 < X < 27	57.4
Down	27 ≤ X ≤ 32	Interpolated between 57.4 and 49.8
Down	32 < X	49.8

5.7. Pathfinder

Pathfinder is a continuous model with a triangular mesh representation, developed by Thunderhead Engineering. The current version is Pathfinder 2014 and is available against a fee. Its use is not restricted to any specific types of buildings.

The model incorporates counter-flows, delay times and fire input and has an individual perspective of the occupants. The occupants have a local view of the model and will choose the shortest route to the exit of the space currently located in.

Pathfinder has two different modes to choose from when simulating. One is SFPE mode and the other one is Steering mode. The velocity is calculated in the same way except for in steering mode the density in constant and set to 0 while in SFPE mode the velocity is calculated through equation 11 or equation 12 depending on the density.

To summarise the walking speed in Pathfinder depends on the density, the maximum speed of the occupant and the evacuation speed constant. The walking speed distributions available are constant, uniform, standard normal and log normal.

The base speed is assigned to the occupants and is then depending density conditions, if containing multiple occupants. The governing density (D) is 0.55 pers/m^2. The following equations give the base speeds of the SFPE mode:

$$v(D) = v_{max} * \frac{0.85*k}{1,19}, \mathrm{D} < 0.55\ \mathrm{per}/m^2 \qquad \text{(eq. 5)}$$

and

$$v(D) = v_{max} * \frac{k-0.266*k*D}{1.19}, D \geq 0.55 \qquad \text{(eq. 6)}$$

Where k is the evacuation speed constant which depends on the type of terrain being travelled. For stairs, k is changing with the inclination of the stairs as in .

Table 4. A speed modifier is used to alter the speed at different locations. The maximum walking speed has a speed modifier of 1,0 and it is then reduced for walking speed in stairs depending on its inclination (Thunderhead Engineering, 2014).

Table 4. The evacuation speed constant (*k*) in Pathfinder is specific for stairs and depends on the inclination of the stair (Thunderhead Engineering, 2014).

Stair Riser (inches)	Stair Riser (cm)	Stair Tread (inches)	Stair Tread (cm)	*k*
7.5	19.0	10.0	25.4	1.00
7.0	17.8	11.0	27.9	1.08
6.5	16.5	12.0	30.5	1.16
6.5	16.5	13.0	33.0	1.23

5.8. Simulex

Simulex is a continuous model developed by Dr Thompson at the University of Edinburgh and then validated by Lund University. It is provided by Integrated Environmental Solutions Limited (IES) against a fee.

The model does not consider merging flows on stairs, counter flow on stairs and its commercial version does not allow importing fire data and thus do not consider smoke as an obstructive parameter. The model can simulate delay times and has an in individual perspective of the occupants.

Each occupant is assigned a normal unimpeded walking speed. The default unimpeded walking speed is assigned to occupants randomly between the speeds 0.8-1.7 m/s. This walking speed is then depending on the inter-person distance. Walking speed is depending on the inter-person distance according to Figure 6 which illustrates a maximum walking speed of 1.4 m/s. Thus there are two maximum walking speeds namely, 1.7 m/s according to the Simulex User Guide, and 1.4 m/s according to Figure 6. Walking speed on stairs is reduced to fixed fractions of the unimpeded walking speed. Ascending stair movement is 0.35 times the horizontal movement and descending stair movement is 0.5 times the horizontal movement.

Inputs which the user can modify are the occupant type e.g. office staff, commuters, male, female, children, etc., different distance maps can be applied and the occupants initial position can be assigned manually. A response time can be set with a random-, triangular- or a normal distribution. This can be used as a combination of reaction time and pre-movement time.

Different profiles (32) are available for application as occupant characteristics. The type of characteristics applied will affect the body size and the distribution of the type of occupants within a group as well as the occupants' maximum individual velocity. The exact properties of the different characteristics are not explicitly given in the manual, but are available in the model. (Integrated Environmental Solutions Ltd., n.d.)

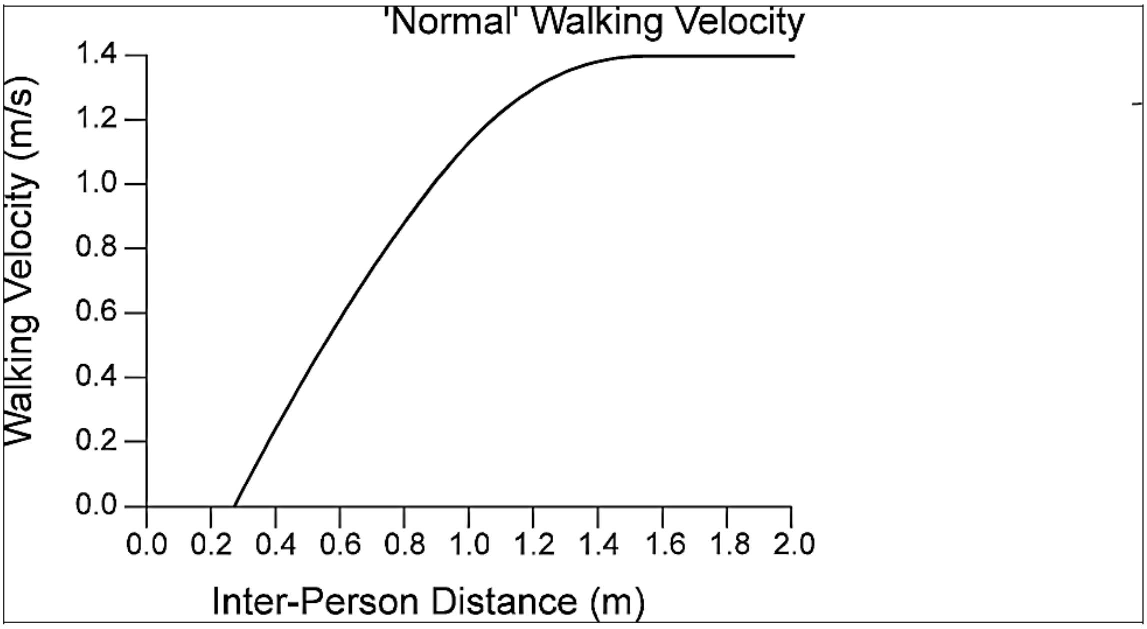

Figure 6. Graph of walking speed versus inter-person distance of Simulex (Integrated Environmental Solutions Ltd., n.d.).

5.9. STEPS

STEPS is a fine network model developed by Mott Macdonald, UK. It is available against a fee. It is designed to simulate evacuation from any type of building.

As STEPS is a fine network model it is also grid based which assumes that the occupants are the same size as the grid cells, i.e. one occupant occupies one grid cell. This entails that small changes in geometry or building dimensions will not affect the evacuation time and travel speeds are not automatically depending on density (Lord, et al., 2005). STEPS can import fire and smoke files from CFAST (Jones, et al., 2009).

Two different modes are available within STEPS; normal mode and evacuation mode. Normal mode is used to track movement pattern of a large population where the occupants can have assigned aims to fulfil before or during their walk to the assigned destination. In evacuation mode a local view of the model is applied. The occupants make their way to the nearest exit which they know about and that is available for evacuation and will only reach the final system exit when the occupant have reached a position where a system exit is available. The reason for the applied local view of the model is according to the user manual "…if someone is to evacuate from a building he knows very well, he can only have a good idea of the shortest route that can get him out but he cannot be aware of possible events that may slow down people along this route or block it altogether." (Mott MacDonald, 2014)

Stairs can be modelled in two ways, with a staircase function or as an inclined floor. With the stair function occupants cannot overtake others in the stairs. The model does not take physical or physiological aspects into consideration (Pelechano & Malkawi, 2008).

The people types used in this model make use of distributions with the Fruin distribution as default.

The walking speed algorithms based on the walking speeds of SFPE. Each people type has an assigned maximum walking speed and the possibility to further specify the walking speed. There are several ways to specify the maximum walking speed of a person.

- Fixed walking speed, the walking speed can be manually set by the user. A fixed value in meters per second.
- Predefined speed distribution, the walking speeds of the occupants is set within the characteristics of the person. The maximum walking speed is defined through a Fruin distribution. It is a normal distribution with the following characteristics:
- User defined speed distributions; three further distributions are available for walking speeds; uniform, normal and log-normal distribution.

