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Literature study and evacuation experiments

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Abstract:
Evacuating through inward opening doors can present challenges for safe egress during fire incidents. This study comprehensively investigates the dynamics and challenges associated with this type of evacuation, aiming to provide valuable insights for fire safety design. A literature review and experimental evacuation experiments were conducted. The experiments compare occupant movement towards and through inward opening doors with outward opening doors. Crucial parameters such as occupant density, door opening force, presence of a corridor (flow constriction), and walking distance, were examined.

The findings highlight that evacuating through inward opening doors is slower during the initial stage of egress due to the increased interactions required between evacuees. Further, high occupant densities near the door can obstruct door opening, emphasizing the importance of managing occupant density. The presence of a corridor, or other flow congestion, in front of the door slightly reduces people flow. In contrast, it promotes organized group formation, facilitating door opening. Increased walking distance to the door reduces occupant density for people reaching the door first, easing the door opening process. The number of people evacuating through the door does not significantly impact door opening, supporting the importance of managing occupant density instead. The study concludes that key parameters when safeguarding evacuation through inward opening doors include appropriate door fittings, low occupant density near the door, and fast door opening maneuvers, even for larger numbers of people.

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Foreword

This report summarizes the project Inward opening doors for evacuation (project number 323-005) financed by Brandforsk. The project has been carried out through a collaboration between Brandskyddslaget and the Division of Fire Safety Engineering at Lund University. The research group consisted of Martin Forssberg, Alexander M. Elias, and Johan Lundin from Brandskyddslaget and Håkan Frantzich from Lund University.

The authors of this report would like to thank **Brandforsk – The Swedish Fire Research Foundation** for the financial support to perform the study and valuable help regarding the publicity of the project and its results. Thank you, The **Swedish National Property Board** through **Johan Hanberger**, for supporting with insights, dedication, and financial support during the pilot study of the project, help with finding a place to perform the evacuation experiments and the loan of Västra Stallet where the evacuation experiments were conducted. We would also want to thank the **Reference Group** for valuable input when planning the experiments and peer reviewing the report.

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Last, but not least, we would like to thank all the **participants of the evacuation experiments**. Without your participation, this project would not have been possible.

Sammanfattning

Utrymning genom dörrar som öppnar inåt mot utrymningsriktningen har länge varit och är fortfarande betraktat som problematiskt. Detta till följd av att fara för kö och hög persontäthet i direkt anslutning till dörren kan förhindra eller begränsa möjligheten att öppna dörren, vilket kan påverka utrymningsmöjligheten negativt. Denna studie syftar till att undersöka dynamiken vid och utmaningar med utrymningsförlopp genom inåtgående dörrar. Målet med studien är att kunna bidra till utformning av välfungerande utrymning i byggnader med inåtgående dörrar genom att utöka kunskapen inom ämnet. Studien utfördes dels genom en litteraturstudie, dels genom en serie experimentella försök. I dessa försök jämfördes bland annat utrymningsförloppet genom dörrar som öppnar inåt med dörrar som öppnar utåt.

Försöken som utfördes i studien använde en försökslokal och dörrmiljöer uppbyggda för att återspegla realistiska utrymningsförutsättningar. Flertalet olika parametrar undersöktes, inklusive exempelvis persontäthet, dörröppningskraft, förekomst av en kort korridor framför dörren samt gångavstånd till utrymningsdörr. Detta för att få en djupare förståelse för parametrarnas påverkan på möjligheten att öppna dörren initialt, flöde av människor och övergripande möjlighet till utrymning.

Resultaten från denna studie ger flera viktiga insikter om utrymning genom dörrar som öppnar inåt. En observation är att utrymning genom inåtgående dörrar ofta är långsammare under den initiala fasen av utrymning jämfört med dörrar som öppnar utåt. Detta beror främst på det ökade antalet interaktioner och samarbete som krävs mellan utrymmande vid öppning av dörren. Dörrar som öppnar inåt kräver samordning och samarbete mellan utrymmande, vilket leder till en viss fördröjning i det inledande skedet av utrymningsprocessen.

Påverkan av persontäthet i dörrens direkta närhet undersöktes också i de utförda försöken. Det konstaterades att hög belastning av personer (överstigande 3 personer/m²) medför utmaningar när det gäller att öppna dörren i det inledande skedet, medan det vid försök med lägre personbelastningar inte uppstod några betydande svårigheter vid dörröppning eller utrymning. En slutsats blir därmed att för att möjliggöra utrymning via inåtgående dörr är det viktigt att kunna säkerställa en låg persontäthet i närheten av dörren för att underlätta dörröppning.

Förekomst av en kort korridor framför en dörr som öppnar inåt kan enligt de genomförda försöken förväntas minska flödet av människor genom dörren något. Dock främjar det en mer organiserad gruppformation, liknande en dragkedjeformation, vilket potentiellt underlättar dörröppning under den initiala utrymningsfasen. Utöver detta resulterar ökat gångavstånd innan man når dörren en lägre belastning av personer i omedelbar närhet av dörren, vilket gör det lättare att öppna dörren till följd av minskad trängsel och färre krävda interaktioner mellan evakuerande. Antalet personer som utrymmer genom en dörr påverkar i sig inte signifikant dörröppning eller personflödet genom dörren. Fokus vid utformning av byggnader och lokaler bör därmed ligga på att hantera persontäthet snarare än att begränsa antalet personer som evakuerar genom dörrar som öppnar inåt.

Försöken visar att förekomst av dörrvred förlänger tiden det tar att öppna dörren och kan potentiellt hindra utrymningen, särskilt när den kombineras med hög persontäthet eller ett stort antal utrymmande personer. Dörröppningskraften, inom det undersökta intervallet 45–100 N, har dock inte kunnat påvisas ha någon signifikant påverkan på utrymningsförloppet utifrån de genomförda försöken.

Baserat på observationer från genomförda försök samt genomförd litteraturstudie dras slutsatsen att evakuering genom dörrar som öppnar inåt kan vara acceptabelt för högre antal personer än tidigare föreslaget i bygglagstiftning och forskningsrapporter, förutsatt att vissa villkor är uppfyllda.

Summary

Evacuation through inward opening doors has been, and is still, considered problematic. This may be due to the possible hazard with queues and high occupant densities in direct proximity of the door, preventing or limiting the possibility of opening the door; thus, preventing or limiting the possibility of safe egress in case of a fire. This study aims to comprehensively investigate the dynamics and challenges associated with evacuating through inward opening doors, with the goal of providing valuable insights for optimizing the evacuation process. A series of evacuation experiments were conducted, comparing the performance of inward opening doors to outward opening doors.

The experiments conducted as part of this study used a dedicated test facility that replicated realistic evacuation scenarios. Various crucial parameters were examined, including occupant density, door opening force, presence of a short corridor in front of the door, and walking distance to the door. The experiments were conducted to gain a deeper understanding of each parameters impact on door opening, people flow, and overall evacuation efficiency.

The findings from this study reveal several important insights regarding evacuation through inward opening doors. One key observation is that evacuating through inward opening doors tends to be slower during the initial stage of egress compared to outward opening doors. This is primarily found to be due to the increased number of interactions required between evacuees to open the door. Inward opening doors necessitate coordination and cooperation between evacuees, resulting in a delay in the initial egress process.

The impact of occupant density in the proximity of the door connected the capability to open the door was examined. It was found that high occupant densities, exceeding 3 persons/m², pose challenges in opening an inward opening door, while lower densities do not exhibit significant impediments. Therefore, ensuring a low occupant density close to the door is crucial to facilitate the opening process. This can be achieved by managing the flow of people and ensuring sufficient space near the door.

The presence of a corridor in front of inward opening doors modestly reduces the people flow through the door. However, it promotes a more organized group formation (like a zipper), potentially facilitating the door opening process during the initial stage of evacuation. Additionally, increased walking distance before reaching the door yields a lower occupant density in the immediate vicinity of the door, thereby facilitating easier door opening due to reduced crowding with fewer interactions needed between evacuees. The number of people does not significantly affect the door opening process or the flow rate through the door. This finding suggests that the focus should be on managing occupant density adjacent to the door rather than strictly limiting the number of people evacuating through inward opening doors.

The inclusion of a door knob prolongs the door opening time, potentially impeding egress, particularly when combined with high occupant densities or large numbers of evacuees. In contrast, the door opening force, within the examined range of 45-100 N, does not exert a significant influence on the evacuation process. Nevertheless, further investigation encompassing a wider range of door opening forces is warranted to obtain more conclusive results.

Based on the observations, it is concluded that evacuation through inward opening doors can be acceptable for higher occupant numbers than previously suggested, provided certain conditions are met, such as appropriate door fittings, low occupant density near the door, and fast door opening maneuvers.

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1. Introduction

1.1 Background

In the current Swedish building regulations [1], it is stated that doors used for evacuation must generally have an outward opening direction, i.e., in the direction of travel during evacuation. Exceptions are allowed for doors where queuing cannot be expected to occur. The regulation's general recommendations state that queuing is not expected to occur within several different types of premises, including premises with a maximum of 30 people. The purpose behind the requirement is not clearly documented, but the motive is deemed to be reducing the risk of difficulties in opening a door during an evacuation situation when people behind the person opening the door can make it difficult to open or prevent the door from opening. Outward opening doors should be easier to open in such situations since the door does not have to be opened by pulling the door towards a potentially crowded area. However, there may also be other aspects, connected to inward opening doors, having a negative impact on an evacuation situation, a lower flowrate of people through such a configuration being an example.

In Sweden, the requirement for doors opening in the direction of evacuation has a long tradition and can, at least, be traced back to the 1874 Royal Building and Fire Safety Regulations [2] where requirements for outward facing doors are specified for certain types of premises. The requirement was later clarified and generalized in SBN 67 (Statens Planverk Publication no. 1, 1967) [3] to be applied to escape routes in general. In the later regulation, the exception that we recognize today from the current regulations was stated, that inward swinging doors are accepted for premises intended for 30 people or less. This exception was adopted as part of the requirement formulation to enable evacuation from classrooms in schools, where outward facing doors risked opening into corridors, obstructing the greater evacuation flow in the corridors. The specific number of a maximum of 30 people was probably based on the size of a normal-sized class of pupils.

Many buildings that were built earlier than 1874 have, thus, been constructed without the requirement of outward opening doors. In Sweden, inward opened doors are quite common in buildings built before year 1874 since the requirement first appeared in the regulations at this time. In addition, when renovating such buildings, it is important to keep in mind that many of the buildings from this era have a high cultural and historical value. Building regulations are not normally applied retroactively to buildings in Sweden, rather the regulations in place at the time of the building's construction govern matters like fire protection and evacuation safety. On the other hand, during supervision according to the Civil Protection Act [4] it is possible to impose increased requirements on the technical fire safety in an existing building if it is assessed to be reasonable and justifiable with regard to fire and evacuation safety as well as economic and cultural values.

In recent years, many injunction orders have been issued for buildings of cultural and historical value where inward swinging doors combined with premises exceeding the capacity of 30 people, have been highlighted as the problem. In some cases, this judgment is seen as an unvarnished application of the regulations listed above, resulting in a large negative impact on built cultural heritage. At the same time, the benefit in terms of evacuation safety of the measure, has a deficient scientific background.

A change in the opening direction of a door can affect the door’s appearance in the form of changed fittings, moved hinges and other visual impacts in the appearance. Consequently, this may cause alterations of the door and/or its surrounding parts, which is often highly valued for preservation. An aged door in its original design has great significance for the experience of the building, particularly when it comes to front doors, which often create the first impression of a building. In an untouched environment, a change in door opening direction will also result in different experience of the building.

Measures to ensure evacuation safety in existing buildings of high cultural or historical value with inward opening doors can include limiting the number of people in the premises, keeping the door open during times when a lot of people are present, or changing the door's opening direction [5]. However, the first option, limiting the number of people, can often have a significant impact on the ongoing activities in the premises, especially for buildings with long-standing cultural and historical value, such as churches and assembly halls. The second option, keeping the door open, could be a feasible solution in many cases, although it may not be optimal during wintertime. Lastly, the third option, changing the opening direction of the door potentially has a substantial impact on the original design of the building and consequently affect its cultural and historical value.

In addition to historically valuable buildings, there are also other applicable situations that could benefit from inward opening doors for evacuation. This includes, for example, doors that face other populated spaces such as evacuation corridors or doors in facades facing busy streets, doors swinging inwards as a measure of availability for people with movement impairment, etc. The impact of changing the direction of opening of the door needs to be explored for each of these cases.

1.2 Purpose and goal

This project aims to enhance our understanding of evacuation scenarios involving inward opening doors in comparison to doors that open in the direction of escape. The project primarily focuses on buildings of cultural and historical significance and value, where the possibility of alterations of the building's design is limited. However, the findings may have relevance for new buildings. Additionally, the results can be utilized in the assessment of acceptable occupant capacities in various types of premises equipped with inward opening doors.

The goal of the project is to identify key parameters influencing the risk of queuing and other factors affecting evacuation conditions when utilizing inward opening doors. To achieve this, a comprehensive literature study and a series of evacuation experiments has been conducted.

1.3 Research questions

The project aims to investigate the following research questions that stem from the identified problems listed below.

1.3.1 Problem 1: Key factors

It is not fully understood what aspects that are important regarding evacuation safety when evacuating through inward opening doors. Previous studies regarding evacuation through inward opening doors (see chapter 3) are largely focused on determining the flow of people. However, that is likely not the only factor of interest. The research question associated with this problem is:

- What factors influence the feasibility of evacuation through inward opening doors?

1.3.2 Problem 2: Occupant threshold

Limiting the number of occupants to 30 people can significantly impact activities in older buildings with inward opening doors. This may lead to a conflict between fire protection and conservation requirements in culturally valuable buildings. The research question associated with this problem is:

- Are there situations and room configurations where required safety levels during evacuation can be met even if more than 30 people evacuate through an inward opening door?

1.3.3 Problem 3: Queuing

The probability of the formation of a queue and the door's operability during the initial stages of evacuation are crucial factors that requires further investigation. The research question associated with this problem is:

- Under what conditions, if any, is the risk of the formation of a queue and ability to open the door independent of its opening direction?

1.3.4 Problem 4: Trade-offs

There are other advantages to inward opening doors, such as doors not swinging out into busy pedestrian streets.

- How can a trade-off be achieved when conflicting interests arise regarding the opening direction of a door?

1.4 Limitations and delimitations

The study presented here is limited to assessments related to the above stated purpose and goal regarding possibilities to evacuate through inward opening doors in the event of a fire. It does not cover evacuations prompted by threats other than fires. Additionally, the study does not consider the effects of group formations or the flow of individuals with movement impairments, as it was conducted solely with physically healthy participants. This limitation was chosen due to limitations of the premises in which the experiments were conducted and the ethical review of the study that was conducted prior of the experiments.

Only actual travel time and effects on the possibility to open the egress door is assessed in the trials. Other parts of the evacuation procedure and their possible effects are not studied (e.g., awareness time and pre-movement time). The experiments are performed as announced evacuations, meaning that participants are aware that they are supposed to evacuate.

The physical parameters of the premises and evacuation door that were examined and varied during the conduction of the experiments was limited to the prerequisites described in section 2.2. No scenarios included automatic door opening, or similar.

It is important to note that the scope of the project is limited to evacuation through inward opening doors. Other aspects related to fire safety and inward opening doors, such as difficulties in opening the door due to pressure build-up within the fire-compartment, are not addressed in this study.

2. Method

The project was divided into two parts. The first part consisted of a literature study to compile previous research on the subject. Within the literature study, scientific literature, accident investigations and differences between different countries' building legislation regarding inward opening doors for evacuation were studied. The second part consisted of carrying out several evacuation experiments with a variation of parameters regarding door configuration, room layout and initial setup of participants. The evacuation experiments were planned based on the results of the literature study by changing parameters that were identified as problematic in previous research/literature. After performed evacuation experiments, an analysis of aspects that are interesting regarding the opening of the door and the flow through the door was conducted. The foundation of the analysis was to compare scenarios with identical set-up, except for a single varied parameter. Most interesting in terms of comparison is the comparison between inward opened- and outward opened doors. A detailed description of the method of each part of the project follows below.

2.1 Part 1 – Literature review

As part of increasing knowledge about the use of doors hung to open against the direction of travel, a literature review was carried out. The literature review focused on the following topics:

- Regulations and other recommendations governing the use of inward opening doors for escape in new buildings.
- Research linked to people flows and people's actions when using inward opening doors for escape.
- Fires that have occurred where it can be suspected that inward opening doors may have had an impact on the evacuation process or on deaths that have occurred.
- Comments during building fire inspection concerning inward opening doors.