When the maximum speed or maximum speed distribution is defined, other parameters can be used to further specify how environmental effects affect the walking speed. The parameters are: the slope of the path or stairs, proximity or inter-person distance, local density, local factor as well as an additive local velocity and a velocity of movement within smoke. The equation for walking speed is

$$V= a_{slope} * a_{proximity} * a_{density} * a_{local} * V_{max} + V_{local} \qquad \text{(eq.13)}$$

To further conform the walking speeds to different scenarios three types of speed curves are available, these are

- speed/distance curve: the walking speed depends on the distance to the next person ahead,
- speed/density curve: the walking speed depends on the person density around and
- speed/smoke curve: the walking speed depends on the smoke concentration within the space.

The speed/density curve takes the inter-person distance into consideration. The walking speed varies between 0.0 m/s and 1.4 m/s depending on the inter-person distance with a higher walking speed the bigger the inter-person distance is. The possible shortest inter-person distance is 0.3 m as this is the body depth. The longest inter-person distance affecting the walking speed is 1.55 m, at this length the maximum walking speed of 1.4 m/s is reached. This relationship is shown in Figure 6.

If using the speed/density curve a multiplier is used to reduce the maximum walking speed depending on the density. The speed multiplier is retrieved according to

density <0.5	multiplier 1.0
0.54< density <3.8	linear interpolation
density >3.8	multiplier 0.0.

When working with speed/density curves assigned maximum speeds for walking in stairs and assigned local factors are available. The local factor is multiplied with the maximum walking speed of the occupant. Both the maximum speed and local factor is depending on the inclination of the stairs as defined in Table 5. (Mott MacDonald, 2014)

Table 5. Speed and local factors in STEPS depending on the stair inclination (Mott MacDonald, 2014).

Stair inclination (°)	Max speed (m/s)	Local factor
32,5	0,93	0,771
28,4	0,99	0,829
26,6	1,05	0,879

The default speed/smoke curve calculations are based on a Jin-Yamada relationship between smoke density and walking speed. (Mott MacDonald, 2014) The two curves available in the library are with non-irritant smoke and with irritant smoke (Jin & Yamada, 1985).

5.10. VISSIM/VISWALK

VISWALK is an add-on module to the traffic simulation program VISSIM. It is developed by the PTV Group (Planung und Transport Verkehr AG) and can be used to study pedestrian movement in situations such as train stations, traffic intersections and stadiums but is suitable for any type of building in general. It is a continuous model which is available on consultancy basis or against a fee.

The movement of the occupants is calculated using the social force model which affects the walking speed thorough the density. A higher density will give lower walking speeds and vice versa. The route choice can be a user setting. Static route, shortest route and quickest route options can be applied to the occupants (PTV AG, 2014).

VISWALK provides a number of distributions for the initial pedestrian walking speeds. By default uniform distributions are used but normal distributions are also available for selection. Both distributions can be modified by the user. Two occupant characteristics with predefined walking speed distributions are defined. One defined as male and one as female.

Walking speed on stairs is independent of the direction. The same reduction in speed is applied to the descending and ascending direction of movement by default. Local speed alterations can be applied to different parts of the stairs or throughout the stairs.

Delay times can be set with distributions and counter flows are considered. Fire and smoke input is not supported (Blomstrand Martén & Henningsson, 2014).

6. ANALYSIS

This section describes the selection of models for review and validation and later is a full description of the configuration of modelled scenarios presented.

6.1. Review of evacuation models

The selection of model to review was determined in discussion with the supervisor. The models are a representation of the most known evacuation model among the users of evacuation models (Ronchi & Kinsey, 2011). Other models selected were proposed by the supervisor, with extensive knowledge in the topic, to get a versatile selection of models to review. The models selected for further evaluation are

- EGRESS
- EXIT89
- FDS+Evac
- Legion
- MassMotion
- Pathfinder
- Simulex
- STEPS
- VISSIM/Wiswalk.

6.2. Evacuation model selection

The models selected for validation are all well known to the evacuation model users (Ronchi & Kinsey, 2011), except EXIT89 which is selected as a coarse network model. This selection represents each of the type of model space representation (coarse network, fine network and continuous). Given the criteria discussed above, the models selected are also available to the author through Lund University and Briab – Brand & Riskingenjörerna AB. Other models are available as demo versions or only during a trial period which is not consistent with the scope and the time period of the expected work of the thesis. The five models selected for validation are:

- EXIT89
- FDS+Evac
- Pathfinder
- Simulex
- STEPS

6.3. Factors of decreasing speed

The level of decreasing speed per five floors is presented as a factor. The factor is determined by calculating the percental decrease in walking speed every five floors from data given in the benchmark experiment. The data given is the average walking speed for female and male participants at every five floors. The average speed of floor five is the average walking speed between floor 0 and to the arrival at floor five. The average walking speed of floor ten is the average walking speed from floor five to the arrival at floor ten etc. The factor is averaged between female and male participants. It is assumed that the speed of floor 0-5 is factor 1.0 and the succeeding factors are based on this as an initial walking speed. The factors of decreasing speed are presented in Table 6.

Table 6. Distribution of the decreasing speed factor.

Floors	Decreasing Speed Factor
0 - 5	1.00
5 - 10	0.84
10 - 15	0.61
15 - 20	0.55
20 - 25	0.50
25 - 30	0.50
30 - 35	0.50
35 - 40	0.50
40 - 45	0.50
45 - 50	0.55

6.4. Modified normal distribution

The modified distribution is based on the data from the benchmark experiment of the male and female ascending walking speeds of the first and second floor. The given values are maximum, average and minimum walking speed of first to second floor for female and male participants. The values given are (max, average, min) for females 1.25, 0.89, 0.68 and males 1.88, 1.26, and 0.44. The mean walking speed of the modified distribution is the mean of the average walking speed for females and males. The calculated normal distribution is:

- mean = 1.08
- standard deviation =1.11
- minimum = 0.44 and
- maximum = 1.88.

6.5. Configuration of modelled scenarios

The configuration of all modelled scenarios is summarised in this section. Initially the configuration of scenarios is represented with the models default properties in configuration 1. Later the scenarios are modified with speed reduction factors in configuration 2. The last modification, configuration 3, is to alter the distribution of the initial walking speed.

It should be noted that the geometry was adapted to match the space representation adopted by the models (if required) but otherwise kept identical to the experiment. Handrails are not included in the simulations and the initial position of the occupant is randomly chosen within the area of the ground floor. The models are placing the occupants randomly within this area. The random initial positions of the occupants will give small differences in the total distance walked but is considered negligible compared to the total distance. Reaction time and pre movement time is not considered.

6.5.1. Input Configuration 1

The models are run with their default settings according to the blind calculation methodology.

Default settings of *EXIT89* is a constant speed (with low density) of 0.95 m/s with two different conditions available, normal and emergency conditions. EXIT89 calculate walking speed with the equations of Predtechenskii and Milinskii.

Occupant characteristics have to be set within *FDS+Evac*. To make the settings of all models as equal as possible the occupant characteristics used are adult. The initial walking speed is a uniform distribution of 1.25 +/- 0.3 m/s. The speed factor is set to 1.0 uniformly at all floors and stairs which will have no impact on the initial walking speed.

Pathfinder has a constant walking speed of 1.19 m/s as default. The model has two different modes, steering mode and SFPE mode.

Within *Simulex* the occupant characteristics have to be set and it is what defines the walking speed within the uniform distribution 0.8-1.7 m/s. The characteristics applied are 'commuters' and 'HK commuters'. The occupant characteristics are considered representative characteristics of people who would be required to evacuate through long ascending stairs.

The default settings of *STEPS* are the Fruin distribution for walking speed and a slope factor of 0.387.

The scenarios are listed below.

EXIT89: Default constant speed (0.95 m/s)

i. Normal conditions
ii. Emergency conditions

FDS+Evac: Default uniform distribution / occupant characteristics adult (1.25 +/- 0.3 m/s)

i. Speed factor: horizontal = 1.0 stair = 1.0

Pathfinder: Default constant speed (1.19 m/s)

i. Steering mode
ii. SFPE mode

Simulex: Default uniform distribution (0.8-1.7 m/s)

i. Occupant characteristics commuters
ii. Occupant characteristics HK commuters

STEPS: Default Fruin distribution

i. Slope factor = 0.387.

6.5.2. Input Configuration 2

In configuration 2 for the modelled scenarios, open calculations are simulated with the same walking speed properties as configuration 1. Properties influencing walking speed are applied in configuration 2. Different possible alterations are available within the different models.

EXIT89 does not support further modification of walking speed properties.

In *FDS+Evac* the distribution of walking speed is kept identical to configuration 1. The speed factor is applied in various alterations. Scenario i have has a horizontal factor of 1.0 and on stairs equal to 0.4. Scenario ii has a constant speed factor throughout the staircase. Scenario iii has a horizontal speed factor equal to 1.0 and the factor distributed in the stairs. Scenario iv has the distributed speed factor throughout the staircase. The speed factor is distributed according to the decreasing speed factor in Table 6.

The constant walking speed is kept identical to configuration 1 in *Pathfinder*. Both modes are run, Steering mode and SFPE mode. A speed modifier is applied to all floors. The speed modifier is distributed according to the decreasing speed factor in Table 6.

Simulex does not support further modification of walking speed properties. In order to achieve different times on stairs, the user should modify the geometric characteristics of the stairs, thus not allowing the simulation of different speeds upwards and downwards.

In *STEPS* a local factor is applied to all runs with a varying slope factor. Scenario *i* has a slope factor of 0.387 (default), Scenario *ii* has the slope factor disabled and run *iii*, *iv* and *v* have slope factors equal to 0.300, 0.250 and 0.200 respectively. The local factor is distributed according to the decreasing speed factor in Table 6.

The scenarios are listed below.

EXIT89: *not applicable*

FDS+Evac: Uniform distribution

i.	Speed factor: horizontal = 1.0	stair = 0.4
ii.	Speed factor: horizontal = 0.4	stair = 0.4
iii.	Speed factor: horizontal = 1.0	stair = distribution
iv.	Speed factor: horizontal = distribution	stair = distribution

Pathfinder: Constant walking speed 1.19 m/s

i.	Steering mode	distribution of speed modifiers
ii.	SFPE mode	distribution of speed modifiers

Simulex: *not applicable*

STEPS: Fruin distribution

i.	Distributed local factor	slope factor 0.387
ii.	Distributed local factor	no slope factor
iii.	Distributed local factor	slope factor 0.300
iv.	Distributed local factor	slope factor 0.250
v.	Distributed local factor	slope factor 0.200

6.5.3. Input Configuration 3

In configuration 3 for the modelled scenarios, open calculations are simulated. The distribution of walking speed is altered to a modified normal distribution. The modified distribution is based on the data from the benchmark experiment of the male and female ascending walking speeds of the first and second floor. The normal distribution has:

- mean = 1.08
- standard deviation =1.11
- minimum = 0.44 and
- maximum = 1.88.

The scenarios selected to be modelled with the new distribution of walking speed in *FDS+Evac* is scenario *i* (horizontal speed factor = 1.0 and speed factor stair = 0.4) and scenario *iv* (horizontal speed factor = distribution and horizontal speed factor = distribution) from configuration 2. Scenario *i* is selected because these are the speed factors given as examples by the developers. Scenario *iv,* is selected since it gave the total evacuation time with the least difference from the benchmark experiment.

In *Pathfinder* the new modified walking speed distribution is applied to both Steering mode and SFPE mode with the distribution of speed modifier kept like in configuration 2.

In STEPS the best corresponding scenario from configuration 2, scenario *ii* with distributed local factor no slope factor, is altered with the modifier distribution of walking speed.

The scenarios are listed below.

EXIT89: *not applicable*

FDS+Evac: Modified normal distribution

i.	Speed factor: horizontal = 1.0	stair = 0.4
ii.	Speed factor: horizontal = distribution	stair = distribution

Pathfinder: Modified normal distribution

i.	Steering mode	distribution of speed modifier
ii.	SFPE mode	distribution of speed modifier

Simulex: *not applicable*

STEPS: Modified normal distribution

i.	Distributed local factor	no slope factor.

7. RESULTS

The results are divided into four main parts; configuration 1, configuration 2, configuration 3 and the average walking speed per five floors. The results of each part summarised in a table or graph and given an explanatory summary.

7.1. Configuration 1 – default properties

In this section the results of the models with the properties according to configuration 1 is presented.

Table 7. Results of configuration 1 with default properties.

Model	Walking speed distribution	Default properties	Total evacuation time		
			s	min	Difference
EXIT89	Constant walking speed 0.95 m/s	Normal	263	4.4	-64.0%
		Emergency	208	3.5	-71.5%
FDS+Evac	Uniform distribution 1.25 ± 0.3 m/s	Adult characteristics. speed factor 1.0	591	9.9	-19.2 %
Pathfinder	Constant walking speed 1.19 m/s	Steering mode	523	8.7	-28.5 %
		SFPE mode	387	6.5	-47.1 %
Simulex	Uniform distribution 0.8-1.7 m/s	Commuters	725	12.1	-0.8 %
		HK commuters	691	11.5	-5.5 %
STEPS	Fruin distribution	Slope factor 0.387	506	8.4	-30.7 %

EXIT89 gives large under estimates of the total evacuation time in the specific case of evacuation, 64.0 % and 71.5 % for normal respectively emergency conditions.

The default properties of *FDS+Evac* provides a difference to the experimental results equal to19,2 % where the model underestimates the total evacuation time.

Pathfinder underestimates the total evacuation time with 28,5 % with the default properties and steering mode while the default properties of SFPE mode underestimates the total evacuation time with 47,1 %.

Within *Simulex* the occupant characteristics of commuters and HK commuters gives an underestimated difference of total evacuation time of 0,8 % and 5,5 % respectively.

The difference in total evacuation time with *STEPS* is an underestimation of 30,7 %.

7.2. Configuration 2 – default walking speed distributions with reducing speed factors

In this section the results of the models with the properties according to configuration 2 is presented.

Table 8. Results of configuration 2 with modified speed reduction parameters

Model	Walking speed distribution	Properties	Total evacuation time		
			s	min	Difference
EXIT89	Not applicable	-	-	-	-
FDS+Evac	Uniform distribution 1.25 ± 0.3 m/s	Horizontal speed factor = 1.0 Stair speed factor = 0.4	805	13.4	10.1 %
		Horizontal speed factor = 0.4 Stair speed factor = 0.4	767	12.8	4.9 %
		Horizontal speed factor = 1.0 Stair speed factor = dist	590	9.8	-19.3 %
		Horizontal speed factor = dist Stair speed factor = dist	710	11.8	-2.9 %
Pathfinder	Constant walking speed 1.19 m/s	Steering mode / speed modifier dist	652	10.9	-10.8 %
		SFPE mode / speed modifier dist	690	11.5	-5.6 %
Simulex	Not applicable	-	-	-	-
STEPS	Fruin distribution	Slope factor 0.387 / local factor dist	556	9.3	-23.9 %
		No slope factor / local factor dist	725	12.1	-0.8 %
		Slope factor 0.300 local factor dist	677	11.3	-7.4 %
		Slope factor 0.250 / local factor dist	776	12.9	6.2 %
		Slope factor 0.200 / local factor dist	886	14.8	21.2 %

FDS+Evac gives its best corresponding estimation of the total evacuation time with its default uniform distribution and the speed factors distributed both on horizontal surfaces and in the stairs. The difference is an underestimation of 2.9 %. With the constant speed factor of 0.4 throughout the staircase the difference of the total evacuation time is an overestimation equal to 4.9 %. Other configurations with different speed factors on horizontal and vertical routes give less corresponding results. With a horizontal speed factor of 1.0 and a stair speed factor of 0.4 the difference is a 10.1 % overestimation while with a horizontal speed factor of 1.0 and a distributed stair speed factor the difference is a 19.3 % overestimation.

With applied speed modifiers according to the decreasing speed factor throughout the staircase *Pathfinder* underestimates the total evacuation time with 10.8 % in Steering mode and 5.6 % in SFPE mode.

Simulex does not provide the possibility to apply speed reducing factors and thus configuration 2 is not applicable.

With *STEPS'* potential to apply both a slope factor and a local factor to the geometry the results are as follows. A default slope factor of 0.387 and with local factors distributed according to the speed reduction the total evacuation time is underestimated by 23.9 % while without the slope factor and with the same speed reducing factors the estimation of evacuation time is almost identical to the benchmark experiment, only a small difference of a 0.8% underestimation. With distributed local factors and slope factors of 0.300, 0.250 and 0.200 the difference is an underestimation of 7.4 %, an overestimation of 6.2 % and an overestimation of 21.2 % respectively.

7.3. Configuration 3 – modified walking speed distributions with reducing speed factors

In this section the results of the models with the properties according to configuration 3 is presented.