The literature review, focused mainly on scientific articles and reports, was carried out using Lund University's search function LUBSearch. This is a search function that includes material registered in several different publishers' databases such as Science Direct from Elsevier, Scopus, and Web of Science. LUBSearch also includes the university's publication database, which means that, among other publications, reports are included. Reports within the subject have also been reviewed via DiVA, which is a search function used by several Swedish universities, research organizations and other authorities. Users of DiVA include RISE and Luleå University of Technology, among others.

In addition to the use of the search services, a search was made in the proceedings from the Human Behavior in Fire symposium, which includes material from six symposiums between 1998 and 2015. Furthermore, literature manually identified within the research group has been used, such as national building regulations, The SFPE Handbook of Fire Protection Engineering [6] and accident investigation reports.

Since the number of hits is often relatively large when searching the publication databases, a number of keywords were used, also in combination with, for example, information about the journal or equivalent in which the article should be found. Keywords or phrases used are primarily:

- inåtgående+dörr+utrymning (search in Swedish, only in DiVA)
- inward+door+evacuation
- "inward door" + "door swing"
- "inward door" + fire
- evacuation+door

In addition, the keywords or search phrases were combined with information that limits to, for example, the subject of "building evacuation" or pedestrians. Also, the search was limited to the following journals to reduce the number of relevant articles to a manageable number:

- Fire Safety Journal (Elsevier)
- Physica A (Elsevier)
- Fire and Materials (Wiley)
- Journal of Fire Protection Engineering (Sage)
- Fire Technology (Springer)
- Safety Screen (Elsevier)

The number of hits was further reduced by inclusion of additional search items. When the number of relevant papers or reports was below 100, an evaluation was made based on the title of the publication. Those that were found relevant for the current topic were evaluated then by abstract and finally by full publication text. The results from the literature review are presented in brief in chapter 3.

2.2 Part 2 – Evacuation experiments

As part of the project, evacuation experiments were carried out. The implementation of these experiments is described in this section. Before implementation, the experiments underwent an ethics review by the Ethical Review Authority with approved results. The registration number of the ethical review is 2023-01496-01.

2.2.1 Description of the premises

The choice of premises in which the evacuation experiments were carried out was made by listing several prerequisites that the premises needed to fulfil. Aspects that were needed to perform evacuation experiments included the possibility to perform evacuation experiments with an inward opening and outward opening door, flexibility regarding room layout and premises large enough to accommodate approximately 100 people.

Evacuation experiments were carried out in premises belonging to the National Property Board in Västra Stallet, Stockholm. Within the premises, there is a door between two larger spaces, which means that experiments with a door enabling both inward and outward opening directions could be conducted. Furthermore, there was enough space in front of the door to allow the researchers to examine different room configurations adjacent to the door and their impact on the evacuation process. The room is illustrated in Figure 1, with the door used in the experiments marked with a red circle.

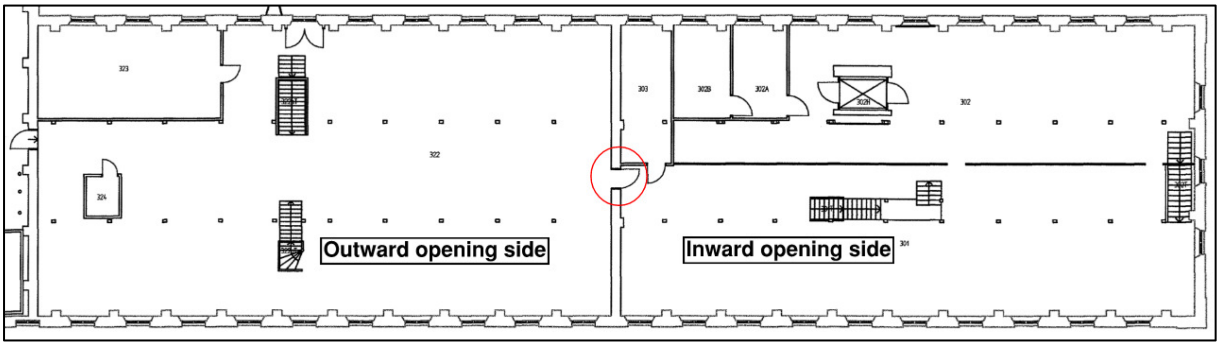


Figure 1. Layout of current premises.

The door that was used in the tests had inner frame dimensions of 1,0 m width and 2,0 m height, see Figure 2. The door leaf encroached 0,03 m on the free width, which meant that the free door opening width corresponded to 0,97 m. The door was equipped with a door handle on each side of the door. The right side of the door in Figure 1, where the door is opening inwards, also had a door knob (see Figure 3) making it possible to lock the door. The door knob was, however, not used in most scenarios and the door could be opened without using it. The left side of the door in Figure 1, where the door was opened outward, had an additional emergency door handle designed in accordance with SS-EN 179 (see Figure 3). The height from the floor to the door handle was 0,96 m and the height from the floor to the door knob/emergency door handle was approximately 1,1 m. During the evacuation experiments, the door opening force generally amounted to approximately 70 N. However, the door opening force was varied in some scenarios.

The experiments were carried out in lighted rooms during the day. This means that the lighting in the premises was relatively good, even if there was partial shading near the door due to several ventilation ducts in the proximity of the door.

Figure 2. Design of the door. Inward opening side to the left, and outward opening side to the right.

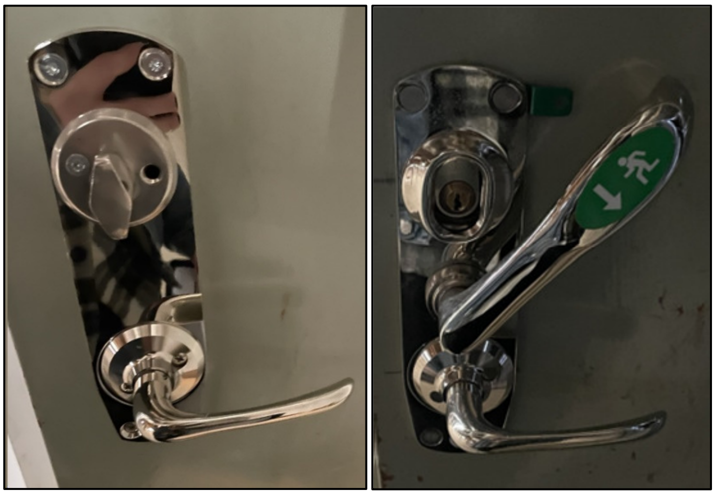


Figure 3. Design of door fittings. Inward opening side to the left, and outward opening side to the right.

2.2.2 Recruitment of participants

The evacuation experiments were intended to be carried out with a larger number of participants than previous studies [7, 8]. The aim was to include around 100 people with an even spread in terms of both gender and age. The idea was to investigate the evacuation conditions with a higher number of people than previous studies to investigate how this affects the conclusions when evacuating through inward opening doors.

In the trials in question, all participants had to fulfill the following criteria:

- 18 years or older,
- In good health, and
- Have no difficulty moving on their own without aids such as a wheelchair, crutches or similar.

Participants were recruited through a combination of the following groups:

- Students at universities and colleges,
- Network of project members and their organizations,
- Network of the reference group's members and their organizations,
- Accindi (a digital recruitment pool for research studies), and
- Social Media.

The recruitment was carried out in two stages, where the participants first had to register their interest. People who had shown an interest in participating then received further information about the experiments in a second stage of recruitment. They then had to answer definitely about attendance at the experiments. In connection with the registration, the participants had to state their gender and age, which is used to compile the demographics of the population.

A total of 95 participants attended the evacuation experiments. The demographics of the population is presented in Figure 4 and Figure 5.

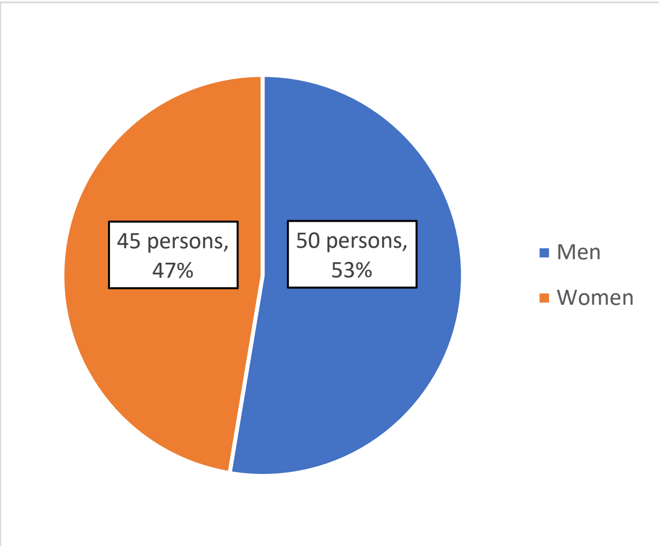


Figure 4. Gender distribution within the trial population.

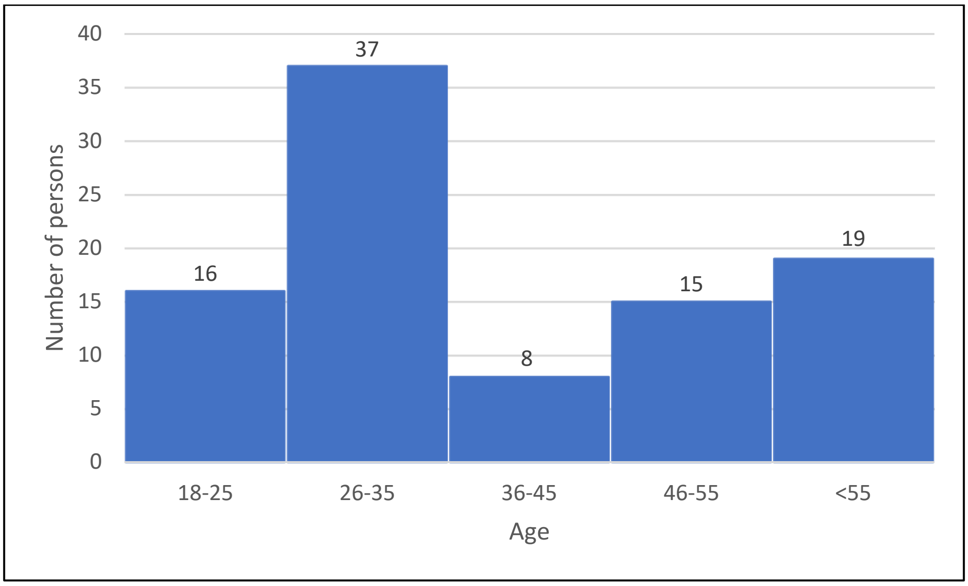


Figure 5. Age distribution within the trial population.

In scenarios performed in small groups, groups were formed to achieve similar demographic distribution as for the population as a whole. Groups were formed with the following number of people:

Group A	27 participants
Group B	30 participants
Group C	30 participants
Group D	8 participants

2.2.3 Data collection

Data was collected by filming the evacuation experiments. A total of eight cameras (Rollei Actioncam 11S and Sony handycam) were used. Placement and direction were set up according to Figure 6, to document different parts of the premises.

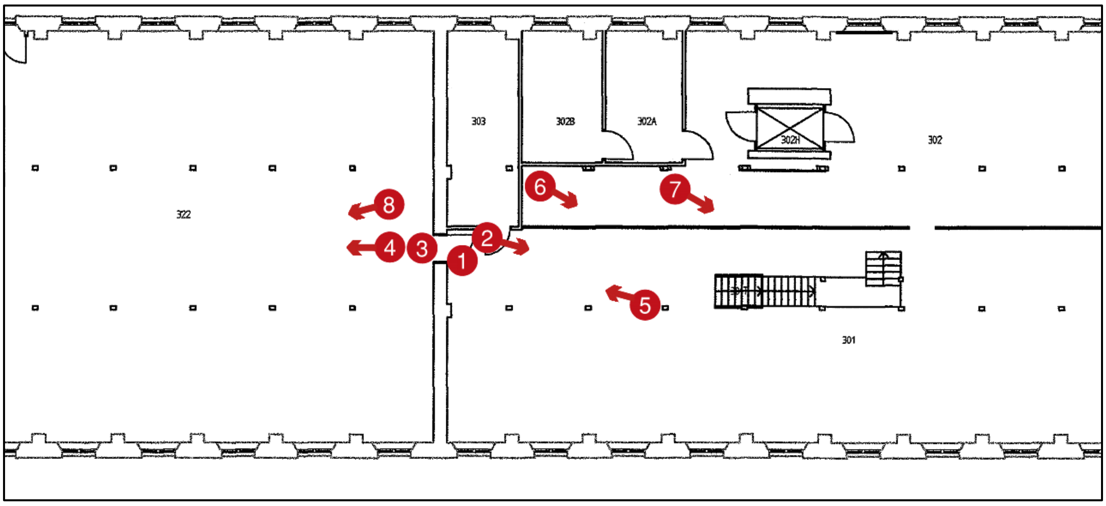


Figure 6. Camera placement and direction. Camera 1 and 3 was placed over the door and was filming downwards.

Camera 1 was placed above the inward opening door, filming downwards, see Figure 7.

Figure 7. Camera angle 1.

Camera 2 was placed to film away from the inward opening door, see Figure 8.

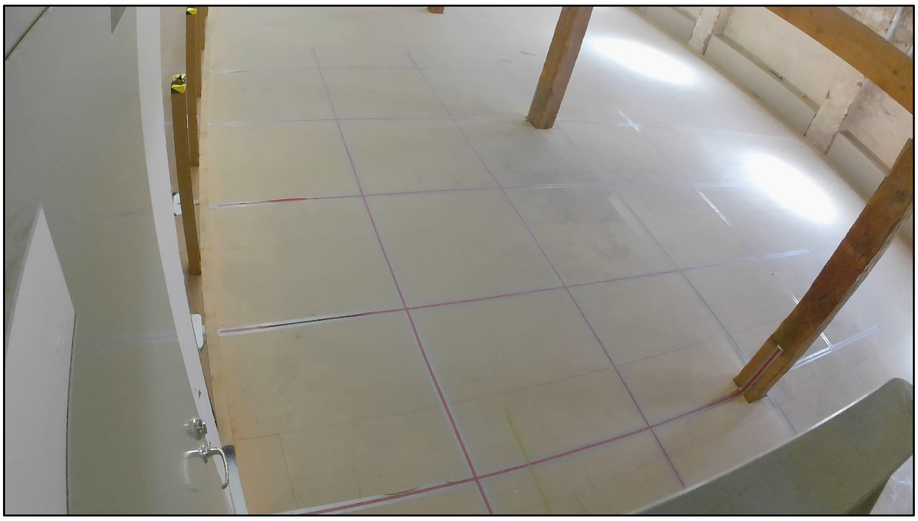


Figure 8. Camera angle 2.

Camera 3 was placed above the outward opening door, filming downwards, see Figure 9.

Figure 9. Camera angle 3.

Camera 4 was placed to film the area in front of the outward opening door, see Figure 10.

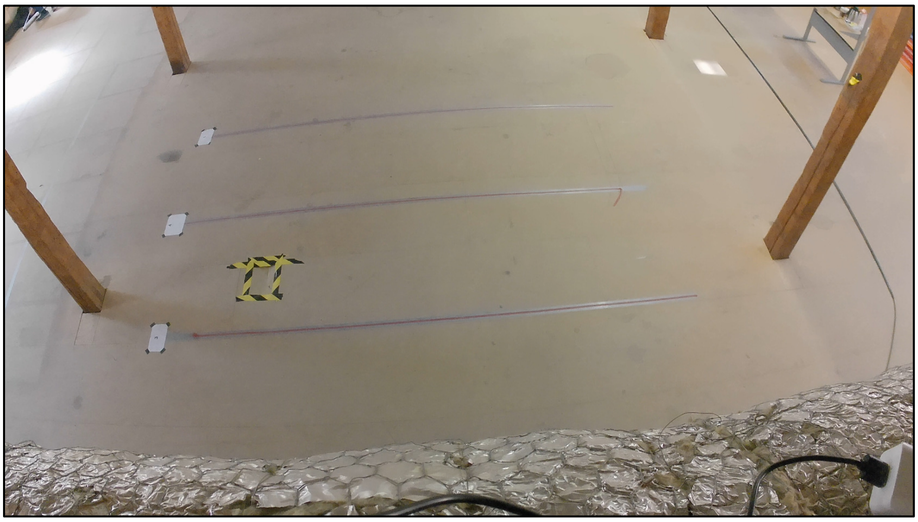


Figure 10. Camera angle 4.

Camera 5 was placed to film the area in front of the inward opening door, see Figure 11.

Figure 11. Camera angle 5.

Camera 6 was placed to film away from the inward opening door, see Figure 12.

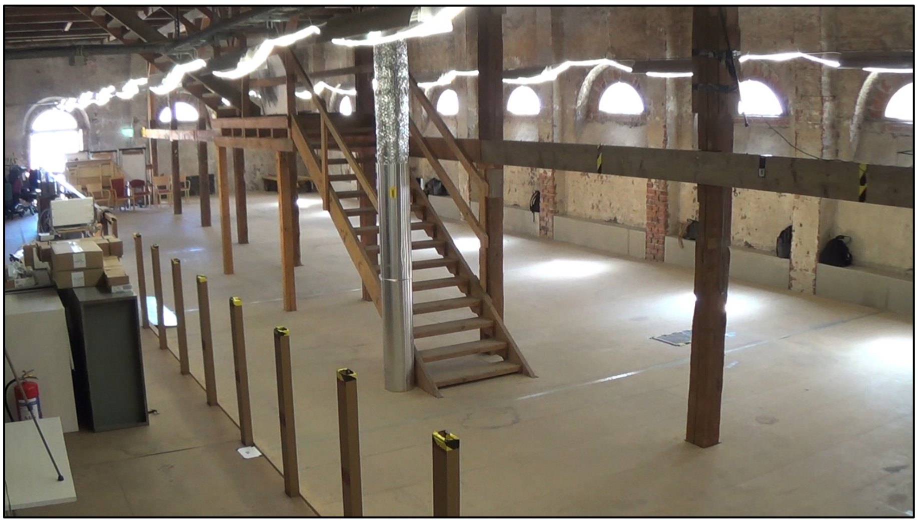


Figure 12. Camera angle 6.

Camera 7 was placed to film away from the inward opening door, see Figure 13.

Figure 13. Camera angle 7.

Camera 8 was placed to film away from the outward opening door, see Figure 14.

Figure 14. Camera angle 8.

Lines were taped to the floor at even intervals to mark distances in the room relative to the door. This was used partly for instructions to experiment participants and partly to enable distance assessment during video analysis. On the inward opening side of the door, lines were taped in a grid of 1 m x 1 m starting 0,5 m away from the door and ending 6,5 m away from the door. Additionally, lines were taped on 10 m, 15 m, 20 m, and 25 m away from the door. On the outward opening side of the door, lines were taped marking 1-5 m, 10 m, and 15 m distance from the door.

Prior to the start of the experiments all participants signed an informed consent form.

2.2.4 Scenarios

A total of 33 scenarios were conducted during the evacuation experiments. For all scenarios, participants were given instructions to walk with a clear goal, such as having decided to evacuate. The people were asked not to stroll or run. Further, all evacuees started their movement at the same time when a whistle was blown.

Each scenario received a number based on the type of scenario. Scenarios were grouped with the first number indicating which parameter was being studied, while the second number indicates differences between scenarios studying the same parameter. When an experiment was repeated, this is marked with letters.

Between scenarios, the participants were asked to shuffle their approach to the door, so that different participants would go in the front, center and back in different scenarios.

2.2.4.1 Summary of scenarios

An overview of the premises and the parameters that were varied between the different scenarios is shown in Figure 15.

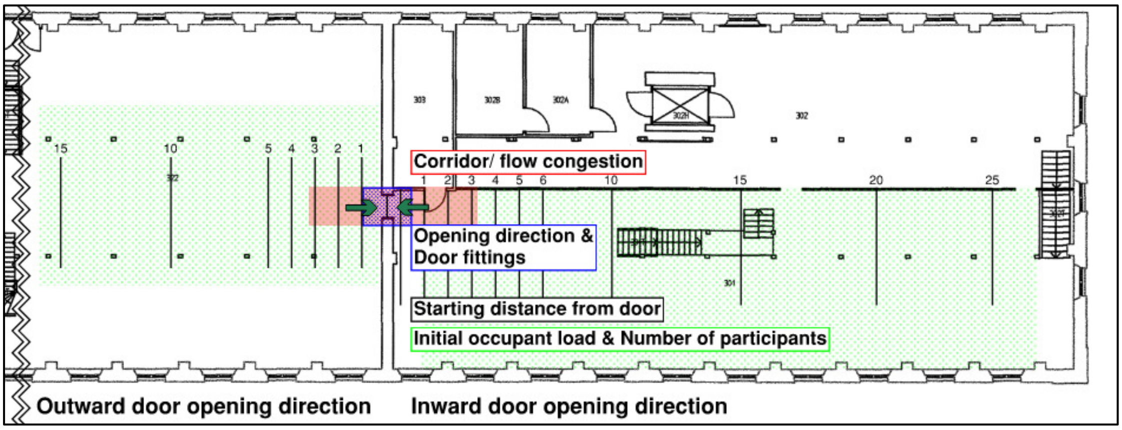


Figure 15. Experimental set-up and overview of varied parameters and their orientation in the premises.

A summary of all scenarios is presented in Table 1, with an overview of variance in parameters between the different set ups. The colours in the table correspond to the categorization utilized in the visualization in Figure 15.

Table 1. Description of each scenario, see also section 2.2.4.1 - 2.2.4.20.

Scenario	Opening direction	Door fittings	Corridor/ flow congestion	Starting distance from door	Initial occupant density (approximation)	Number of participants
1.1.A	Inward	Handle	Yes	10- 30 m	1 p/m^2	95
1.1.B	Inward	Handle	Yes	10-30 m	1 p/m^2	95
1.2.A	Inward	Handle	Yes	3-22 m	1 p/m^2	95
1.2.B	Inward	Handle	Yes	3-22 m	1 p/m^2	95
2.1.A	Outward	Handle	Yes	10-20 m	1 p/m^2	95
2.1.B	Outward	Handle	Yes	10-20 m	1 p/m^2	95
2.2.A	Outward	Handle	Yes	3-12 m	1 p/m^2	95
2.2.B	Outward	Handle	Yes	3-12 m	1 p/m^2	95
3.1.A	Inward	Handle	Yes	3-7 m	2 p/m^2	27
3.1.B	Inward	Handle	Yes	3-7 m	2 p/m^2	30
3.1.C	Inward	Handle	Yes	3-7 m	2 p/m^2	30
3.1.D	Inward	Handle	Yes	3-7 m	1 p/m^2	8
3.2.A	Inward	Handle	No	3-7 m	2 p/m^2	27
3.2.B	Inward	Handle	No	3-7 m	2 p/m^2	30
3.2.C	Inward	Handle	No	3-7 m	2 p/m^2	30

Scenario	Opening direction	Door fittings	Corridor/ flow congestion	Starting distance from door	Initial occupant density (approximation)	Number of participants
3.2.D	Inward	Handle	No	3-7 m	1 p/m^2	8
4.1.1.A	Inward	Handle	No	5-25 m	1 p/m^2	95
4.1.1.B	Inward	Handle	No	5-25 m	1 p/m^2	95
4.1.2.A	Outward	Handle	No	5-15 m	1 p/m^2	95
4.1.2.B	Outward	Handle	No	5-15 m	1 p/m^2	95
4.2.A	Inward	Handle	No	5-15 m	2 p/m^2	95
4.2.B	Inward	Handle	No	2-10 m	2 p/m^2	95
4.2.C	Inward	Handle	No	15-25 m	2 p/m^2	95
4.2.D	Inward	Handle	No	15-25 m	2 p/m^2	95
4.3	Inward	Handle	No	2-5 m	3 p/m^2	95
4.4	Inward	Handle	No	5-10 m, 10-15 m, 15-20 m, 20-25 m	n/a	95
4.5.A	Inward	Door knob	No	5-25 m	1 p/m^2	95
4.5.B	Inward	Door knob	No	5-25 m	1 p/m^2	95
4.6.A	Inward	Handle*	No	5-25 m	1 p/m^2	95
4.6.B	Inward	Handle**	No	5-25 m	1 p/m^2	95
5.1	Inward	Handle	No	0,5-6 m	3 p/m^2	95
5.2	Inward	Handle	No	0,5-5 m	4 p/m^2	95
5.3	Inward	Handle	No	0,5-4 m	5 p/m^2	95

* Door opening force approximately 100 N.
** Door opening force approximately 45 N.

2.2.4.2 Scenario 1.1.A and 1.1.B

A short corridor was built adjacent to the inward opened side of the door. The corridor consisted of bookshelves and had a width corresponding to 1,3 m and a length of 2,85 m, see Figure 16 and Figure 17.

The participants were spread out in an area with between 10 m – 30 m walking distance to the door (7 m – 27 m to the corridor), corresponding to an occupant density of between 0,8–1,0 persons/m^2. Evacuation was performed with all participants through an inward opened door.

The scenario was repeated once.

Figure 16. Design of the corridor.

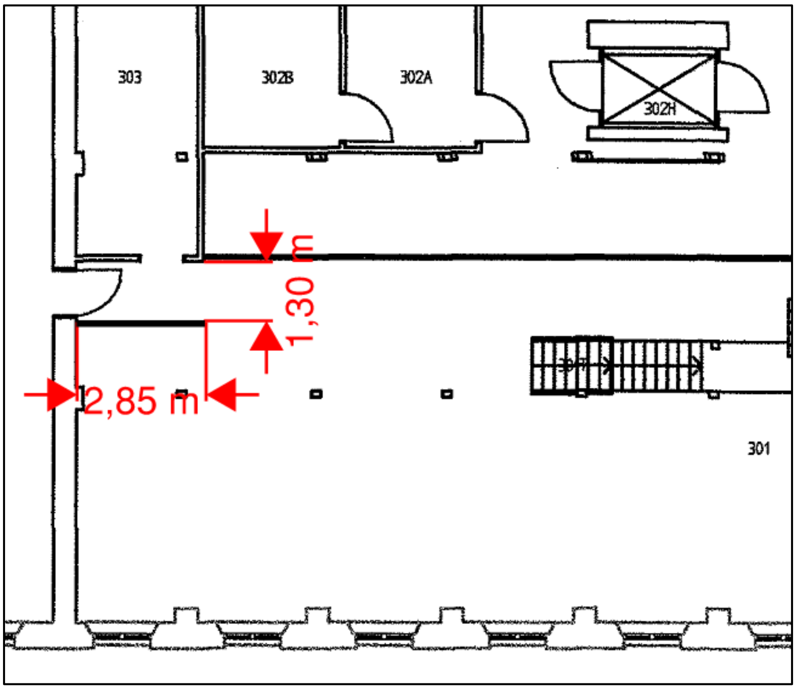


Figure 17. Corridor dimensions.

2.2.4.3 Scenario 1.2.A and 1.2.B

The scenarios used the same corridor as the previous scenario (scenario 1.1.A/1.1.B). In this scenario, the participants started directly in front of the corridor and 22 m back. The scenario had approximately the same occupant density as scenario 1.1.A/1.1.B, 0,8-1,0 persons/m^2. The difference from the previous scenario was the length that the participants had to walk to reach the corridor. Evacuation was performed with all participants through an inward opened door.

The scenario was repeated once.

2.2.4.4 Scenario 2.1.A and 2.1.B

A short corridor was built adjacent to the outward opened side of the door. The corridor consisted of bookshelves and had a width corresponding to 1,3 m and a length of 2,90 m, see Figure 18 and Figure 19.

The participants were spread out in an area between 10 m – 20 m to the door (7 m – 17 m to the corridor), corresponding with an occupant density of between 0,8-1,0 persons/m^2. Evacuation was performed with all participants through an outward opened door.

The scenario was repeated once.

Figure 18. Design of the corridor.

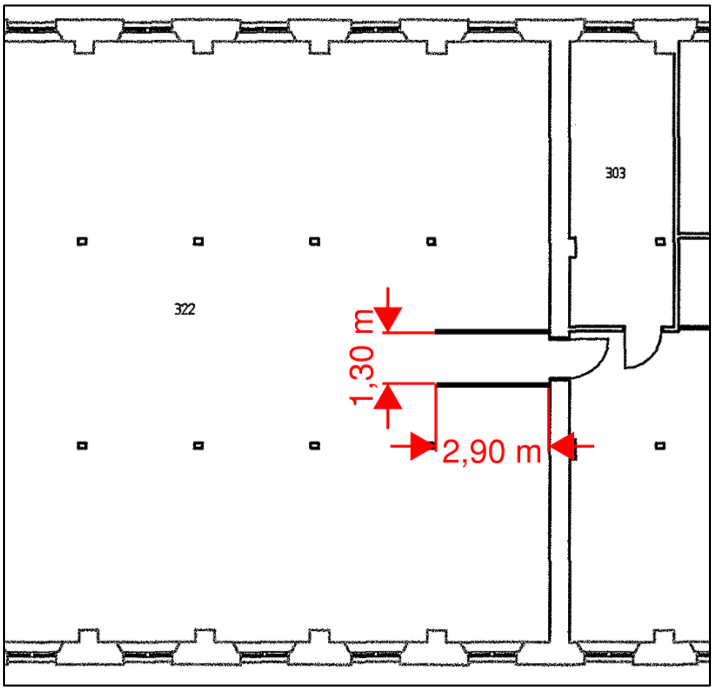


Figure 19. Corridor dimensions.

2.2.4.5 Scenario 2.2.A and 2.2.B

The scenarios used the same corridor as the previous scenario (scenario 2.1.A/2.1.B). In this scenario, the participants started directly in front of the corridor and 12 m back. The scenario had approximately the same occupant density as scenario 2.1.A/2.1.B, 0,8-1,0 persons/m^2. The difference from the previous scenario was the length that the participants had to walk to reach the corridor. Evacuation was performed with all participants through an outward opened door.

The scenario was repeated once.

2.2.4.6 Scenario 3.1.A, 3.1.B, 3.1.C and 3.1.D

In this scenario, smaller groups of participants were evacuating through an inward opened door. The scenarios used the same corridor as scenarios 1.1 and 1.2. The participants started directly in front of the corridor. Participants were allowed to freely position themselves behind the starting line, resulting in an occupant load density of approximately 1-2 persons/m^2.

The groups were divided with corresponding demographics to the group as a whole. Some adjustments had to be made to achieve the desired group size. The number of participants in each scenario was:

3.1.A	27 participants
3.1.B	30 participants
3.1.C	30 participants
3.1.D	8 participants

2.2.4.7 Scenario 3.2.A, 3.2.B, 3.2.C and 3.2.D

In this scenario, smaller groups of participants than previous scenarios were evacuating through an inward opened door. The participants started 3 m from the door. The same groups were used as in scenario 3.1.A-3.1.D.

No corridor was used in the scenario.

2.2.4.8 Scenario 4.1.1.A and 4.1.1.B
The participants spread out in an area 5 m – 25 m from the inward opened door, resulting in an initial occupant density of ca 1 person/m^2. Evacuation was performed with all participants.

No corridor was used in the scenario.

The scenario was repeated once.

2.2.4.9 Scenario 4.1.2.A and 4.1.2.B
The participants spread out in an area 5 m – 15 m from the outward opened door on an area resulting in an occupant density of ca 1 person/m^2. Evacuation was performed with all participants.

No corridor was used in the scenario.

The scenario was repeated once.

2.2.4.10 Scenario 4.2.A
The participants spread out in an area 5 m – 15 m from the inward opened door, resulting in an initial occupant density of ca 2 person/m^2. Evacuation was performed with all participants.

No corridor was used in the scenario.

2.2.4.11 Scenario 4.2.B
The participants spread out in an area 2 m – 10 m from the inward opened door, resulting in an initial occupant density of ca 2 person/m^2. Evacuation was performed with all participants.

No corridor was used in the scenario.

2.2.4.12 Scenario 4.2.C and 4.2.D
The participants spread out in an area 15 m – 25 m from the inward opened door, resulting in an initial occupant density of ca 2 person/m^2. Evacuation was performed with all participants.

No corridor was used in the scenarios.

2.2.4.13 Scenario 4.3
The participants spread out in an area 2 m – 5 m from the inward opened door, resulting in an initial occupant density of ca 3 person/m^2. Evacuation was performed with all participants.

No corridor was used in the scenario.

2.2.4.14 Scenario 4.4
The participants were grouped in groups of ca 15 participants. The groups started with approximately 15 s delay between groups resulting in a pulsating flow of people reaching the door.

No corridor was used in the scenario.

2.2.4.15 Scenario 4.5.A and 4.5.B
The participants spread out in an area 5 m – 25 m from the inward opened door, resulting in an initial occupant density of ca 1 person/m^2. The door was locked with the doorknob (without the knowledge of the participants) and had to be unlocked before the door could be opened. Evacuation was performed with all participants.