Table 9. Results of configuration 3 with modified speed reduction parameters

Model	Walking speed distribution	Properties	Total evacuation time		
			s	min	Difference
EXIT89	Not applicable	-	-	-	-
FDS+Evac	Modified normal distribution	Horizontal speed factor = 1.0 Stair speed factor = 0.4	994	16.6	36.0 %
		Horizontal speed factor = dist Stair speed factor = dist	627	10.5	-14.2 %
Pathfinder	Modified normal distribution	Steering mode / speed modifier	871	14.5	19.2 %
		SFPE mode /speed modifier	792	13.2	8.3 %
Simulex	Not applicable	-	-	-	-
STEPS	Modified normal distribution	No slope factor / local factor dist	835	13.9	14.2 %

The corresponding scenarios with configuration 2 but with the new initial walking speed distribution with *FDS+Evac* gives larger differences. When keeping the horizontal speed factor to 1.0 and the stair speed factor to 0,4 the difference is 25.9 % larger (36 %) compared to 10.1 %. Keeping the distributed speed factors with a new distribution of the initial walking speed causes a higher underestimation of the total evacuation time equal to 11.9 % (-14.2 %) compared to the default walking speed distribution (2,9 %).

With the new walking speed distribution *Pathfinder* overestimates the total evacuation time with 19.2 % in Steering mode and 8,3% in SFPE mode.

STEPS also overestimate the evacuation time with the modified walking speed distribution. The overestimation is 14.2 %.

7.4. Average walking speed per five floors

The average walking speeds over five floors are calculated for the scenario with the best approximation of total evacuation time for the models where it is possible. EXIT89, and Simulex do not provide the possibility to calculate the walking speed per floor. FDS+Evac, Pathfinder and STEPS do not explicitly calculate the local walking speed but can be calculated manually by plotting trajectories and the time passed. The output required for the calculation of walking speed in Pathfinder was not obtained by the author. Thus the average walking speed distribution of FDS+Evac and STEPS is presented. Two different walking speeds are calculated for FDS+Evac (default walking speed distribution with uniformly distributed speed factors) and STEPS (default walking speed distribution, no slope factor and local factor uniformly distributed) with different walking distances as basis. The total walking distance of STEPS is 240 m and of the benchmark experiment 375 m (7.5 m x 50 floors) and those two distances are applied to FDS+Evac. The results are presented as a comparison to the walking speeds of the experiment in Figure 7.

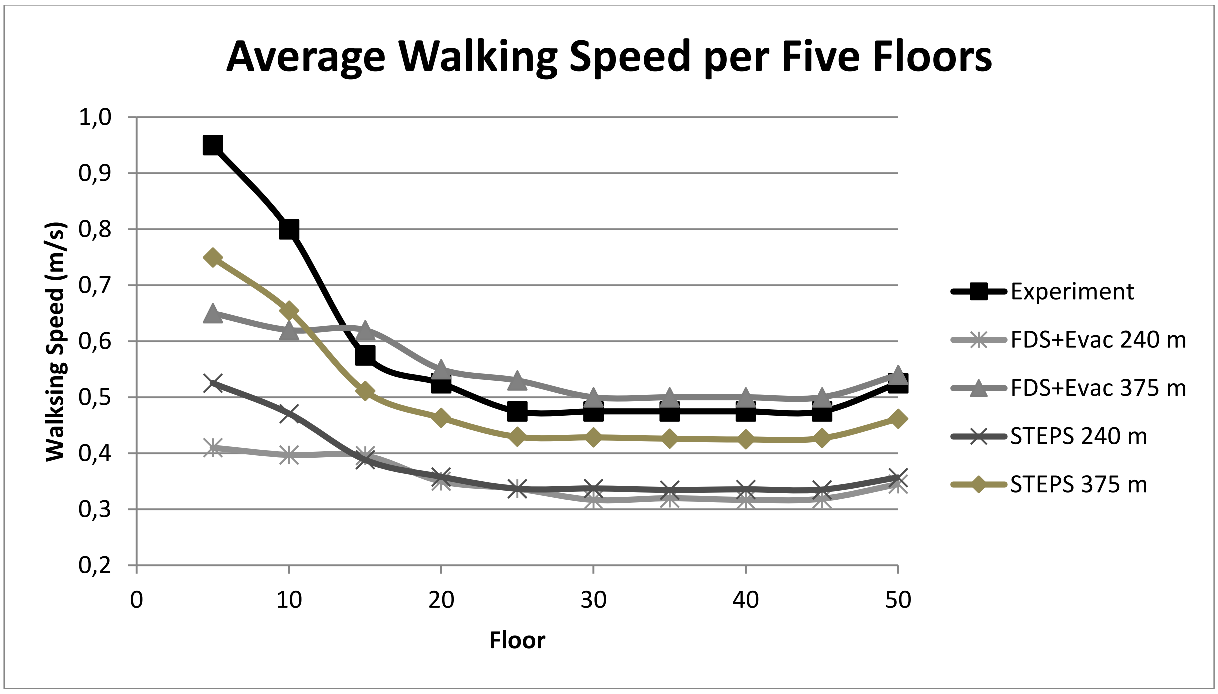

Figure 7. Average walking speed per five floors for FDS+Evac and STEPS vs. benchmark study.

8. DISCUSSION

The scope of this study is a comparison of a simple experimental case study with evacuation simulation results. Within the study the participants are ascending the stairs individually with no physical or psychological interference from other occupants. In a more complex scenario there could be groups of occupants evacuating simultaneously with occupants arriving to the staircase from different floors and thus crowded areas and counter flow could occur. More complex scenarios could include behavioural factors, social interactions, merging flows etc. It would also be difficult to estimate the reducing speed factors due to a possibly higher density, the different walking speeds of the occupants, different entry levels and thus the different total walked distance amongst the occupants.

For models where the walking speed depends on density the maximum unimpeded walking speed will always be used since the density within this scenario is low. In a case where there is more than one occupant, the influence of other occupants will affect the walking speed which could lead to different total evacuation times.

Within simulations the total walking speed depends on the models assumptions regarding calculation of travelled distance as explained further in section 8.3.

The vertical distance should be the deciding parameter regarding reduced walking speed. The walking speed is reduced more in the stair (vertical part of the staircase) while the walking speed in over the landings (horizontal part of the staircase) is reduced less with increasing travelled distance. Thus the vertical distance travelled should be determining when implementing reduced speed factors in evacuation models.

In general more strict convergence criteria concerning model runs of each type of simulation would increase the reliability of the modelled results in terms of behavioural uncertainty and could possibly contribute to a more accurate assessment of evacuation simulation results. The acceptance criterion for the additive average is 5 % but as a large amount of the different configurations are resulting in an additive average of <1 %, due to the minimum of 20 runs, the results can be seen as reliable for the different configurations.

8.1. Reducing speed factors

The reducing speed factors are applied to the initial walking speed percentually. The reducing speed factors are calculated based on visual estimations averaged over five floors with the assumption that floors 0-5 have a factor of 1.0. Due to this there are undisputedly errors in the application of the factors. More accurate estimations of the reducing speed factors could give further conforming results or, it can be the reversed, that more reliable speed factors give more deviating results. It is in the author's opinion that using the reducing speed factors is a good way of modelling the reduced speed due to the walked distance. One way of enhancing the models possibility to predict the time of ascending evacuation is to implement reducing speed factors adapted after the vertical distance travelled. This requires further studies on how the walking speed is reduced with the horizontal and vertical distance travelled.

8.2. Total evacuation time

With default settings all models underestimate the total evacuation time which not give conservative results. The underestimated total evacuation time may be due to over estimation of walking speeds. As mentioned previously, calculations of ascending walking speed are often derived from the calculation of descending walking speeds. The underestimation of total evacuation time of all models shows that the default settings may not be applicable for modelling evacuation in long ascending stairs.

The models default walking speed distribution with uniformly distributed reducing speed factors (same speed reducing factor on horizontal parts and stairs) gives the better conforming total evacuation time with the benchmark experiment.

EXIT89 is only applicable for descending evacuation, not ascending evacuation and thus gives no results in this study.

FDS+Evac underestimates the total evacuation time with its default settings but give better conforming results with configuration 2 when applying speed factors to the default walking speed distribution. Only when applying a horizontal speed factor of 1.0 and distributed speed factors in the stairs, the difference is as large as the default settings. Remaining scenarios gives better conforming results with the uniformly distributed (same speed factor applied vertically and horizontally) speed factor giving the best fit. Modifying the default walking speed distribution does not give better results but give more under- or overestimated results compared to the scenario with the same properties in configuration 2. The results show that the speed factor is a useful tool to achieve comparable total evacuation times with FDS+Evac within the studied evacuation scenario. The default walking speed distribution is well suited for this ascending evacuation scenario together with distributed speed factors.