No corridor was used in the scenarios.

2.2.4.16 Scenario 4.6.A
The participants spread out in an area 5 m – 25 m from the inward opened door, resulting in an initial occupant density of ca 1 person/m^2. The door opening force were adjusted to approximately 100 N (approximately 70 N in other scenarios). Evacuation was performed with all participants.

No corridor was used in the scenario.

2.2.4.17 Scenario 4.6.B
The participants spread out in an area 5 m – 25 m from the inward opened door, resulting in an initial occupant density of ca 1 person/m^2. The door opening force were adjusted to approximately 45 N (approximately 70 N in other scenarios). Evacuation was performed with all participants.

No corridor was used in the scenario.

2.2.4.18 Scenario 5.1
A grid of size 1 m x 1 m had been marked on the floor starting 0,5 m from the inward opened door. In the scenario, the participants were placed with an initial density of 3 persons/m^2 adjacent to the door. Evacuation was performed with all participants.

No corridor was used in the scenario.

2.2.4.19 Scenario 5.2
A grid of size 1 m x 1 m had been marked on the floor starting 0,5 m from the inward opened door. In the scenario, the participants were placed with an initial density of 4 persons/m^2 adjacent to the door. Evacuation was performed with all participants.

No corridor was used in the scenario.

2.2.4.20 Scenario 5.3
A grid of size 1 m x 1 m had been marked on the floor starting 0,5 m from the inward opened door. In the scenario, the participants were placed with an initial density of 5 persons/m^2 adjacent to the door. Evacuation was performed with all participants.

No corridor was used in the scenario.

2.2.5 Analysis of data
Video analysis was performed after the evacuation experiments had been carried out. During the analysis, a distinction was made between the terms *Parameter* and *Aspects*. *Parameter* refers to variables that change between scenarios whilst *Aspect* refers to the studied phenomena, behaviors or measurables when assessing data.

Means of assessment are explained in the subsections below.

2.2.5.1 Studied aspects
Based on the project's research questions, the following aspects have been identified as interesting to study within the scope of the project. All aspects are not applicable to every scenario.

Group formation

A general review of group formation when the population was approaching the door was executed for the different room layouts to form a basis for assessing the density of people when the door is opened. Human behaviour of people passing through the door was also studied briefly. This analysis was carried out by studying how a group of people form when passing through the door. This is described in qualitative terms.

Thus, assessment of the group formations was divided into two stages of an evacuation process, approaching the door, and passing through the door.

Studied aspects are defined as pre-defined group formation types, which are described as below.

- **Triangle** – People moving in a triangle with a distinct point in the front of the group, see Figure 20.

Figure 20. Triangle - Example of group formation.

- **Cluster** – People moving/queuing in a cluster with no clear shape, see Figure 21.

Figure 21. Cluster - Example of group formation.

- **Line** – People moving/queuing in straight lines, see Figure 22.

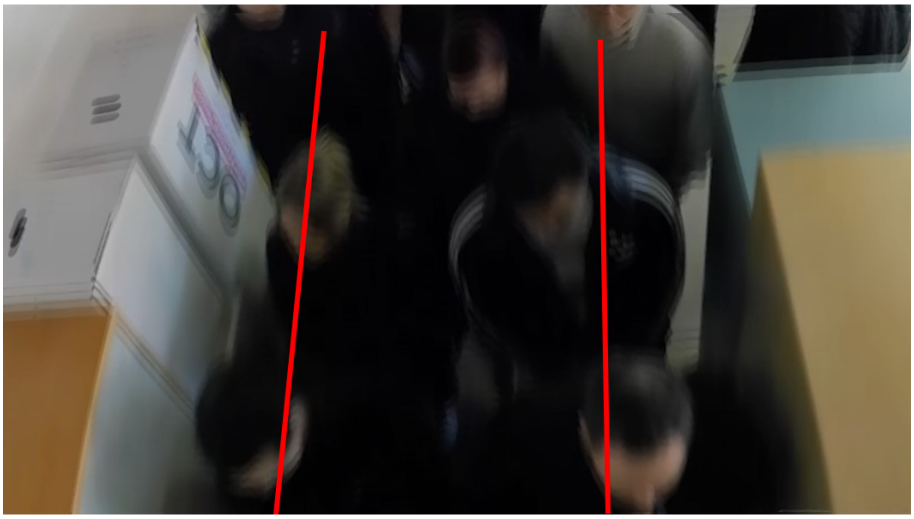


Figure 22. Lines - Example of group formation.

- **Zipper** – People moving/queuing in two lines with an offset corresponding to one person, see Figure 23.

Figure 23. Zipper - Example of group formation.

- **Funnel** – The combination of triangle and line/zipper, see Figure 24.

Figure 24. Funnel – Example of the group formation.

Opening the door

The ability, or more specific any difficulty, associated with opening the door was studied for all scenarios. This analysis was divided into the following aspects:

- Interaction of people when opening the door,
- Occupant density, and
- Time to open the door.

Assessment of interaction between people when opening the door was carried out in a qualitative- and semi-quantitative manner by answering the following questions:

- Is interaction between two or more people required to open the door?
  - Yes, or No?
- If yes, how do people have to interact?
  - People near/behind the person who opens the door need to slow down for the door to open.
  - People near/behind the person who opens the door need to stop for the door to open.
  - People near/behind the person who opens the door need to move for the door to open.
- How many participants must interact for the door to be opened?

Occupant density close to the door, when the first person passes the door threshold, was studied for all scenarios except for scenarios 5.1, 5.2 and 5.3 since these scenarios had a fixed occupant density when the scenarios were started. The occupant density was measured in the intervals 0-1, 1-2 and 2-3 meters from the door to capture variations of the occupant density in the vicinity of the door. Occupant density was measured by counting the number of people in a specific area and is presented as persons/m^2.

The time to open the door was measured from when the first person grabs the door handle until the door was fully open (approximately 90 degrees open), or when the opening maneuver was considered finished.

Occupant flow through door

Occupant flow through the door was assessed by studying the following aspects:

- Overall people flow, and
- Initial stage of passing through the door.

Averaged overall flow of people during the evacuation scenario was studied for all scenarios excluding scenario 4.4. The flow of people was measured by measuring the time it took from the first person passing the threshold until the last person had passed the threshold and is presented as persons/second.

Based on previous studies regarding inward opening doors for evacuation [7, 8], the possibility to open the door in an initial part of egress is essential for the evacuation possibilities. This was studied for all scenarios, except for scenario 4.4, by measuring the time from when the first person touched the door handle, to when the fourth-, fifth- and sixth person passed through the door.

Summary

In summary, the analysis was conducted by studying the following aspects:

- Group formations:
    - Approaching the door
    - Passing through the door
- Opening the door:
    - Interaction of people when opening the door
    - Occupant density when opening the door
    - Time to open the door
- Occupant flow through the door:
    - Overall people flow
    - Initial stage passing through the door.

These aspects were studied based on the variation of the following parameters:

- Door opening direction
- Presence of corridor
- Starting distance from the door
- Initial occupant density
- Number of people in the experiment
- Door configuration.

2.2.5.2 Comparison between scenarios

A total of 33 evacuation experiments were conducted with different variations of parameters including the design of the room, door, or the initial formation of the evacuees.

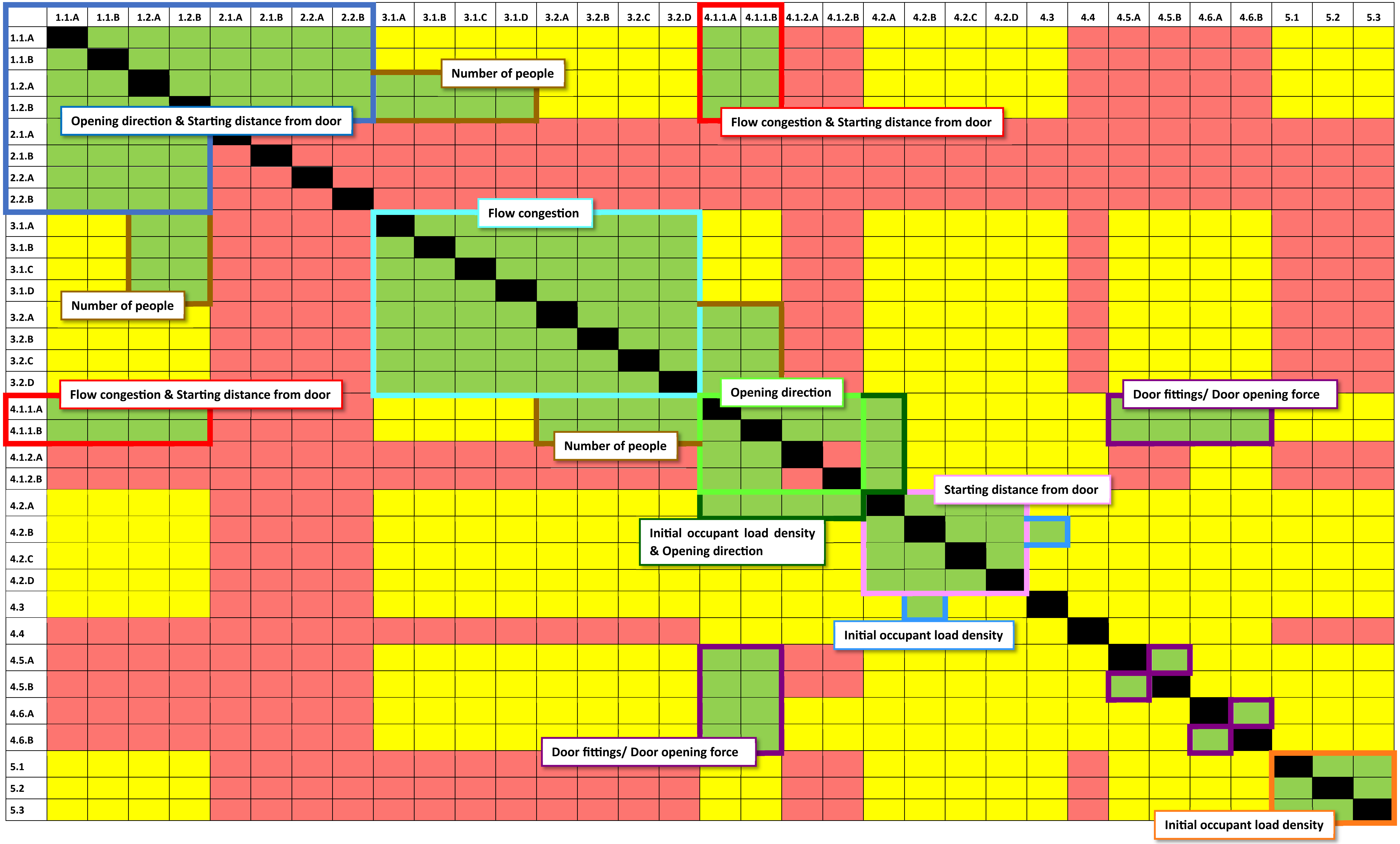
A comparison between the scenarios was made to analyse the differences in results between the scenarios. Scenarios with the same scenario set-up, but with one parameter changed were considered comparable, e.g., scenarios with a corridor, the same starting distance to the door, but different opening direction of the door. Scenarios with different scenario set-ups (several varied parameters) were not seen to be directly comparable but could be compared regarding some aspects, e.g., a scenario with a corridor and long walking distance to the door is not directly comparable with a scenario without the corridor, a shorter walking distance and a higher initial occupant density and is not included in the comparison overview. Since all scenarios were not considered to be comparable, a matrix was created to visualize which scenarios were compared to each other to draw conclusions from the results.

The matrix consists of a colour code of three colours.

- Green combinations indicate scenarios that could be directly compared. This could be scenarios with inward opened door, but with differences in room design, door configuration or initial people formations. It also includes comparison between scenarios with inward opened- and outward opened doors but with otherwise fixed room design. In general, variance of parameters is limited to one, or a maximum of two parameters when the differences are small, in comparison between "green scenarios".
- Yellow combinations indicate scenarios where some aspects could be compared. This includes, e.g., comparison between scenarios including all participating participants and scenarios that were executed using the smaller groups. All aspects might not be compared, however, differences are observed and commented if found relevant. Generally, the possibility to open the door in an initial state of evacuation could be compared, but other aspects might not be comparable. A discussion regarding compared parameters between specific scenarios is presented in chapter 5. In this category more than one or two parameters could be changed, which makes direct comparison between scenarios more uncertain. Assessment of "yellow scenarios" is made in more general terms and only in cases where interesting observations could be made.
- Red combinations indicate scenarios that should not be compared. Meaning that the comparison of the combinations is not of interest based on the scope of this study.

The matrix is presented in Table 2. As an example, the matrix shows that the scenario series 3.1 and 3.2 are directly comparable to each other. This since only the door opening direction is varied between the two scenarios and all other parameters are kept identical. This combination is categorized as a green combination.

Table 2. Matrix of comparison between different evacuation scenarios.



3. Results – Literature review

3.1 Movement studies

To determine evacuation times from buildings, extensive research has been conducted to determine flows and walking speeds through door openings, up and down stairs and on horizontal surfaces [9, 10, 11, 12, 13, 14, 15]. In some cases, obstacles have also been included in the flow of people to establish that there are cases where the flow through openings was increased using bollards in the passageway [16, 17]. There are also studies where the corresponding situation was investigated and where a similar increase of the flow could not be ascertained [15].

When moving within a group, people try to adapt their own movement in an efficient way. As an example, people do not walk in rows one behind the other if the width allows two people to walk next to each other. Instead, they tend to position themselves alternately to the right and left to create a space in front so that the distance to the one in front does not become an obstacle [18]. This is likely to happen up to a level of the occupant density hindering the person from influencing the conditions.

When a group of people moves in a corridor configuration, a typical distribution tends to emerge quite naturally [10]. The section of the group where the most people are moving is shaped like a rectangle, where the walking speed is largely controlled by the person closest to the front. At the front of the group, a tip occurs, where people move more freely and independently of other people. This results in a higher walking speed and with it a spread of people, which in turn leads to a lower density of people in the front of the group. At the end of the group, a "tail" is formed where the walking speed is lower, which in turn means that the density of people in this part is also lower (see Figure 25). This applies above all when moving within corridors or other narrow passages. In larger premises the end of the formation of people can be expected to spread out even if a certain tip can be expected in connection with the escape route where escaping people move.

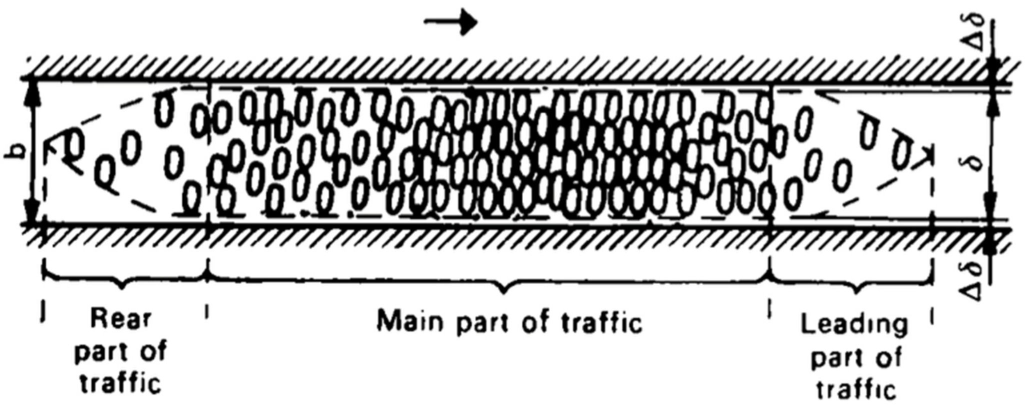


Figure 25. Distribution of people when moving in a group [10].

It is therefore conceivable that the first persons to reach an inward opening door will theoretically have the opportunity to open the door at the initial stage, without obstructive interference from other persons in the group.

Predtechenskii & Milinskii [10] and Khisty [19] have also stated that evacuation takes place faster if it is a real evacuation compared to if the movement takes place under more normal conditions. Both the flow and the speed through a passage are affected by the conditions, for example, factors like age and age distribution, physical conditions of the persons and the motivation of people to walk through the door opening. People carrying luggage are also expected to occupy a larger horizontal area which will lead to a reduction in the expected flow rate. The density of people in front of a doorway and more person-related characteristics will, thus, affect how many people pass per second. The historical data on movement characteristics is to a certain degree, however, questioned because of changes in the population characteristics, mainly in terms of e.g., obesity and physical mobility [20]. Therefore, new data is collected to reflect this change and older data should be used with this knowledge in mind. Still, trends in movement patterns can be expected to be unchanged.