Pathfinder underestimates the total evacuation time with its default settings. When applying distributed speed modifiers to the default walking speed distribution, the results deviate less and are the best corresponding results with Pathfinder within this study. Applying the modified walking speed distribution does not give better corresponding results with Pathfinder. From the results it is supposed that the speed modifiers with the default walking speed distribution is the best estimation. Studies of more scenarios with different alterations of speed modifiers could give better results.

Simulex is the model with the better conforming results with default settings. Simulex provides 32 different occupant characteristics where ‘commuters’ and ‘HK commuters’ were assumed to be a representative group of occupants for an ascending evacuation. It should be noted that Simulex does not provide any further possible alterations than the ones used as default settings. This is a limitation within the model which makes the model incapable of modelling reducing speed and thus fatigue.

The properties of *STEPS* that gives the distinguishably best corresponding total evacuation time is the default walking speed distribution without slope factor but with distributed local factors. None of the slope factors used with the default walking speed distribution gives a conformable evacuation time. In this case the local factors are a better tool to distribute the walking speeds like in the benchmark experiment. The slope factors may be more useful when a uniform reduction in speed is required, not when the walking speed change with time.

8.3. Average walking speeds

Only using FDS+Evac and STEPS was possible to directly extract the walking speed along the floors by plotting trajectories over time. This feature is available in Pathfinder but could not be deduced from the output acquired. The time of arrival at floor 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50 were compared to the estimated walked distance. The resulting walking speeds within this study should be seen as an indication that the walking speeds can be estimated near the actual walking speeds, but that they are not absolute.

STEPS provides the total distance walked for each run with an estimated average distance of 240 m. Comparing this distance to the calculated distance of the benchmark experiment which is 375 m (7,5 m x 50 floors) it is more than 30 % difference. This indicates that of the two parameters walking speed depends on, time and distance, time is the easier parameter to define while the distance may be difficult to estimate. As with STEPS, the occupants walk different total distances in each run, participants of the experiment do the same. The calculated total distances travelled within the experiment and STEPS have most likely been calculated with different radius as a basis, since the total walked distance deviates to this extent. STEPS uses a shortest distance algorithm while the radius of the travelled route within the benchmark experiment is assumed to be 0.5 m. To get credible walking speeds the total distance walked should be determined accurately.

The validation study indicates that the vertical distance should be determining for decelerating walking speed and indirectly fatigue.

8.4. Methodology

No scientific methodology has been fully used for this study but it has been chosen by the author.

The review of model capabilities followed the methodology of Kuligowski (2005) but did not incorporate all parts since this study is relatively basic and do not cover all parts of the Kuligowski review. For instance, the methodology for modelling uncertainty and type of simulations performed by Lord et.al. (2005) could have been used, but due to time constraints and the type of experimental data available, this method would have been excessive and has not been used.

The methodology of the analysis is partially the methodology of (Lord, et al., 2005) where the methodology of model evaluation; blind calculations and open calculations are followed.

Both methods used are from relevant sources, however, a complete methodology for this type of validation may give more substantial results due to possibly lower uncertainty. A methodology explicitly developed for validation of evacuation models could give more reliable results.

9. CONCLUSION

For this specific case of evacuation the properties for better conforming total evacuation times of the models are recurrent among the models with the possibility to apply reduced speed factors. The default walking speed distribution with uniformly distributed reducing speed factors (same speed reducing factor horizontally and on stairs) gives the better conforming total evacuation time with the benchmark experiment in this specific case of evacuation. This is the case for FDS+Evac, Pathfinder and STEPS while the remaining two, EXIT89 and Simulex do not provide these properties. Simulex provide a good estimation of the total evacuation time with its default settings with the occupant characteristics ‘Commuters’ while EXIT89 give largely under estimated total times of evacuation and is considered not applicable in this case.

FDS+Evac and STEPS have the better conforming total evacuation times of the validated models using reducing speed factors. Simulex has its best conforming results with its default properties for this specific case of evacuation, other cases of evacuation and different number of floors may provide different results.

The average walking speeds per five floors of FDS+Evac and STEPS are not consistent with the benchmark speeds but indicate a similar gradient in the resulting graph. The walking speeds are an indication that FDS+Evac and STEPS have the capability to model estimations of decreasing walking speeds in this case of evacuation if further configurations are applied. The results shows that the walking speed, and thus the total evacuation time, is greatly depending on the calculated travelled distance within the simulations. The reduction of speed is depending more on the vertical distance travelled than the horizontal distance travelled. The vertical distance should therefore be determining regarding the reduction of speed, and indirectly fatigue.

This study indicates that the models under consideration are not conservative with their default settings, which may have implications if using the models for design purposes. Thus, default settings are not the best fit for this specific case of evacuation with the models, EXIT89, FDS+Evac, Pathfinder, Simulex and STEPS. The study also indicates that uniform speed reductions do not in general give conforming results but that models which have the possibility to alter the reducing speed factors at each floor give conforming results with the benchmark study. To attain conforming results of total evacuation time and walking speed with the studied models a user effort and prior knowledge on walking speeds are required together with a model which provide the possibility to influence walking speed at each floor and stair.

The models validated within this thesis are not recommended for simulation of ascending stair evacuation with their default settings. The models with the possibility to apply reducing speed factors, FDS+Evac, Pathfinder and STEPS, could be used for simulation of approximately 50 floor ascending stair evacuation with considerable user input such as the factors of reduced speed applied within this study. To use the models for simulation of other vertical distances further studies should be performed to validate the models reliability. To further develop evacuation models to perform more reliable modelling of ascending evacuation factors of reducing speed could be implemented as standard within the model and not a user setting. The reducing speed factors would then have to be further developed to fit different vertical distances.

9.1. Meeting the purpose and objectives

The results of the study have met its purpose and objectives. The purpose was to increase the understanding of the current limitations, differences and similarities of modelling ascending evacuation movement in long stairs and to quantify differences of total evacuation time. The study indicates that some models have the potential to use its settings for reliable results today and some do not have the specific settings available to model reduced walking speeds and thus physical fatigue. The differences in total evacuation time and average walking speeds have been quantified as far as the used methodology allow.

9.2. Future work

There are a number of recommendations on future work within this subject.

- Stricter acceptance criteria and additional scenarios to model could increase the reliability of behavioural uncertainty estimation.
- Further studies of how reducing speed factors should be distributed over the floors depending on the travelled distance and the vertical distance.
- Other models can be used for the same type of validation study.
- Further benchmark experiments could be used to include multiple occupants ascending at a time, arriving to the staircase from different floors, and be used as a benchmark study for further validation of the capabilities of evacuation models to represent ascending stair evacuation.

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APPENDIX A

EXIT89 calculation procedure

The walking speed on a horizontal path (V_0)

$$V_0 = 112 \cdot D^4 - 380 \cdot D^3 + 434 \cdot D^2 - 217 \cdot D + 57 \ m/min \qquad \text{(eq. A1)}$$

Where:

D is the density of a stream of people.

The density of a stream of people (D), in this case only one person is

$$D = \frac{N \cdot f}{w \cdot L} \ m^2/m^2 \qquad \text{(eq. A2)}$$

Where:

N is the number of people in the stream

f is the area of horizontal projection of a person

w is the width of the stream

L is the length of the stream.

Movement up stairs ($V_\uparrow$)

$$V_\uparrow = V_0 \cdot m_\uparrow \ m/min \qquad \text{(eq. A3)}$$

where

V_0 is the walking speed on a horizontal path

$$m_\uparrow = 0{,}785 + 0{,}09 \cdot e^{3{,}45 \cdot D_\uparrow} \cdot \sin(15{,}7 \cdot D_\uparrow) \qquad \text{when } 0 < D_\uparrow < 0{,}6 \qquad \text{(eq. A4)}$$

$$m_\uparrow = 0{,}785 - 0{,}10 \cdot \sin(7{,}85 \cdot D_\uparrow + 1{,}57) \qquad \text{when } 0{,}6 \leq D_\uparrow \leq 0{,}92 \qquad \text{(eq. A5)}$$

and where

$D_\uparrow$ is the density of a stream of people walking up stairs, in this case $D_\uparrow = D$.