In many of the experiments reported, it can be stated that the variation in both flow and speed is considerable. As an example, it can be mentioned that the flow of people through one and the same doorway in Lennartsson and Weyler [7] is 1.5 – 2.5 people per second when the occupant density is high in front of the door and between 0.5 and 1.0 people per second when the occupant density is lower. This relatively large variation has led to the introduction of new models to describe the movement of people, which are based on biomechanical aspects within the population, models that aim to better model movement [21].

Therefore, we can conclude that there is solid research behind the knowledge of the movement of people during evacuation; but the aspect of conditions at inward opening doors has been less addressed. Therefore, the regulations presented are likely to be partly based on accidents that have occurred and reasoning around them, and partly on research results for more general situations that have been applied to inward opening doors.

3.2 International building regulations

Many countries' building codes allow the use of inward opening doors in the escape routes. The reason is that in many cases it is practical to let the door swing inwards. However, it may only be allowed within some types of premises or with a limited number of people being expected to pass through such a door. Table 3 presents conditions for the use of inward opening doors for some countries. Note that some countries regulate the number of people in the room served by the door and others regulate the number of persons expected to use a door swinging inwards.

Table 3. Inward opening doors in the building regulations.

Country and building code or similar	Regulation in the building code	Comment
Sweden, BBR [1]	From a room holding maximum 30 persons.	Additional requirement whether persons can be expected to be familiar with the building.
Norway, Guidance to TEK17 [22]	From a fire compartment holding a maximum of 10 persons.	
Denmark, BR18 [23]	For doors serving up to 150 persons.	
USA/NFPA 101 [24]	From a room holding a maximum of 50 persons.	
UK (England) BS 9999:2017 [25]	For doors serving up to 60 persons.	

In the next section, quotes from each of the building regulations are presented. For Norway and Denmark, no official translation was found. It should be noted that the English translation of the code texts for Norway and Denmark are not the official text.

3.2.1 Sweden (BBR 29)

5:335 Doors

Doors to be used for evacuation shall open outwards in the escape direction and be readily identifiable as exits. Inward opening doors may only be used if queues are not expected to occur in front of the door. Other variations of doors may be used if they can provide an equivalent level of safety as side-hung doors. (BFS 2011:26).

General recommendation

The doors should be positioned to ensure when open, they do not prevent the escape of other people.

Queues are not expected to occur in

– dwellings in occupancy class 3 and residential rooms in occupancy class 4,

– premises designed for a maximum of 30 people and where people are aware of the environment such as classrooms in occupancy class 2A, small offices and engineering workshops in occupancy class 1 and entrance doors in residential buildings in occupancy class 3,

– premises for a maximum of 30 people and where people cannot be expected to have knowledge of the environment and where the walking distance to the escape route is no more than 15 meters, such as places of assembly in occupancy classes 1 or 2A, shops, bank premises and restaurant operations in occupancy class 2A.

3.2.2 Norway (TEK17, guiding document)

IV Conditions for evacuation and rescue. §11-13. Exit from fire compartment.

Door to an escape route from a fire compartment allowed for a low number of occupants may swing inwards. A low number of occupants means 10 persons or less. A fire compartment holding a low number of occupants can, for example, be an apartment, nursing room in a hospital, a hotel room and smaller offices and stores.

3.2.3 Denmark (BR18 - Building regulation guiding document to chapter 5 - Fire Safety)

2.3.4.2 Opening direction and door fittings

According to BR18 § 94, sect 2, no. 7, doors in or to an escape route shall be easy to open. Further, doors shall open in the direction of evacuation if the evacuation routes are used by more than 150 persons.

3.2.4 USA/NFPA 101

7.2.1.4.2 Door Leaf Swing Direction. Door leaves required to be of the side-hinged pivot-swinging type shall swing in the direction of egress travel under any of the following conditions:

(1) Where serving a room or area with an occupant load of 50 or more, except under the following conditions:

a) Door leaves in horizontal exits shall not be required to swing in the direction of egress travel where permitted by 7.2.4.3.8.1 or 7.2.4.3.8.2.

b) Door leaves in smoke barriers shall not be required to swing in the direction of egress travel in existing health care occupancies, as provided in Chapter 19.

(2) Where the door assembly is used in an exit enclosure, unless the door opening serves an individual living unit that opens directly into an exit enclosure.

(3) Where the door opening serves a high-hazard contents area.

3.2.5 UK (BS 9999)

15.6.3 Direction of opening

The door leaf of any doorway or exit should, where reasonably practicable, be hung to open in the direction of escape, and should always do so if the number of persons that might be expected to use the door at the time of a fire is more than 60.

3.3 Research on inward opening doors

The result from the literature review indicates that there is a need to investigate the consequence of evacuating through inward opening doors. In practice, there are only two bachelors theses in the area that address questions connected to inward doors in a more detailed manner, i.e. Babayan [8] and Lennartsson and Weyler [7]. Both Babayan and Lennartsson & Weyler report experimental results from trials with escape through inward opening doors. These reports are, therefore, summarized in the following sections.

Furthermore, Kecklund, Hedskog and Bengtson [26] describe that the design of the fittings on a door is important because unclearly designed fittings can delay the door being opened. This is likely to be more important if the door opens inwards. The fittings must be designed so that it can intuitively be understood how they should be used. However, inward opened doors are not specifically mentioned. Brand and Sörqvist [27] describe escape experiments through passages and doors for people with movement impairment, among other things, and state that the design of fittings is particularly important for this category of people. Otherwise, they conducted no experiments using inward opening doors. Li and Xu [28] describe egress through different doors and state that inward opening doors are to be preferred in a classroom configuration as the door leaf does not encroach on the space in the corridor outside. The same aspect is also addressed by Svensson [29], but from the perspective that people with visual impairments may have difficulty moving in a corridor if a door leaf swings out into the corridor. Svensson therefore recommends that doors facing corridors open into the room unless the door is in an escape route.

3.3.1 Summary of Babayan's study

Babayan [8] conducted experiments with a mixed group of participants, i.e., with varying ages (19-75 years), with an even gender distribution, who are said to represent the general public. The experiments were carried out in a university building in Lund. The tests were carried out with a door, 1,20 meters wide, but where the door's opening device could be modified so that it would correspond to different fitting types (both according to SS-EN 179 and SS-EN 1125), see Figure 26. The tests were carried out in both directions of the doors, i.e., inward and outward opening directions. The fitting type SS-EN 1125 was simulated such that the participants only had to press the door leaf to open it and did not use a traditional door handle.

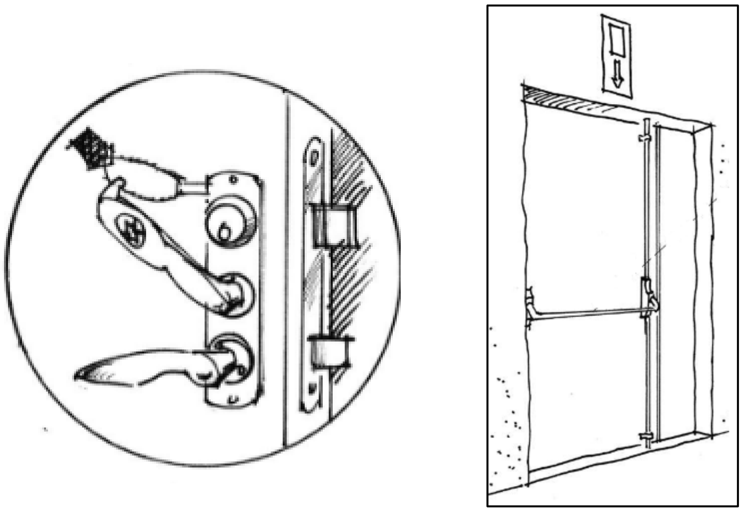


Figure 26. Door fittings according to SS-EN 179 (left) and SS-EN 1125 (right), illustrations from Brandskyddshandboken [30].

In the current case differences in the door's opening force were not investigated. The opening force was in all cases 50 N. The door was glazed, i.e., it was possible to see through it even in the closed position.

The size of the experimental group varied between 42 participants, who in part 1 used a so-called SS-EN 179 device, and 56 participants in part 2 who opened the door by just pushing at it. The trials were varied with respect to the group size walking together towards the door and the time interval between two following groups. The group sizes were 1, 7, 14 or 22 participants in a group and the time intervals were either 7 seconds or 15 seconds. In addition, some trials were conducted with an even larger group walking towards the door, 30 participants or the maximum number of people for a trial round i.e., 42 or 56 participants.

Queuing occurred in practice in all cases within a group when the number of participants was 14 or more regardless of whether the passage was through an inward or outward opening door. When the interval time was 7 seconds, queuing could also occur between two consecutive groups.

To be able to compare passage between the two door swing directions, the total time for the passage of all participants was measured. The difference between passage times for inward and outward opening doors was marginal. The type of opening device was also stated not to affect the passage times for otherwise equal conditions. The flow rate was not measured in the experiment as it was designed to compare several groups passing a door with different number of participants in each group and with two different time intervals between following groups. Therefore, comparisons of total time between first and last person is reported for each trial. There were no reports of any typical problems when people passed the doorway. It is mentioned that some participants held the door to make it easier for the person coming next.

Holding the door open, to make it easier for the next subject to pass, was something the author considers to be intuitive behavior.

3.3.2 Summary of Lennartsson's and Weyler's study

The second thesis was carried out by Lennartsson and Weyler [7]. They used students of almost the same age as participants. The participants had an average age of 24 and most of knew each other prior to the tests. The group had an even gender distribution with 54% men and 46% women. A total of 60 participants participated in the trials. The experiments were carried out in a university building in Lund and two different doors were used which had different hanging sides, i.e., they were either right- or left-hung. Additionally, the doors' automatic closing mechanism was disconnected in some trials. The opening width of the doors was 90 cm, and the opening force was 75 N. The opening devices were equivalent to SS-EN 179. Both doors were fitted with glass, making it possible to see through them. The purpose of the trials was to investigate the influence of several variables that could have an impact on the flow through a doorway.

A total of 52 trials were carried out with different conditions regarding the hanging of the door, the direction of leaf swing, with or without an automatic closing mechanism and with high or low occupancy. Each trial was repeated between one and five times. High occupant density was achieved by all the participants walking towards the door at the same time (about 2,5 people/m^2) and for low person density, the participants walked in small groups towards the door with about three second intervals (maximum 1,3 people/m^2).

The flow of people through the opening was not affected by the door's swing direction or whether the door was right- or left-hung. There was also no noticeable difference in the flow of participants if the door was equipped with an automatic closing mechanism or not. The flow through a door with such a closing mechanism was higher if the door opened inward compared outward for the high-density condition. The difference was, however, small.

There were differences in how the participants approached and passed the door depending on whether the door was an inward or outward opening door. When the door opened in the direction of travel, it was usually the person who opened the door who also went through it first. In the case of an inward opening door, in some cases it was a person other than the one opened it who first passed through the door while the person who opened the door and held it open.

In all cases, people helped each other to get out by holding the door open for other people. In no case could it be established that the inward opening door could not be opened due to people pushing from behind. The way people passed through the doorway varied slightly depending on whether the door was inward or outward. The authors explain this by the fact that people adapted their position and possible twisting of the body to get through the opening faster.

3.4 Accident investigations

Several serious fire incidents with large numbers of people involved have been investigated to try to identify cases where an inward opening door played a major role in the consequence of the accident. A total of 20 fires were investigated, see Table 4. The selection of cases investigated was based on information from the reference group of the project. The cases mainly include some more severe accidents investigated by the National Fire Protection association (NFPA) in the United States. This means that there are, most likely, numerous other cases which could have been included. The cases investigated represent a variety of building occupancies and the first incident occurred in 1822. It should, however, be noted that the quality of the investigation reports following the cases differs. Not all the cases included have reported any inward swinging doors, but this does not preclude them having been present as the opening situation of the evacuation doors is present in only a few of the cases. In addition, it is also in some cases not clear whether the door opening direction of the door, even in cases it was swinging inward, had anything to do with the outcome of the fire. Based on the circumstances not being clearly described, there are situations where the door itself could have been locked.

Table 4. Investigated fire incidents.

Fire incident	Year	Inward opening door present	Comment
Grue church, Kirkenaer, Norway [31]	1822	Yes	116 persons died in the fire and the report claim they were prevented from evacuation because of the inward swinging doors.
Iroquois theatre, Chicago, IL [32]	1903	No	
School, Collinwood, Ohio, USA [33]	1908	No	
Triangle shirtwaist factory, New York, NY, USA [34]	1911	Yes	Approximately 75 persons were found dead inside, in the proximity, of the inward swinging doors to the two staircases (8^{th} floor). No evidence about locked doors or that they were unlocked.
Cocoanut Grove night club, Boston MA, USA [35]	1942	Yes	Approximately 100 fatalities were found in proximity of the inward opening door. The fire development was extremely rapid. Door most likely not locked.
Hartford Circus, Hartford, CT, USA [36]	1944	No	
Winecoff Hotel, Atlanta, GA, USA [37]	1946	No	
Our Lady of the Angels school, Chicago, IL, USA [38]	1958	No	
The Upstairs Lounge nightclub, New Orleans, LA, USA [39]	1973	No	
Beverly Hills Supper Club, Southgate, KY, USA [40]	1977	Unclear	Not clear if inward opening doors were present. Inward opening doors were shown on drawing, but nothing mentioned in the text.
MGM Grand Hotel, Las Vegas, NV, USA [41]	1981	No	
Stardust Nightclub, Dublin, Ireland [42]	1981	No	

Fire incident	Year	Inward opening door present	Comment
Six Flags Haunted Castle, Jackson, NJ, USA [43]	1984	No	
Bradford stadium, UK [44]	1985	Yes	The door was locked during the match and does not seem to have been used at all during the incident.
Dupont Plaza hotel, San Juan, Puerto Rico [45]	1986	Yes	Several fatalities in the Casino part, approximately 35 of them found close to inward opening door. Door may have been locked. Rapid fire spread.
World Trade Center Terrorist attack, New York, NY, USA [46]	1993	No	
Düsseldorf airport, Germany [47]	1996	No	
Göteborg nightclub, Sweden [48]	1998	No	
Station Nightclub, West Warwick, RI, USA [49]	2003	Yes	A door close to the stage was inward opening but it seems not to have been used as the fire started on the stage.
Lame Horese nightclub, Perm, Russia [50]	2009	No	

3.4.1 Grue church, Kirkenaer 1822

Rapid fire progress with unclear cause. According to descriptions, there were 500-600 people in the church when the fire started. Of these, between 113 and 116 died because they could not open the inward opening doors, but still the majority were able to evacuate at an early stage. The description is based on recent documents and the credibility of the descriptions is unclear, although many perished in the fire. It is claimed that this fire is the origin of why there must be outward opening doors from public premises.

3.4.2 Triangle shirtwaist factory, New York 1911

The fire occurred in a textile production facility with 240 sewing machines. Each floor was about 750 m^2 and there were two stairwells that could be used for evacuation. The fire covered several floors and a total of around 145 people died. On the 8^{th} floor, where the shirtwaist factory was located, 75 people died at the doors to the stairwells and these doors were inward opening. The investigation states that there was a considerable delay in opening the doors, which indicates difficulties in opening them. There is some hearsay that doors were locked but this cannot be verified based on the investigation reports.

3.4.3 Cocoanut Grove, Boston 1942

The fire started in the basement of a nightclub with furnishings that caused a very rapid fire spread throughout the premises. The interior consisted partly of easily flammable decoration to resemble a South Sea theme. Information indicates that approximately 1 000 people were present in the room, which was intended for 600 people. Almost 500 people died in the fire. Several conceivable theories have been discussed as the cause of the serious consequences. Several doors were locked, however, the inward swinging door where approximately 100 fatalities were found was most likely not locked. It was difficult to find one's way around the premises and several dead people were found sitting at the tables, which is said to be the result of the rapid progress of the fire.

3.4.4 Dupont Plaza, Puerto Rico 1986

In the casino part of this hotel building, a total of 84 people died and about 35 of these were found in the proximity of an inward opening door. In the investigation report, it is stated that the door may have been locked, which would have been the reason why the people could not get to safety. The door was closed at the time of the investigation, and it cannot be ascertained whether it was possible to use it or not. The door also required a two-handed grip to open. The course of the fire was rapid. The majority of those who died, died due to direct fire exposure and not from exposure to the smoke.

3.4.5 Summary of investigation reports

All in all, it can be stated that there are reported cases where inward opening doors hindered escape. However, it is not always determined what the reason for this is and whether the opening direction itself made it impossible to open the door and get out. In some cases, there are also suspicions that the door was locked.