Predtechenskii and Milinskii also defined a change in walking speed during emergency conditions (V_e) according to

$$V_e = \mu_e \cdot V \qquad \text{(eq. A6)}$$

where

$\mu_e = 1.49 - 0.36 \cdot D$ for horizontal paths and through openings, and

$\mu_e = 1.26$ for ascending stairs.

Calculation of total time of evacuation in normal conditions:

$D_{\rightarrow}0$ so $V_0 = 57\ m/min$

$D_{\uparrow\ \rightarrow}0$ so $m_{\uparrow} = 0.785$ and $V_{\uparrow} = V_0 \cdot m_{\uparrow} = 57 \cdot 0.785 = 44.75\ m/min$

$L_0 = radius \cdot \pi \cdot 50\ floors = 0.510 \cdot \pi \cdot 50 = 1.60 \cdot 50 = 80.11\ m$

$L_{\uparrow up} = l_{stair} \cdot\ 50\ floors = 2.66 \cdot 50 = 133.00\ m$

$t_0 = L_0 /\ V_0 = 80.11\ /57\ = 1.41\ min$

$t_{\uparrow} = L_{\uparrow} /\ V_{\uparrow} = 133.00\ /44.75\ = 2.97\ min$ and

$t_{tot} = t_0 + t_{\uparrow} = 1.41 + 2.97\ min = 4.38\ min = 263\ s.$

Calculation of total time of evacuation in emergency conditions:

$V_{0\ em} = V_0 \cdot \mu_e = 57\ \cdot 1.26 = 71.82\ m/min$

$V_{\uparrow\ em} = V_{\uparrow} \cdot \mu_e = 44.75 \cdot 1.26 = 56.38\ m/min$

$t_{0\ em} = L_0 /\ V_{0\ em} = 80.11\ /71.82\ = 1.12\ min$

$t_{\uparrow\ em} = L_{up} /\ V_{\uparrow em} = 133.00\ /56.38\ = 2.36\ min$ and

$t_{tot\ em} = t_0 + t_{\uparrow} = 1.12 + 2.36\ min = 3.47\ min = 208\ s.$

APPENDIX B

Results configuration 1

In the section the results from the simulations of the default settings are summarised. The results are from EXIT89, FDS+Evac, Pathfinder, Simulex and STEPS respectively.

EXIT89

Result for EXIT89 with settings according to configuration 1.

Table A 1. EXIT89 default settings results.

Calculation	Mode	Tot evacuation time		Difference
		s	min	%
Constant walking speed 0.95 m/s	Normal	263	4.4	-64.0 %
	Emergency	208	3.5	-71.5 %

FDS+Evac

Result for FDS+Evac with settings according to configuration 1.

Table A 2. FDS+Evac default settings results.

FDS+Evac Default distribution			
Speed factor		**horizontal**	**1.0**
		stair	**1.0**
Run n	**Tot evacuation time**	**Additive average**	**Difference**
	s	**s**	**%**
1	649	649	
2	702	676	3.9%
3	519	623	-8.4%
4	612	621	-0.5%
5	571	611	-1.6%
6	612	611	0.0%
7	556	603	-1.3%
8	616	605	0.3%
9	514	595	-1.7%
10	560	591	-0.6%
11	720	603	1.9%
12	534	597	-1.0%
13	635	600	0.5%
14	623	602	0.3%
15	517	596	-0.9%
16	565	594	-0.3%
17	601	594	0.1%
18	688	600	0.9%
19	523	596	-0.7%
20	511	591	-0.7%
Average (s)	**591**		

Pathfinder

Result for Pathfinder with settings according to configuration 1.

Table A 3. Pathfinder results with default settings and steering mode.

Default distribution

Steering mode

Run nbr	Tot evacuation time	Additive average	Difference
	s	s	%
1	523	523	-

Table A 4. Pathfinder results with default settings and SFPE mode.

Default distribution

SFPE mode

Run nbr	Tot evacuation time	Additive average	Difference
	s	s	%
1	387	387	-

Simulex

Result for Simulex with settings according to configuration 1.

Table A 5. Simulex results with default settings and occupant characteristics 'Commuters'.

Commuters

Run nbr	Tot evacuation time	Additive average	Difference
	s	s	%
1	652	652	
2	1241	947	31,1%
3	624	839	-12,8%
4	597	779	-7,8%
5	672	757	-2,8%
6	569	726	-4,3%
7	651	715	-1,5%
8	739	718	0,4%
9	888	737	2,6%
10	595	723	-2,0%
11	725	723	0,0%
12	676	719	-0,5%
13	744	721	0,3%
14	681	718	-0,4%
15	571	708	-1,4%
16	636	704	-0,6%
17	1238	735	4,3%
18	756	736	0,2%
19	577	728	-1,2%
20	668	725	-0,4%
Average	**725**		

Table A 6. Simulex results with default settings and occupant characteristics 'HK Commuters'.

HK Commuters

Run nbr	**Tot evacuation time**	**Additive average**	**Difference**
	s	**s**	**%**
1	674	674	
2	631	653	-3.3%
3	680	662	1.4%
4	614	650	-1.8%
5	599	640	-1.6%
6	669	645	0.8%
7	1132	714	9.8%
8	686	711	-0.5%
9	707	710	-0.1%
10	681	707	-0.4%
11	587	696	-1.6%
12	674	695	-0.3%
13	671	693	-0.3%
14	671	691	-0.2%
15	660	689	-0.3%
16	601	684	-0.8%
17	659	682	-0.2%
18	982	699	2.4%
19	643	696	-0.4%
20	599	691	-0.7%
Average	**691**		

STEPS

Result for STEPS with settings according to configuration 1.

Table A 7. Results for STEPS, default walking speed distribution and 0.387 slope factor.

Default distribution
Slopefactor 0.387

Run nbr	Tot evacuation time	Additive average	Difference
	s	s	%
1	537	537	
2	486	512	-5.0%
3	467	497	-3.0%
4	451	485	-2.3%
5	522	493	1.5%
6	826	548	10.1%
7	531	546	-0.5%
8	521	543	-0.6%
9	456	533	-1.8%
10	524	532	-0.2%
11	418	522	-2.0%
12	375	510	-2.4%
13	487	508	-0.3%
14	503	507	-0.1%
15	450	504	-0.8%
16	570	508	0.8%
17	443	504	-0.8%
18	522	505	0.2%
19	652	513	1.5%
20	386	506	-1.3%
Average	**506**		

Results configuration 2

In the section the results from the simulations of the default walking speed distributions with modified reducing speed factors are summarised. The results are from FDS+Evac. Pathfinder and STEPS respectively.

FDS+Evac

Result for FDS+Evac with settings according to configuration 2.

Table A 8. Results for FDS+Evac default walking speed distribution, speed factor horizontal 1.0, stairs 0.4.

	Default distribution		
Speed factor		horizontal	1.0
		stair	0.4
Run nbr	**Tot evacuation time**	**Additive average**	**Difference**
	s	**s**	**%**
1	865	865	
2	804	835	-3.7%
3	793	821	-1.7%
4	944	852	3.6%
5	843	850	-0.2%
6	707	826	-2.9%
7	890	835	1.1%
8	699	818	-2.1%
9	803	816	-0.2%
10	758	811	-0.7%
11	998	828	2.1%
12	796	825	-0.3%
13	741	819	-0.8%
14	829	819	0.1%
15	769	816	-0.4%
16	713	810	-0.8%
17	800	809	-0.1%
18	854	811	0.3%
19	761	809	-0.3%
20	732	805	-0.5%
Average (s)	**805**		

Table A 9. Results for FDS+Evac default walking speed distribution, speed factor horizontal 0.4, stairs 0.4.

	Default distribution		
Speed factor		horizontal	0.4
		stair	0.4
Run nbr	**Tot evacuation time**	**Additive average**	**Difference**
	s	**s**	**%**
1	858	858	
2	938	898	4.5%
3	785	860	-4.4%
4	704	821	-4.8%
5	730	803	-2.3%
6	701	786	-2.2%
7	755	782	-0.6%
8	694	771	-1.4%
9	797	774	0.4%
10	751	771	-0.3%
11	915	784	1.7%
12	737	780	-0.5%
13	735	777	-0.4%
14	691	771	-0.8%
15	688	765	-0.7%
16	763	765	0.0%
17	707	762	-0.4%
18	794	764	0.2%
19	847	768	0.6%
20	754	767	-0.1%
Average (s)	**767**		

Table A 10. Results for FDS+Evac default walking speed distribution, speed factor horizontal 1.0, stairs distributed.

	Default distribution		
Speed factor		**horizontal**	**1.0**
		stair	**distributed**
Run nbr	**Tot evacuation time**	**Additive average**	**Difference**
	s	**s**	**%**
1	571	571	
2	609	590	3.2%
3	589	590	-0.1%
4	584	588	-0.2%
5	649	600	2.0%
6	702	617	2.7%
7	519	603	-2.3%
8	612	604	0.2%
9	571	601	-0.6%
10	612	602	0.2%
11	556	598	-0.7%
12	616	599	0.3%
13	514	593	-1.1%
14	560	590	-0.4%
15	566	589	-0.3%
16	710	596	1.3%
17	652	600	0.5%
18	501	594	-0.9%
19	579	593	-0.1%
20	535	590	-0.5%
Average (s)	**590**		

Table A 11. Results for FDS+Evac default walking speed distribution, uniformly distributed speed factor.

	Default distribution		
Speed factor		**horizontal**	**distributed**
		stair	**distributed**
Run nbr	**Tot evacuation time**	**Additive average**	**Difference**
	s	**s**	**%**
1	655	655	
2	800	728	10.0%
3	742	732	0.7%
4	815	753	2.7%
5	753	753	0.0%
6	639	734	-2.6%
7	802	744	1.3%
8	664	734	-1.4%
9	615	721	-1.8%
10	616	710	-1.5%
11	598	700	-1.5%
12	820	710	1.4%
13	807	717	1.0%
14	735	719	0.2%
15	602	711	-1.1%
16	649	707	-0.5%
17	834	714	1.0%
18	757	717	0.3%
19	658	714	-0.4%
20	629	710	-0.6%
Average (s)	**710**		

Pathfinder

Result for Pathfinder with settings according to configuration 2.

Table A 12. Results for Pathfinder, SFPE mode, default constant walking speed and uniformly distributed speed modifier.

	Default constant speed		
SFPE mode		Distributed speed modifier	
Run nbr	**Tot evacuation time**	**Additive average**	**Difference**
	s	**min**	**%**
1	690	12	-

Table A 13. Results for Pathfinder, Steering mode, default constant walking speed and uniformly distributed speed modifier.

	Default constant speed		
Steering mode		Distributed speed modifier	
Run nbr	**Tot evacuation time**	**Additive average**	**Difference**
	s	**s**	**%**
1	652	11	-

STEPS

Result for STEPS with settings according to configuration 2.

Table A 14. Results for STEPS, default walking speed distribution, 0.387 slope factor and uniformly distributed local factor.

Default Fruin distribution			
Local factors		0.387 slope factor	
Run nbr	Tot evacuation time	Additive average	Difference
	s	s	%
1	509	509	
2	504	507	-0.5%
3	519	511	0.8%
4	702	559	8.6%
5	404	528	-5.9%
6	780	570	7.4%
7	570	570	0.0%
8	571	570	0.0%
9	615	575	0.9%
10	710	588	2.3%
11	502	581	-1.4%
12	637	585	0.8%
13	433	574	-2.0%
14	544	571	-0.4%
15	734	582	1.9%
16	496	577	-0.9%
17	419	568	-1.6%
18	478	563	-0.9%
19	478	558	-0.8%
20	506	556	-0.5%
Average (s)	**556**		

Table A 15. Results for STEPS, default walking speed distribution, no slope factor and uniformly distributed local factor.

Default Fruin distribution			
No slope factor		Local factors	
Run nbr	**Tot evacuation time**	**Additive average**	**Difference**
	s	**s**	**%**
1	857	857	
2	720	789	-8.7%
3	653	743	-6.1%
4	1282	878	15.3%
5	748	852	-3.1%
6	590	808	-5.4%
7	749	800	-1.1%
8	678	785	-1.9%
9	643	769	-2.0%
10	664	758	-1.4%
11	731	756	-0.3%
12	797	759	0.5%
13	661	752	-1.0%
14	793	755	0.4%
15	1050	774	2.5%
16	645	766	-1.1%
17	628	758	-1.1%
18	491	743	-2.0%
19	623	737	-0.9%
20	494	725	-1.7%
Average	**725**		

Table A 16. Results for STEPS, default walking speed distribution,0.300 slope factor and uniformly distributed local factor.

Default distribution			
Local factors		0.3 slope factor	
Run nbr	**Tot evacuation time**	**Additive average**	**Difference**
	s	**s**	**%**
1	733	733	
2	661	697	-5.2%
3	583	659	-5.8%
4	721	675	2.3%
5	572	654	-3.1%
6	699	662	1.1%
7	765	676	2.2%
8	560	662	-2.2%
9	777	675	1.9%
10	619	669	-0.8%
11	675	670	0.1%
12	677	670	0.1%
13	555	661	-1.3%
14	694	664	0.4%
15	707	667	0.4%
16	745	671	0.7%
17	724	675	0.5%
18	624	672	-0.4%
19	757	676	0.7%
20	688	677	0.1%
Average (s)	**677**		

Table A 17. Results for STEPS, default walking speed distribution, 0.250 slope factor and uniformly distributed local factor.

Default distribution

Local factors **0.25 slope factor**

Run nbr	**Tot evacuation time**	**Additive average**	**Difference**
	s	**s**	**%**
1	621	621	
2	1088	855	27.3%
3	736	815	-4.8%
4	824	817	0.3%
5	969	848	3.6%
6	594	805	-5.2%
7	786	803	-0.3%
8	1070	836	4.0%
9	737	825	-1.3%
10	580	801	-3.1%
11	973	816	1.9%
12	806	815	-0.1%
13	793	814	-0.2%
14	493	791	-2.9%
15	853	795	0.5%
16	822	797	0.2%
17	608	785	-1.4%
18	644	778	-1.0%
19	626	770	-1.0%
20	900	776	0.8%
Average (s)	**776**		

Table A 18. Results for STEPS, default walking speed distribution. 0.200 slope factor and uniformly distributed local factor.

Default distribution			
	Local factors	0.2 slope factor	
Run nbr	Tot evacuation time	Additive average	Difference
	s	s	%
1	740	740	
2	866	803	7.8%
3	853	820	2.0%
4	895	839	2.2%
5	640	799	-5.0%
6	1078	845	5.5%
7	1095	881	4.0%
8	852	877	-0.4%
9	695	857	-2.4%
10	698	841	-1.9%
11	892	846	0.5%
12	774	840	-0.7%
13	832	839	-0.1%
14	1225	867	3.2%
15	801	862	-0.5%
16	685	851	-1.3%
17	745	845	-0.7%
18	1120	860	1.8%
19	1196	878	2.0%
20	1030	886	0.9%
Average	**886**		

Results configuration 3

FDS+Evac

Result for FDS+Evac with settings according to configuration 3.

Table A 19. Results for FDS+Evac modified walking speed distribution, speed factor horizontal 1.0, stairs 0.4.

	Modified distribution		
min	0.44		
max	1.88	**Speed factor**	
mean	1.06	**horizontal**	**1.0**
std	1.11	**stairs**	**0.4**

Run nbr	Tot evacuation time	Additive average	Difference
	s	s	%
1	992	992	
2	997	995	0.3%
3	993	994	-0.1%
4	992	994	-0.1%
5	994	994	0.0%
6	1010	996	0.3%
7	988	995	-0.1%
8	990	995	-0.1%
9	999	995	0.1%
10	1004	996	0.1%
11	983	995	-0.1%
12	995	995	0.0%
13	991	994	0.0%
14	987	994	-0.1%
15	979	993	-0.1%
16	1007	994	0.1%
17	992	994	0.0%
18	998	994	0.0%
19	1013	995	0.1%
20	985	994	-0.1%
Average (s)	**994**		

Table A 20. Results for FDS+Evac modified walking speed distribution, uniformly distributed speed factor.

Modified distribution

min	0.44		
max	1.88	**Speed factor**	
mean	1.06	**horizontal**	**dist**
std	1.11	**stairs**	**dist**

Run nbr	**Tot evacuation time**	**Additive average**	**Difference**
	s	**s**	**%**
1	542	542	
2	591	567	4.3%
3	666	600	5.5%
4	627	607	1.1%
5	851	655	7.5%
6	660	656	0.1%
7	575	645	-1.8%
8	639	644	-0.1%
9	543	633	-1.8%
10	573	627	-1.0%
11	833	645	2.9%
12	748	654	1.3%
13	698	657	0.5%
14	537	649	-1.3%
15	574	644	-0.8%
16	602	641	-0.4%
17	581	638	-0.6%
18	549	633	-0.8%
19	600	631	-0.3%
20	555	627	-0.6%
Average (s)	**627**		

Pathfinder

Result for Pathfinder with settings according to configuration 3.