3.5 Inspection reports and other accident investigations

The literature review also searched for supervisory cases that may have been affected by the presence of inward opening doors. The ones that were reviewed are those reported in the report 'I skälig omfattning (To a reasonable extent)' [51] which covers examples of supervisory cases according to the Civil protection act up to 2015 [4] and published by the Swedish Civil Contingencies Agency (MSB). The report should be seen as support for the municipal supervision. One case is reported where there is a remark that an inward opening door in an elderly home should be rebuilt so the swing direction became outwards. However, the County Administrative Board rejects the requirement from the Fire survey officer as it does not comply with recommendations for new buildings of this type of premises.

MSB also presents a selection of municipal investigation reports after accidents and rescue operations. In cases where the investigation refers to assembly buildings or public premises, there are no cases where inward opening doors are specifically noted. This applies to investigations between 2019 and 2022.

Accident investigations carried out by the Swedish Accident Investigation Authority have also been investigated. Of those that refer to fire in a building occurring between 1990 and 2023, there are none that address inward opening doors, neither in general nor as a cause of the outcome of the accident.

3.6 Final remarks from the literature review

It is clear that inward opening doors may be used for evacuation in many countries, but that the requirements vary from one country to another. To some extent, this could be related to differences in terminology, but the variation is still between 10 and 150 people being allowed to pass through an inward opening door.

There is a lack of research that sheds light on the problems associated with inward opening doors for evacuation. Only two publications have been identified and these do not indicate any major differences between inward opening and outward opening doors, at least not for the number of people and other conditions during the experiments. It can be seen that people help each other to make the passage through the doorway work as easily as possible.

A few more serious fires have also been investigated. In some of these cases, information has been found indicating that some doors opened inwards. In one case, the investigation report states that people probably died because the door was opening inwards (Cocoanut Grove), but not that this was the only reason. In the cases where there were inward opening doors, the fire spread was also often very rapid through the building, which means that the total available time for evacuation was very short. In other cases, it cannot be ruled out that doors in fact were locked. There is therefore no clear evidence in the literature that it would be particularly problematic from a general perspective if doors for escape open inward or outward.

4. Results and observations – Evacuation experiments

In the section below, results and observations from completed evacuation experiments are compiled. An analysis of the results is carried out, including a comparison between different scenarios. The comparisons made depend on the aspect studied and the scenarios compared. Therefore, these are listed at the beginning of each section.

4.1 Group formation types

Group formation types when approaching the door affects the occupant density in front of the door when the door is opened and, thus, the possibility of opening the door. Based on the experiments, the group formation when approaching the door is dependent on whether there is flow congestion in front of the door and the walking distance to reach the door.

When assessing group formations, there is a need to distinguish between group formations when:

- approaching the door, and
- passing through the door.

This distinction is made and described based on the variation between scenarios below.

Each group formation described is specified and illustrated in section 2.2.5.1.

4.1.1 Approaching the door

4.1.1.1 Effects of starting distance from the door

A greater starting distance from the door will result in a more distinct point of the group formation. Already at a shorter walking distance, a triangle-like group formation can be observed. This is the case in scenarios 1.1-3.1.C, 4.1.1-4.2.A, 4.2.C-4.2.D and 4.5.A-4.6.B. All these scenarios, except for scenarios 1.2, 2.2 and 3.1, had an initial walking distance of at least 5 m.

Scenarios 1.2, 2.2 and 3.1.A-3.1.C had a starting point directly adjacent to the corridor. When the movement started in these scenarios, a triangle with a somewhat less distinct point/shallow funnel was formed quickly when the participants were moving towards the corridor.

Scenarios 3.1.D and 3.2.D had only eight participants. In these scenarios, the participants formed a group formation of two lines, indicating a need of a critical mass of persons to display distinct group formations.

Scenarios 3.2.A-3.2.C, 4.2.B and 4.3 all had a shorter walking distance to the door. In these scenarios no distinct triangle was observed when approaching the door. Group formations in these scenarios rather resembled clusters of irregular shapes.

4.1.1.2 Corridor

When comparing results regarding group formation depending on the presence of the short corridor, the group formation approaching the corridor corresponds to previous observations regarding walking distance. However, the group formation when approaching the door differs. The corridor gives a restriction of people flow to the door, resulting in a funnel-like group formation in all scenarios but 3.1.D that have a limited number of participants.

4.1.2 Passing through the door

Regarding group formation when passing through the door as a function of initial distance, a distinction is made between scenarios with and without the flow congesting corridor since this parameter is dependent on the layout of the premises.

For scenarios <u>with</u> the short corridor (scenarios 1.1-3.1), no major difference in the type of group formation is observed. In an early stage of passing through the door, the evacuees pass through the door in one line which later transitions into a zipper-formation. In scenarios with a greater distance between the starting point and the corridor, the initial one line-formation consists of more people compared to the scenarios with no distance between the starting point and the corridor. This indicate that the occupant density decreases with greater distance from the door/corridor resulting in a need for more people to touch the door to keep it from closing.

For scenarios <u>without</u> the short corridor (scenarios 3.2-5), the one-line formation is not as obvious. Generally, in these scenarios, there is a combination of two-line- and zipper-formations that occurs relatively early in the process of passing through the door. This is likely due to people reaching the door from several directions instead of only straight ahead, which is the case with corridors.

There is no observed difference between inward and outward opening directions of the door regardless of the presence of the corridor.

4.1.3 Summary of results – Group formation

- Greater walking distance results in a clearer front point of the triangle formation with low occupant density when approaching the door/corridor.
- Shorter walking distance results in a more disordered group formation when approaching the corridor/door. This phenomenon is less distinct in scenarios with a short corridor.
- Regarding the impact of the corridor when passing through the door, the corridor entails a more orderly group formation of a one-person-line that transitions to a zipper compared with scenarios with no corridor in which group formations of two-lines/zipper appear directly.
- The opening direction does not affect the group formations approaching or passing the door.

4.2 Opening the door

When studying evacuation through inward opening doors, the possibility of opening the door in an initial stage of evacuation is an essential part of the assessment. Since previous studies [7, 8] have stated that the people flow through inward opening doors is similar to such flow through outward opening doors, the door opening stage of the evacuation process is what differs between the two designs.

In this section the possibilities of opening of the door depending on the prerequisites in the different scenarios is analysed. This is done by comparing aspects regarding:

- Interaction between evacuees when opening the door,
- Occupant density close to the door at the time of the opening, and
- The time to open the door.

Based on what aspect is studied, a comparison between scenarios is performed by analysing the difference between scenarios with one or maximum two changed parameters. Relevant parameters to analyse and compared scenarios are listed in Table 5 which is based on the matrix of comparison, see Table 2. Each scenario is described in Table 1.

Table 5. Comparison between scenarios – Opening the door.

Studied parameter	Compared scenarios	Comment
Door opening direction	1.1 vs. 2.1	
	1.2 vs. 2.2	
	4.1.1 vs. 4.1.2 vs. 4.2.A	4.2.A has a higher initial occupant density.
Presence of corridor	1.1 & 1.2 vs. 4.1.1	Slight difference between walking distance to door.
	3.1 vs. 3.2	
Starting distance from the door	1.1 vs. 1.2	
	4.2.A vs. 4.2.B vs. 4.2.C & 4.2.D	
Initial occupant density	4.1.1 vs. 4.2.A vs. 4.3	4.3 has a slightly shorter walking distance.
	5.1 vs. 5.2 vs. 5.3	Comparison is not made regarding occupant density when reaching the door.
Number of people	1.2 vs. 3.1	
	4.1.1 vs. 3.2	
Door configuration (door fittings and opening force)	4.1.1 vs. 4.5	
	4.1.1 vs. 4.6	

4.2.1 Interaction of people when opening the door

The interaction between people when opening the door is an aspect indicating to what extent people behind, and people standing close to the person opening the door, need to adapt their movement for the door to be opened. The interaction of people is quantified by counting the number of people having to either slow down, stop or move for the door to be opened.

The observed number of people affected by the opening of the door are accounted for in Table 6. Each scenario is described in Table 1.

Table 6. Interaction of people when opening the door.

Scenario	Is interaction between people required to be able to open the door?	If yes, does people have to slow down, stop, or move to be able to open the door?	How many participants are affected by the interaction?
1.1.A	Yes	Slow down	3
1.1.B	Yes	Stop	5
1.2.A	Yes	Stop	4
1.2.B	Yes	Slow down	3
2.1.A	Yes	Slow down	1
2.1.B	No	N/A	N/A
2.2.A	Yes	Slow down	1
2.2.B	Yes	Slow down	2
3.1.A	Yes	Stop	4
3.1.B	Yes	Slow down	3
3.1.C	Yes	Stop	3
3.1.D	Yes	Stop	2
3.2.A	Yes	Slow down	3
3.2.B	Yes	Stop	5
3.2.C	Yes	Slow down	2
3.2.D	Yes	Stop	5
4.1.1.A	Yes	Stop	5
4.1.1.B	Yes	Slow down	2
4.1.2.A	Yes	Slow down	3
4.1.2.B	No	N/A	N/A
4.2.A	Yes	Stop	3
4.2.B	Yes	Stop	7
4.2.C	Yes	Slow down	2
4.2.D	No	N/A	N/A
4.3	Yes	Stop	3
4.4	N/A	N/A	N/A
4.5.A	Yes	Stop	11

Scenario	Is interaction between people required to be able to open the door?	If yes, does people have to slow down, stop, or move to be able to open the door?	How many participants are affected by the interaction?
4.5.B	Yes	Stop	52
4.6.A	Yes	Slow down	2
4.6.B	Yes	Slow down	1
5.1	Yes	Move	1
5.2	Yes	Move	2
5.3	Yes	Move	4

4.2.1.1 Door opening direction

The effects of door opening direction are analysed by comparing scenarios in Table 7. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 7. Comparison of the aspect "Interaction of people when opening the door" based on the parameter "Door opening direction".

Scenario	Is interaction between people required to be able to open the door?	If yes, does people have to slow down, stop, or move to be able to open the door?	How many participants are affected by the interaction?
1.1.A	Yes	Slow down	3
1.1.B	Yes	Stop	5
2.1.A	Yes	Slow down	1
2.1.B	No	N/A	N/A
1.2.A	Yes	Stop	4
1.2.B	Yes	Slow down	3
2.2.A	Yes	Slow down	1
2.2.B	Yes	Slow down	2
4.1.1.A	Yes	Stop	5
4.1.1.B	Yes	Slow down	2
4.1.2.A	Yes	Slow down	3
4.1.2.B	No	N/A	N/A
4.2.A	Yes	Stop	3

People behind or near the person opening the door interacts with the person opening the door in all scenarios with inward opening direction. For scenarios with outward opening direction, this interaction is observed in 4 out of 6 scenarios.

In scenarios with outward opening doors, there is no need for people behind- or near the person opening the door to stop. Fewer people slow down (1-3) compared to scenarios with inward opening doors (2-5 persons had to stop or slow down).

4.2.1.2 Corridor

The effects of the corridor are analysed by comparing scenarios in Table 8. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 8. Comparison of the aspect "Interaction of people when opening the door" based on the parameter "Presence of corridor ".

Scenario	Is interaction between people required to be able to open the door?	If yes, does people have to slow down, stop, or move to be able to open the door?	How many participants are affected by the interaction?
1.1.A	Yes	Slow down	3
1.1.B	Yes	Stop	5
1.2.A	Yes	Stop	4
1.2.B	Yes	Slow down	3
4.1.1.A	Yes	Stop	5
4.1.1.B	Yes	Slow down	2
3.1.A	Yes	Stop	4
3.1.B	Yes	Slow down	3
3.1.C	Yes	Stop	3
3.1.D	Yes	Stop	2
3.2.A	Yes	Slow down	3
3.2.B	Yes	Stop	5
3.2.C	Yes	Slow down	2
3.2.D	Yes	Stop	5

No clear distinction is observed between comparable scenarios with or without a short corridor in front of the door.

4.2.1.3 *Starting distance from the door*

The effect of starting distance from the door is analysed by comparing scenarios in Table 9. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 9. Comparison of the aspect "Interaction of people when opening the door" based on the parameter "Starting distance from the door ".

Scenario	Is interaction between people required to be able to open the door?	If yes, does people have to slow down, stop, or move to be able to open the door?	How many participants are affected by the interaction?
1.1.A	Yes	Slow down	3
1.1.B	Yes	Stop	5
1.2.A	Yes	Stop	4
1.2.B	Yes	Slow down	3
4.2.A	Yes	Stop	3
4.2.B	Yes	Stop	7
4.2.C	Yes	Slow down	2
4.2.D	No	N/A	N/A

For scenarios with the corridor, no difference is observed regarding if people behind or near had to interact with the person opening the door depending on the starting distance from the door. However, for scenarios without the corridor, a slight difference is observed. The scenarios with the longest walking distance to the door (4.2.C and 4.2.D) have fewer, or no participants (2 and 0 participants) that need to interact with the person opening the door. The scenario with the shortest walking distance (4.2.B) has more participants interacting with the person opening the door (7 participants). This could be linked to the group formation phenomena and the fact that a longer walking distance means lower density of people at the point of the triangle.

4.2.1.4 Initial occupant density

The effects of the initial occupant density are analysed by comparing scenarios in Table 10. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 10. Comparison of the aspect "Interaction of people when opening the door" based on the parameter "Initial occupant density ".

Scenario	Is interaction between people required to be able to open the door?	If yes, does people have to slow down, stop, or move to be able to open the door?	How many participants are affected by the interaction?
4.1.1.A	Yes	Stop	5
4.1.1.B	Yes	Slow down	2
4.2.A	Yes	Stop	3
4.3	Yes	Stop	3
5.1	Yes	Move	1
5.2	Yes	Move	2
5.3	Yes	Move	4

No clear distinction is observed between comparable scenarios with a short walking distance depending on the initial occupant density.

For scenarios with an initial high occupant density directly in front of the door, a difference is observed regarding the number of participants that had to move in order to the door to open. A higher occupant density directly in front of the door, results in a greater need for interaction between people. The difficulty to move is studied qualitatively. The person in scenario 5.1 did not have any difficulty to move out of the way of the door. In 5.2 and 5.3, a greater difficulty and need for collaboration between participants is observed.

4.2.1.5 *Number of people*

The effects of the number of people in the scenarios are analysed by comparing scenarios in Table 11. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 11. Comparison of the aspect "Interaction of people when opening the door" based on the parameter "Number of people".

Scenario	Is interaction between people required to be able to open the door?	If yes, does people have to slow down, stop, or move to be able to open the door?	How many participants are affected by the interaction?
1.2.A	Yes	Stop	4
1.2.B	Yes	Slow down	3
3.1.A	Yes	Stop	4
3.1.B	Yes	Slow down	3
3.1.C	Yes	Stop	3
3.1.D	Yes	Stop	2
4.1.1.A	Yes	Stop	5
4.1.1.B	Yes	Slow down	2
3.2.A	Yes	Slow down	3
3.2.B	Yes	Stop	5
3.2.C	Yes	Slow down	2
3.2.D	Yes	Stop	5

No clear distinction is observed between comparable scenarios.

4.2.1.6 *Door configuration*

The effects of varied door configuration are analysed by comparing scenarios in Table 12. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 12. Comparison of the aspect "Interaction of people when opening the door" based on the parameter "Door configuration".

Scenario	Is interaction between people required to be able to open the door?	If yes, does people have to slow down, stop, or move to be able to open the door?	How many participants are affected by the interaction?
4.1.1.A	Yes	Stop	5
4.1.1.B	Yes	Slow down	2
4.5.A	Yes	Stop	11
4.5.B	Yes	Stop	52
4.1.1.A	Yes	Stop	5
4.1.1.B	Yes	Slow down	2
4.6.A	Yes	Slow down	2
4.6.B	Yes	Slow down	1

As can be seen in Table 12, a difference is observed between scenarios with different door fittings regarding the interaction of people when opening the door. A greater number of participants must stop when the door is opened using a door knob and a door handle (11 and 52 participants) compared to only a door handle (between 1-5 participants). This is the result of a longer time to open the door, since people behind the queue reach the queue before the door is opened.

No clear distinction is observed between comparable scenarios with different door opening force.

4.2.2 Occupant density

The resulting occupant density in front of the door is studied simultaneously when the first person crosses the threshold. The choice of measurement point is made to capture any effects of densification of the group in front of the door, caused by the time that the door opening manoeuvre takes relative to the groups forward moving direction. Data is collected in 1-meter-intervals starting from the door and three meters out (i.e., interval 0-1, 1-2 and 2-3 meters).

Collected data from the performed tests are shown in Table 13, and compared with respect to the different assessed aspects under the following subsections. Each scenario is described in Table 1. Regarding assessment of occupant density in front of the door in the opening phase, scenarios 5.1-5.3 are not studied. This since these scenarios have a fixed occupant density from start and are performed with starting point directly in front of the door.

Table 13. Occupant density in intervals 0-1, 1-2 and 2-3 meters from door.

Scenario	Occupant density, interval 0-1 m [p/m²]	Occupant density, interval 1-2 m [p/m²]	Occupant density, interval 2-3 m [p/m²]
1.1.A	1	1	1
1.1.B	1	2	1
1.2.A	2	2	1
1.2.B	1	1	3
2.1.A	2	2	1
2.1.B	1	1	1
2.2.A	1	2	2
2.2.B	2	1	3
3.1.A	3	4	3
3.1.B	3	2	4
3.1.C	2	3	4
3.1.D	3	2	2
3.2.A	3	4	4
3.2.B	4	5	4
3.2.C	3	3	5
3.2.D	2	2	-
4.1.1.A	2	2	2
4.1.1.B	1	2	2
4.1.2.A	2	2	1-1,5
4.1.2.B	2	2	1
4.2.A	2	2	1-1,5
4.2.B	2	4	3,5-4
4.2.C	2	2	1,5-2
4.2.D	1	1	1-1,5
4.3	2	3	3
4.4	N/A	N/A	N/A
4.5.A	2	2-2,5	2
4.5.B	2-2,5	2	2

Scenario	Occupant density, interval 0-1 m [p/m^2]	Occupant density, interval 1-2 m [p/m^2]	Occupant density, interval 2-3 m [p/m^2]
4.6.A	1	2	1,5-2 (estimated mean value over 2 seconds from the measuring point, due to a brief moment with no participants present in the studied interval)
4.6.B	1	2	1,5-2 (estimated mean value over 2 seconds from the measuring point, due to a brief moment with no participants present in the studied interval)
5.1	N/A	N/A	N/A
5.2	N/A	N/A	N/A
5.3	N/A	N/A	N/A

4.2.2.1 *Door opening direction*

The effects of door opening direction are analysed by comparing scenarios in Table 14. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 14. Comparison of the aspect "Occupant density" based on the parameter "Door opening direction".

Scenario	Occupant density, interval 0-1 m [p/m^2]	Occupant density, interval 1-2 m [p/m^2]	Occupant density, interval 2-3 m [p/m^2]
1.1.A	1	1	1
1.1.B	1	2	1
2.1.A	2	2	1
2.1.B	1	1	1
1.2.A	2	2	1
1.2.B	1	1	3
2.2.A	1	2	2
2.2.B	2	1	3
4.1.1.A	2	2	2
4.1.1.B	1	2	2
4.1.2.A	2	2	1-1,5
4.1.2.B	2	2	1
4.2.A	2	2	1-1,5

No clear distinction is observed between comparable scenarios.

4.2.2.2 Corridor

The effects of the corridor are analysed by comparing scenarios in Table 15. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 15. Comparison of the aspect "Occupant density" based on the parameter "Presence of corridor".

Scenario	Occupant density, interval 0-1 m [p/m^2]	Occupant density, interval 1-2 m [p/m^2]	Occupant density, interval 2-3 m [p/m^2]
1.1.A	1	1	1
1.1.B	1	2	1
1.2.A	2	2	1
1.2.B	1	1	3
4.1.1.A	2	2	2
4.1.1.B	1	2	2
3.1.A	3	4	3
3.1.B	3	2	4
3.1.C	2	3	4
3.1.D	3	2	2
3.2.A	3	4	4
3.2.B	4	5	4
3.2.C	3	3	5
3.2.D	2	2	-

No clear distinction is observed between comparable scenarios.

4.2.2.3 Starting distance from the door

The effects of starting distance from the door are analysed by comparing scenarios in Table 16. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 16. Comparison of the aspect "Occupant density" based on the parameter "Starting distance from door".

Scenario	Occupant density, interval 0-1 m [p/m^2]	Occupant density, interval 1-2 m [p/m^2]	Occupant density, interval 2-3 m [p/m^2]
1.1.A	1	1	1
1.1.B	1	2	1
1.2.A	2	2	1
1.2.B	1	1	3
4.2.A	2	2	1-1,5
4.2.B	2	4	3,5-4
4.2.C	2	2	1,5-2
4.2.D	1	1	1-1,5

Generally, no clear distinction is observed between comparable scenarios. Scenario 4.2.B, however, results in a higher occupant density than the other comparable scenarios. Scenario 4.2.B is designed with a shorter walking distance than the rest of the scenarios, meaning that the group formation is more compact than scenarios with a longer walking distance resulting in the point of the triangle being less protracted.

4.2.2.4 Initial occupant density

The effects of the initial occupant density are analysed by comparing scenarios in Table 17. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 17. Comparison of the aspect "Occupant density" based on the parameter "Initial occupant density".

Scenario	Occupant density, interval 0-1 m [p/m^2]	Occupant density, interval 1-2 m [p/m^2]	Occupant density, interval 2-3 m [p/m^2]
4.1.1.A	2	2	2
4.1.1.B	1	2	2
4.2.A	2	2	1-1,5
4.3	2	3	3

No clear distinction is observed between comparable scenarios.

4.2.2.5 Number of people

The effects of the number of people in the scenarios are analysed by comparing scenarios in Table 18. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 18. Comparison of the aspect "Occupant density" based on the parameter "Number of people".

Scenario	Occupant density, interval 0-1 m [p/m^2]	Occupant density, interval 1-2 m [p/m^2]	Occupant density, interval 2-3 m [p/m^2]
1.2.A	2	2	1
1.2.B	1	1	3
3.1.A	3	4	3
3.1.B	3	2	4
3.1.C	2	3	4
3.1.D	3	2	2
4.1.1.A	2	2	2
4.1.1.B	1	2	2
3.2.A	3	4	4
3.2.B	4	5	4
3.2.C	3	3	5
3.2.D	2	2	-

A slightly higher occupant density is observed for scenarios with a lower number of participants. However, scenario 3.1.D and 3.2.D, with only eight participants have a similar occupant density as scenarios with the higher number of participants.

4.2.2.6 *Door configuration*

The effects of varied door configuration are analysed by comparing scenarios in Table 19. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 19. Comparison of the aspect "Occupant density" based on the parameter "Door configuration".

Scenario	Occupant density, interval 0-1 m [p/m^2]	Occupant density, interval 1-2 m [p/m^2]	Occupant density, interval 2-3 m [p/m^2]
4.1.1.A	2	2	2
4.1.1.B	1	2	2
4.5.A	2	2-2,5	2
4.5.B	2-2,5	2	2
4.1.1.A	2	2	2
4.1.1.B	1	2	2
4.6.A	1	2	1,5-2
4.6.B	1	2	1,5-2

No clear distinction is observed between comparable scenarios.

4.2.3 Time to open the door

The time to open the door is an interesting aspect since it quantifies any difficulties to gain maximum people flow through the door. The aspect is measured by counting the time from when the first person grabs the door handle until the door is fully open, approximately 90 degrees open or until the opening manoeuvre is considered completed (for cases where 90 degrees opening are not reached).

The results of data analysis regarding time to open the door from all scenarios are accounted for in Table 20. Each scenario is described in Table 1.

Table 20. Time to open the door.

Scenario	Time to open the door [s]
1.1.A	2,0
1.1.B	3,0
1.2.A	2,3
1.2.B	2,5
2.1.A	3,0
2.1.B	1,8
2.2.A	3,0
2.2.B	2,7

Scenario	Time to open the door [s]
3.1.A	2,0
3.1.B	2,7
3.1.C	2,7
3.1.D	2,7
3.2.A	2,8
3.2.B	2,8
3.2.C	2,7
3.2.D	2,3
4.1.1.A	2,6
4.1.1.B	2,6
4.1.2.A	2,4
4.1.2.B	2,7
4.2.A	1,9
4.2.B	2,5
4.2.C	2,4
4.2.D	3,1
4.3	1,9
4.4	N/A
4.5.A	3,7
4.5.B	7,3
4.6.A	1,8
4.6.B	2,3
5.1	2,7
5.2	4,2
5.3	6,0

4.2.3.1 Door opening direction

The effects of door opening direction are analysed by comparing scenarios in Table 21. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 21. Comparison of the aspect "Time to open the door" based on the parameter "Door opening direction".

Scenario	Time to open the door [s]
1.1.A	2,0
1.1.B	3,0
2.1.A	3,0
2.1.B	1,8
1.2.A	2,3
1.2.B	2,5
2.2.A	3,0
2.2.B	2,7
4.1.1.A	2,6
4.1.1.B	2,6
4.1.2.A	2,4
4.1.2.B	2,7
4.2.A	1,9

No clear distinction is observed between comparable scenarios.

4.2.3.2 Corridor

The effects of the corridor are analysed by comparing scenarios in Table 22. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 22. Comparison of the aspect "Time to open the door" based on the parameter "Presence of corridor".

Scenario	Time to open the door [s]
1.1.A	2,0
1.1.B	3,0
1.2.A	2,3
1.2.B	2,5
4.1.1.A	2,6
4.1.1.B	2,6
3.1.A	2,0
3.1.B	2,7
3.1.C	2,7
3.1.D	2,7
3.2.A	2,8
3.2.B	2,8
3.2.C	2,7
3.2.D	2,3

No clear distinction was observed between comparable scenarios.

4.2.3.3 Starting distance from the door

The effects of starting distance from the door are analysed by comparing scenarios in Table 23. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 23. Comparison of the aspect "Time to open the door" based on the parameter "Starting distance from door".

Scenario	Time to open the door [s]
1.1.A	2,0
1.1.B	3,0
1.2.A	2,3
1.2.B	2,5
4.2.A	1,9
4.2.B	2,5
4.2.C	2,4
4.2.D	3,1

No clear distinction is observed between comparable scenarios.

4.2.3.4 Initial occupant density

The effects of the initial occupant density are analysed by comparing scenarios in Table 24. Directly comparable scenarios are divided with a bold line (see also Table 5). Each scenario is described in Table 1.

Table 24. Comparison of the aspect "Time to open the door" based on the parameter "Initial occupant density".

Scenario	Time to open the door [s]
4.1.1.A	2,6
4.1.1.B	2,6
4.2.A	1,9
4.3	1,9
5.1	2,7
5.2	4,2
5.3	6,0

No clear distinction is observed between comparable scenarios with some walking distance before reaching the door. For scenarios with a high occupant density directly in front of the door, a higher occupant density results in a longer time to open the door. It should be noted that the occupant density of 3 persons/m^2 results in a similar time to open the door as the scenarios with some walking distance before reaching the door indicating that an occupant density of about 3-4 persons/m^2 might result in an increased difficulty to open the door.

4.2.3.5 Number of people

The effects of the number of people in the scenarios are analysed by comparing scenarios in Table 25. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 25. Comparison of the aspect "Time to open the door" based on the parameter "Number of people".

Scenario	Time to open the door [s]
1.2.A	2,3
1.2.B	2,5
3.1.A	2,0
3.1.B	2,7
3.1.C	2,7
3.1.D	2,7
4.1.1.A	2,6
4.1.1.B	2,6
3.2.A	2,8
3.2.B	2,8
3.2.C	2,7
3.2.D	2,3

No clear distinction is observed between comparable scenarios.

4.2.3.6 Door configuration

The effects of varied door configuration are analysed by comparing scenarios in Table 26. Directly comparable scenarios are divided into sections with bold lines (see also Table 5). Each scenario is described in Table 1.

Table 26. Comparison of the aspect "Time to open the door" based on the parameter "Door configuration".

Scenario	Time to open the door [s]
4.1.1.A	2,6
4.1.1.B	2,6
4.5.A	3,7
4.5.B	7,3
4.1.1.A	2,6
4.1.1.B	2,6
4.6.A	1,8
4.6.B	2,3

In scenarios with a door knob, a longer time to open the door is observed (3,7-7,3 seconds compared to approximately 2-3 seconds). The door knob requires a two-step manoeuvre when opening the door (turn the knob and use the handle), compared to the one-step opening in comparable scenarios. A door knob could also vary in its function, meaning that the evacuee might try to turn the knob in the wrong direction resulting in an even longer opening time. This is observed in scenario 4.5.B which also resulted in a longer time to open the door.

No clear distinction is observed between comparable scenarios with varied door opening force.

4.2.4 Summary of results – Opening the door

4.2.4.1 Door opening direction

The door opening direction affects the number of people needing to interact when opening the door. There is a greater need for coordination when using inward opening doors, i.e., people behind and nearby the person opening the door need to slow down or stop to a greater extent. However, no difference between inward opening doors and outward opening doors has been observed regarding the occupant density of people at the time of opening, or the time to fully open the door in the assessed experiments.

4.2.4.2 Corridor

There is no clear difference regarding interactions between people, occupant density when opening the door or the time to open the door depending on the presence of a corridor in the trials.

4.2.4.3 Starting distance from the door

The results indicate that the walking distance will affect the opening of the door when it comes to how many participants that needs to interact to get the door to open, and the occupant density close to the door when opening the door. This is connected to the group formation and the fact that a longer walking distance means lower density of people at the point of the triangle in the front part of the group. This can be observed already after an initial walking distance of approximately five meters. However, the time to open the door was not affected by the walking distance in the trials.

4.2.4.4 Initial occupant density

The initial occupant density affects the ease of opening the door when there is no- or a short walking distance before reaching the door, see scenario 4.2.B and 5.1-5.3. This affects the number of people that needs to interact to open the door and the time it takes to fully open the door. It can be noted that scenario 5.1, with an occupant density of 3 persons/m^2, has a similar time to open the door as scenarios with some walking distance to reach the door and no difficulty to move is observed for the person that initially is placed behind the door.

The effect is not as clear when people need to walk some distance before reaching the door, likely due to the effects of group formations caused by the walking distance.

4.2.4.5 Number of people

Regarding the occupant density close to the door, a slightly higher occupant density is observed in scenarios with a lower number of participants. No difference is observed regarding the interaction of people or the time to open the door depending on the number of participants.

4.2.4.6 Door configuration

The door fittings affect the opening of the door to a great extent. In the experiments, this is observed both regarding the interaction of people when opening the door and the time to open the door. Scenarios with a door knob calls for greater interaction between people when opening the door and a slower opening of the door. No difference is observed regarding occupant density in the experiments.

No clear distinction between the assessed aspects in different scenarios is observed with variated door opening force.

4.3 Occupant flow through door

The occupant flow through the door is studied briefly in this project. This is done by studying the overall people flow through the door in each scenario. Additionally, the time it takes from when the first person touches the door handle until the fourth-, fifth- and sixth person passes through the door is measured to capture the initial stage of evacuation.

Based on aspect being studied, a comparison between scenarios is performed by analysing the difference between scenarios with one or maximum two changed parameters. Interesting parameters to analyse and compared scenarios are listed in Table 27, that is based on the matrix of comparison, see Table 2. Each scenario is described in Table 1.

Table 27. Comparison between scenarios – Occupant flow through door.

Studied parameter	Compared scenarios	Comment
Door opening direction	1.1 vs. 2.1	
	1.2 vs. 2.2	
	4.1.1 vs. 4.1.2 vs. 4.2.A	4.2.A has a higher initial occupant density.
Presence of corridor	1.1 & 1.2 vs. 4.1.1	Slightly difference between walking distance to door.
	3.1 vs. 3.2	
Starting distance from the door	1.1 vs. 1.2	
	4.2.A vs. 4.2.B vs. 4.2.C & 4.2.D	
Initial occupant density	4.1.1 vs. 4.2.A vs. 4.3	4.3 has a slightly shorter walking distance.
	5.1 vs. 5.2 vs. 5.3	Comparison is not made regarding occupant density when reaching the door.
Number of people	1.2 vs. 3.1	
	4.1.1 vs. 3.2	
Door configuration (door fittings and opening force)	4.1.1 vs. 4.5	
	4.1.1 vs. 4.6	

4.3.1 Overall people flow

The overall people flow is determined by measuring the time from when the first person crosses the threshold until the last person crosses. The number of people is then divided with the time. The people flow vary somewhat during the evacuation process. Persons with slower walking speed results in a temporary decrease of people flow. This is, however, not studied in detail in this study. The overall people flow is an interesting aspect regarding movement time out of the premises after the door is opened. The results of data analysis regarding the overall people flow from all scenarios are accounted for in Table 28. Each scenario is described in Table 1.

Table 28. Overall people flow through the door.