Table A 21. Results for Pathfinder, SFPE mode, modified walking speed distribution and uniformly distributed speed modifier.

Modified distribution

min	0.44
max	1.88
mean	1.06
std	1.11

SFPE mode

Distributed speed modifier

Run nbr	Tot evacuation time	Additive average	Difference
	s	s	%
1	799	799	
2	1589	1194	33.1%
3	646	1011	-18.1%
4	1377	1103	8.3%
5	490	980	-12.5%
6	563	911	-7.6%
7	1100	938	2.9%
8	503	883	-6.2%
9	990	895	1.3%
10	488	855	-4.8%
11	621	833	-2.5%
12	1429	883	5.6%
13	650	865	-2.1%
14	452	836	-3.5%
15	953	843	0.9%
16	505	822	-2.6%
17	714	816	-0.8%
18	549	801	-1.9%
19	763	799	-0.3%
20	650	792	-0.9%
Average	**792**		

Table A 22. Results for Pathfinder, SFPE mode, modified walking speed distribution and uniformly distributed speed modifier.

Modified distribution

min	0.44
max	1.88
mean	1.06
std	1.11

Steering mode

Distributed speed modifier

Run nbr	Tot evacuation time	Additive average	Difference
	s	s	%
1	688	688	
2	493	591	-16.5%
3	1424	868	32.0%
4	794	850	-2.2%
5	931	866	1.9%
6	1249	930	6.9%
7	554	876	-6.1%
8	722	857	-2.2%
9	1052	879	2.5%
10	1140	905	2.9%
11	951	909	0.5%
12	593	883	-3.0%
13	514	854	-3.3%
14	1506	901	5.2%
15	717	889	-1.4%
16	565	868	-2.3%
17	1099	882	1.5%
18	571	865	-2.0%
19	689	855	-1.1%
20	1160	871	1.7%
Average	**871**		

STEPS

Result for STEPS with settings according to configuration 3.

Table A 23. Results for STEPS, modified walking speed distribution and uniformly distributed local factors.

	Modified distribution		
	No slope factor	Distributed local factors	
Run nbr	**Tot evacuation time**	**Additive average**	**Difference**
	s	**s**	**%**
1	571	571	
2	576	574	0.4%
3	582	576	0.5%
4	643	593	2.8%
5	1272	729	18.6%
6	1006	775	6.0%
7	866	788	1.6%
8	1047	820	3.9%
9	1214	864	5.1%
10	779	856	-1.0%
11	662	838	-2.1%
12	644	822	-2.0%
13	936	831	1.1%
14	893	835	0.5%
15	722	828	-0.9%
16	484	806	-2.7%
17	885	811	0.6%
18	1074	825	1.8%
19	1040	837	1.4%
20	806	835	-0.2%
Average	**835**		

Results walking speed per five floors

The results of the runs as basis for calculation of walking speed per five floors for FDS+Evac and STEPS.

Table A 24. Results for FDS+Evac default walking speed distribution and uniformly distributed reduction of speed factors.

FDS+Evac d=375	Run										
To floor	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Average (m/s)**
5	0.61	0.58	0.65	0.57	0.63	0.69	0.60	0.67	0.77	0.72	0.65
10	0.66	0.56	0.57	0.56	0.58	0.68	0.55	0.64	0.72	0.69	0.62
15	0.64	0.54	0.58	0.54	0.59	0.69	0.54	0.67	0.71	0.71	0.62
20	0.63	0.49	0.49	0.46	0.51	0.60	0.47	0.59	0.64	0.65	0.55
25	0.56	0.47	0.51	0.45	0.48	0.59	0.46	0.56	0.60	0.60	0.53
30	0.54	0.42	0.47	0.43	0.46	0.54	0.43	0.53	0.58	0.56	0.50
35	0.54	0.44	0.46	0.43	0.46	0.56	0.43	0.54	0.57	0.59	0.50
40	0.57	0.44	0.47	0.43	0.46	0.54	0.43	0.51	0.54	0.57	0.50
45	0.53	0.44	0.47	0.43	0.46	0.56	0.43	0.51	0.58	0.58	0.50
50	0.59	0.47	0.51	0.45	0.51	0.58	0.46	0.60	0.61	0.63	0.54

Table A 25. Results for FDS+Evac default walking speed distribution and uniformly distributed reduction of speed factors.

FDS+Evac d=240 m	**Run**										
To floor	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Average (m/s)**
5	0.39	0.37	0.41	0.36	0.40	0.44	0.38	0.43	0.49	0.46	0.41
10	0.42	0.36	0.36	0.36	0.37	0.44	0.35	0.41	0.46	0.44	0.40
15	0.41	0.34	0.37	0.34	0.38	0.44	0.35	0.43	0.45	0.45	0.40
20	0.40	0.31	0.32	0.30	0.32	0.38	0.30	0.38	0.41	0.41	0.35
25	0.36	0.30	0.33	0.29	0.31	0.38	0.30	0.36	0.38	0.38	0.34
30	0.35	0.27	0.30	0.28	0.30	0.34	0.27	0.34	0.37	0.36	0.32
35	0.35	0.28	0.29	0.28	0.30	0.36	0.28	0.34	0.36	0.38	0.32
40	0.36	0.28	0.30	0.27	0.29	0.35	0.27	0.33	0.35	0.36	0.32
45	0.34	0.28	0.30	0.28	0.29	0.36	0.28	0.33	0.37	0.37	0.32
50	0.38	0.30	0.33	0.29	0.32	0.37	0.30	0.38	0.39	0.40	0.35

Table A 26. Results for STEPS default walking speed distribution, no slope factor and uniformly distributed reduction of speed modifier.

STEPS d=375	Run										
To floor	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Average (m/s)**
5	0.51	0.99	1.01	0.89	1.14	1.44	0.36	0.37	0.49	0.29	0.75
10	0.41	0.85	0.87	0.78	0.96	1.21	0.34	0.37	0.47	0.28	0.65
15	0.31	0.63	0.66	0.59	0.71	0.89	0.31	0.34	0.43	0.25	0.51
20	0.28	0.56	0.59	0.52	0.63	0.80	0.30	0.32	0.41	0.24	0.46
25	0.25	0.51	0.54	0.47	0.57	0.72	0.29	0.31	0.40	0.24	0.43
30	0.25	0.51	0.53	0.47	0.58	0.72	0.29	0.31	0.40	0.23	0.43
35	0.25	0.51	0.53	0.47	0.57	0.72	0.29	0.31	0.39	0.23	0.43
40	0.25	0.51	0.53	0.47	0.57	0.71	0.28	0.31	0.40	0.23	0.42
45	0.25	0.51	0.53	0.47	0.58	0.72	0.29	0.31	0.39	0.23	0.43
50	0.28	0.56	0.58	0.52	0.61	0.80	0.30	0.32	0.41	0.24	0.46

Table A 27. Results for STEPS default walking speed distribution, no slope factor and uniformly distributed reduction of speed modifier.

STEPS d=240 **Run**

To floor	1	2	3	4	5	6	7	8	9	10	Average (m/s)
5	0.33	0.60	0.53	0.65	0.57	0.73	0.63	0.36	0.29	0.58	0.53
10	0.26	0.53	0.47	0.56	0.50	0.62	0.55	0.34	0.28	0.55	0.47
15	0.20	0.39	0.35	0.42	0.38	0.45	0.40	0.31	0.25	0.50	0.37
20	0.18	0.35	0.31	0.38	0.33	0.40	0.35	0.30	0.24	0.48	0.33
25	0.16	0.32	0.28	0.34	0.30	0.36	0.32	0.29	0.24	0.47	0.31
30	0.16	0.32	0.28	0.34	0.30	0.37	0.32	0.29	0.23	0.47	0.31
35	0.16	0.32	0.28	0.34	0.30	0.36	0.32	0.29	0.23	0.47	0.31
40	0.16	0.32	0.28	0.34	0.30	0.36	0.32	0.28	0.23	0.47	0.31
45	0.16	0.31	0.28	0.34	0.30	0.37	0.32	0.29	0.23	0.47	0.31
50	0.18	0.35	0.31	0.37	0.33	0.39	0.35	0.30	0.24	0.48	0.33