Scenario	Overall people flow [persons/s]
1.1.A	1,4
1.1.B	1,4
1.2.A	1,4
1.2.B	1,5

Scenario	Overall people flow [persons/s]
2.1.A	1,5
2.1.B	1,5
2.2.A	1,5
2.2.B	1,5
3.1.A	1,3
3.1.B	1,4
3.1.C	1,4
3.1.D	1,1
3.2.A	1,5
3.2.B	1,9
3.2.C	1,4
3.2.D	1,3
4.1.1.A	1,7
4.1.1.B	1,8
4.1.2.A	1,8
4.1.2.B	2,0
4.2.A	1,8
4.2.B	1,9
4.2.C	2,0
4.2.D	1,8
4.3	2,0
4.4	N/A
4.5.A	1,8
4.5.B	1,9
4.6.A	1,8
4.6.B	1,7
5.1	2,0
5.2	2,0
5.3	1,9

4.3.1.1 Door opening direction

The effects of door opening direction are analysed by comparing scenarios in Table 29. Directly comparable scenarios are divided into sections with bold lines (see also Table 27). Each scenario is described in Table 1.

Table 29. Comparison of the aspect "Overall people flow" based on the parameter "Door opening direction".

Scenario	Overall people flow [persons/s]
1.1.A	1,4
1.1.B	1,4
2.1.A	1,5
2.1.B	1,5
1.2.A	1,4
1.2.B	1,5
2.2.A	1,5
2.2.B	1,5
4.1.1.A	1,7
4.1.1.B	1,8
4.1.2.A	1,8
4.1.2.B	2,0
4.2.A	1,8

No clear distinction is observed between comparable scenarios.

A general observation is that the door, in the outward opening scenarios, rarely is opened fully to 90 degrees. The door closing mechanism and the way the participants are handing over the door to each other results in a more or less continuous "shading effect" where the door springs back a little (approximately 10-20 cm) between each time a person passed, see Figure 27. The same phenomenon has been observed in previous studies, e.g., Lennartsson & Weyler [7] where it is discussed in further detail. It does, however, not seem to have affected the overall people flow in this study, which could relate to the available door opening width still being enough to facilitate egress in the observed person formation of "line" or "zipper".

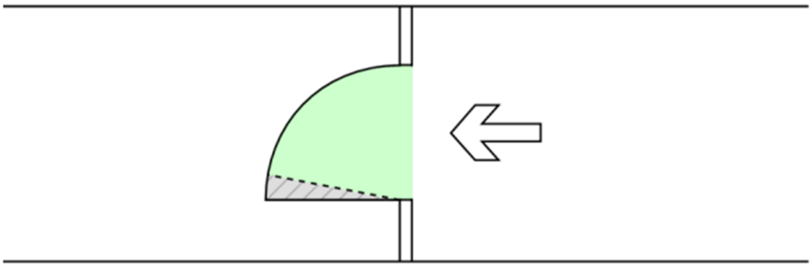


Figure 27. Visualization of the "shading effect" noted in scenarios with outward opening door. Figure reproduced from [7].

4.3.1.2 Corridor

The effects of the corridor are analysed by comparing scenarios in Table 30. Directly comparable scenarios are divided into sections with bold lines (see also Table 27). Each scenario is described in Table 1.

Table 30. Comparison of the aspect "Overall people flow" based on the parameter "Presence of corridor".

Scenario	Overall people flow [persons/s]
1.1.A	1,4
1.1.B	1,4
1.2.A	1,4
1.2.B	1,5
4.1.1.A	1,7
4.1.1.B	1,8
3.1.A	1,3
3.1.B	1,4
3.1.C	1,4
3.1.D	1,1
3.2.A	1,5
3.2.B	1,9
3.2.C	1,4
3.2.D	1,3

In scenarios with a corridor, a slightly lower overall people flow is observed compared to scenarios without a corridor (1,4-1,5 persons/s compared to 1,7-1,8 persons/s). This is probably a result of the lower occupant density in front of the door due to the constriction of flow that affects the group formation (zipper compared to two lines, see section 4.1). When people can approach the door from multiple directions, and not only directly from straight in front of the door, it is easier to reach the full flow potential of the door.

4.3.1.3 Starting distance from the door

The effects of starting distance from the door are analysed by comparing scenarios in Table 31. Directly comparable scenarios are divided into sections with bold lines (see also Table 27). Each scenario is described in Table 1.

Table 31. Comparison of the aspect "Overall people flow" based on the parameter "Starting distance from the door".

Scenario	Overall people flow [persons/s]
1.1.A	1,4
1.1.B	1,4
1.2.A	1,4
1.2.B	1,5
4.2.A	1,8
4.2.B	1,9
4.2.C	2,0
4.2.D	1,8

No clear distinction is observed between comparable scenarios.

4.3.1.4 Initial occupant density

The effects of the initial occupant density are analysed by comparing scenarios in Table 32. Directly comparable scenarios are divided into sections with bold lines (see also Table 27). Each scenario is described in Table 1.

Table 32. Comparison of the aspect "Overall people flow" based on the parameter "Initial occupant density".

Scenario	Overall people flow [persons/s]
4.1.1.A	1,7
4.1.1.B	1,8
4.2.A	1,8
4.3	2,0
5.1	2,0
5.2	2,0
5.3	1,9

No clear distinction is observed between comparable scenarios.

4.3.1.5 Number of people

The effects of the number of people in the scenarios are analysed by comparing scenarios in Table 33. Directly comparable scenarios are divided into sections with bold lines (see also Table 27). Each scenario is described in Table 1.

Table 33. Comparison of the aspect "Overall people flow" based on the parameter "Number of people".

Scenario	Overall people flow [persons/s]
1.2.A	1,4
1.2.B	1,5
3.1.A	1,3
3.1.B	1,4
3.1.C	1,4
3.1.D	1,1
4.1.1.A	1,7
4.1.1.B	1,8
3.2.A	1,5
3.2.B	1,9
3.2.C	1,4
3.2.D	1,3

No clear distinction is observed between comparable scenarios.

4.3.1.6 Door configuration

The effects of varied door configuration (door fittings and door opening force) are analysed by comparing scenarios in Table 34. Directly comparable scenarios are divided into sections with bold lines (see also Table 27). Each scenario is described in Table 1.

Table 34. Comparison of the aspect "Overall people flow" based on the parameter "Door configuration".

Scenario	Overall people flow [persons/s]
4.1.1.A	1,7
4.1.1.B	1,8
4.5.A	1,8
4.5.B	1,9
4.1.1.A	1,7
4.1.1.B	1,8
4.6.A	1,8
4.6.B	1,7

No clear distinction is observed between comparable scenarios. Note that the flow of people does not consider the opening process of the door.

4.3.2 Initial stage of passing through the door

The initial stage of passing through the door is considered an interesting measurable with regard to how the opening moment of the door varies as a consequence of altering the different parameters. The time from when the first person touched the door handle, until the fourth-, fifth- and sixth person passed the threshold, is measured. The initial part of evacuation through an inward opened door is a possible problem when evacuating through inward opening doors if the opening manoeuvre is interfered. By sampling data for person number four to six a greater number of data points could be extracted from the trials, and any variations on an individual basis could be identified.

The results of data analysis regarding the initial stage of passing through the door from all scenarios are accounted for in Table 35. Each scenario is described in Table 1.

Table 35. Compilation of observed data regarding the initial stage of passing through the door.

Scenario	Fourth person passing the door [s]	Fifth person passing the door [s]	Sixth person passing the door [s]
1.1.A	4,4	5,3	6,1
1.1.B	5,0	5,7	6,3
1.2.A	4,3	5,1	5,9
1.2.B	4,3	5,3	5,3
2.1.A	3,0	3,4	4,2

Scenario	Fourth person passing the door [s]	Fifth person passing the door [s]	Sixth person passing the door [s]
2.1.B	3,0	3,7	3,9
2.2.A	2,6	3,1	3,7
2.2.B	3,2	3,2	4,0
3.1.A	3,7	3,9	4,7
3.1.B	3,9	4,6	5,1
3.1.C	3,6	4,8	5,7
3.1.D	4,9	5,6	6,0
3.2.A	3,7	4,1	4,7
3.2.B	3,9	4,7	5,2
3.2.C	4,3	4,6	5,2
3.2.D	4,1	4,7	5,3
4.1.1.A	4,2	4,4	5,1
4.1.1.B	3,4	4,1	4,7
4.1.2.A	2,2	3,2	3,2
4.1.2.B	2,6	3,1	3,3
4.2.A	3,3	3,7	4,0
4.2.B	3,7	4,3	4,6
4.2.C	3,4	3,9	4,2
4.2.D	3,5	3,8	4,6
4.3	3,4	4,1	4,4
4.4	N/A	N/A	N/A
4.5.A	5,4	6,1	6,5
4.5.B	7,9	8,1	8,6
4.6.A	3,5	4,0	4,4
4.6.B	3,9	4,6	4,9
5.1	4,2	5,0	5,6
5.2	4,1	4,5	5,0
5.3	4,2	5,2	5,8

4.3.2.1 Door opening direction

The effects of door opening direction are analysed by comparing scenarios in Table 36. Directly comparable scenarios are divided into sections with bold lines (see also Table 27). Each scenario is described in Table 1.

Table 36. Comparison of the aspect "Initial stage of passing through the door" based on the parameter "Door opening direction".

Scenario	Fourth person passing the door [s]	Fifth person passing the door [s]	Sixth person passing the door [s]
1.1.A	4,4	5,3	6,1
1.1.B	5,0	5,7	6,3
2.1.A	3,0	3,4	4,2
2.1.B	3,0	3,7	3,9
1.2.A	4,3	5,1	5,9
1.2.B	4,3	5,3	5,3
2.2.A	2,6	3,1	3,7
2.2.B	3,2	3,2	4,0
4.1.1.A	4,2	4,4	5,1
4.1.1.B	3,4	4,1	4,7
4.1.2.A	2,2	3,2	3,2
4.1.2.B	2,6	3,1	3,3
4.2.A	3,3	3,7	4,0

Scenarios with an outward opening direction result in a faster initial stage of egress through the door. Even though the time to open the door 90 degrees are similar with the changed parameter, there is a greater need of interaction between people at the time of opening the door. This, in combination to the need for the person opening the door to pull the door towards him-/herself before passing, results in a slower initial egress for inward opening doors compared to outward opening doors.

4.3.2.2 Corridor

The effects of the corridor are analysed by comparing scenarios in Table 37. Directly comparable scenarios are divided into sections with bold lines (see also Table 27). Each scenario is described in Table 1.

Table 37. Comparison of the aspect "Initial stage of passing through the door" based on the parameter "Presence of corridor".

Scenario	Fourth person passing the door [s]	Fifth person passing the door [s]	Sixth person passing the door [s]
1.1.A	4,4	5,3	6,1
1.1.B	5,0	5,7	6,3
1.2.A	4,3	5,1	5,9
1.2.B	4,3	5,3	5,3
4.1.1.A	4,2	4,4	5,1
4.1.1.B	3,4	4,1	4,7
3.1.A	3,7	3,9	4,7
3.1.B	3,9	4,6	5,1
3.1.C	3,6	4,8	5,7
3.1.D	4,9	5,6	6,0
3.2.A	3,7	4,1	4,7
3.2.B	3,9	4,7	5,2
3.2.C	4,3	4,6	5,2
3.2.D	4,1	4,7	5,3

For scenarios with a higher number of participants, the corridor results in slightly longer times until the fourth-, fifth- and sixth person passes the door. This effect was not as clear in scenarios with fewer participants. This could be due to the group formation reaching the door, affecting the people flow. Fewer participants also have an impact on the occupant density, see section 4.2.2, which may affect the people flow in the initial stage.

4.3.2.3 Starting distance from the door

The effects of starting distance from the door are analysed by comparing scenarios in Table 38. Directly comparable scenarios are divided into sections with bold lines (see also Table 27). Each scenario is described in Table 1.

Table 38. Comparison of the aspect "Initial stage of passing through the door" based on the parameter "Starting distance from the door".

Scenario	Fourth person passing the door [s]	Fifth person passing the door [s]	Sixth person passing the door [s]
1.1.A	4,4	5,3	6,1
1.1.B	5,0	5,7	6,3
1.2.A	4,3	5,1	5,9
1.2.B	4,3	5,3	5,3
4.2.A	3,3	3,7	4,0
4.2.B	3,7	4,3	4,6
4.2.C	3,4	3,9	4,2
4.2.D	3,5	3,8	4,6

A slight difference is observed depending on starting distance for scenarios with a corridor. This could be due to the lower occupant density as a result of walking distance.

Generally, no clear distinction is observed between comparable scenarios without the corridor. A slight difference is observed for scenario 4.2.B, which have the shortest walking distance. A shorter walking distance results in a higher occupant density when opening the door, and a greater number of participants that must interact with the person opening the door. This may indicate that it takes slightly longer to fulfill the opening maneuver and reach the door's full people flow capacity.

4.3.2.4 Initial occupant density

The effects of the initial occupant density are analysed by comparing scenarios in Table 39. Directly comparable scenarios are divided into sections with bold lines (see also Table 27). Each scenario is described in Table 1.

Table 39. Comparison of the aspect "Initial stage of passing through the door" based on the parameter "Initial occupant density".

Scenario	Fourth person passing the door [s]	Fifth person passing the door [s]	Sixth person passing the door [s]
4.1.1.A	4,2	4,4	5,1
4.1.1.B	3,4	4,1	4,7
4.2.A	3,3	3,7	4,0
4.3	3,4	4,1	4,4
5.1	4,2	5,0	5,6
5.2	4,1	4,5	5,0
5.3	4,2	5,2	5,8

No clear distinction is observed between comparable scenarios. One interesting observation of the results listed in Table 39 is that the time for the fourth-, fifth- and sixth person to pass the door is similar even though the time to open the door is longer in cases with high occupant density. This indicate that the high occupant density gives a high people flow even when the door is not fully open.

4.3.2.5 Number of people

The effects of the number of people in the scenarios are analysed by comparing scenarios in Table 40. Directly comparable scenarios are divided into sections with bold lines (see also Table 27). Each scenario is described in Table 1.

Table 40. Comparison of the aspect "Initial stage of passing through the door" based on the parameter "Number of people".

Scenario	Fourth person passing the door [s]	Fifth person passing the door [s]	Sixth person passing the door [s]
1.2.A	4,3	5,1	5,9
1.2.B	4,3	5,3	5,3
3.1.A	3,7	3,9	4,7
3.1.B	3,9	4,6	5,1
3.1.C	3,6	4,8	5,7
3.1.D	4,9	5,6	6,0
4.1.1.A	4,2	4,4	5,1
4.1.1.B	3,4	4,1	4,7
3.2.A	3,7	4,1	4,7
3.2.B	3,9	4,7	5,2
3.2.C	4,3	4,6	5,2
3.2.D	4,1	4,7	5,3

No clear distinction is observed between comparable scenarios.

4.3.2.6 *Door configuration*

The effects of varied door configuration (door fittings and door opening force) are analysed by comparing scenarios in Table 41. Directly comparable scenarios are divided into sections with bold lines (see also Table 27). Each scenario is described in Table 1.

Table 41. Comparison of the aspect "Initial stage of passing through the door" based on the parameter "Door configuration".

Scenario	Fourth person passing the door [s]	Fifth person passing the door [s]	Sixth person passing the door [s]
4.1.1.A	4,2	4,4	5,1
4.1.1.B	3,4	4,1	4,7
4.5.A	5,4	6,1	6,5
4.5.B	7,9	8,1	8,6
4.1.1.A	4,2	4,4	5,1
4.1.1.B	3,4	4,1	4,7
4.6.A	3,5	4,0	4,4
4.6.B	3,9	4,6	4,9

In scenarios with a door knob, the initial stage of evacuation takes longer time than scenarios with a door handle. The door knob results in a two-step opening manoeuvre of the door (turn the knob and use the handle), compared to the one-step opening in the comparable scenarios. A door knob could also vary in its function, meaning that the evacuee might try to turn the knob in the wrong direction resulting in an even longer initial state of passing through the door. This is observed in scenario 4.5.B.

No clear distinction is observed between comparable scenarios with variated door opening force.

4.3.3 Summary of results – Occupant flow through door

4.3.3.1 *Door opening direction*

The overall flow when the door is opened is not affected by the door opening direction. However, the initial stage of passing through the door is slower with an inward opened door. The need for the person that opens the door to stop and pull the door, affects the initial stage resulting in a minor delay in the initial stage of egress through the door.

4.3.3.2 *Corridor*

The presence of a short corridor results in a slightly lower overall people flow and longer times for the fourth-, fifth- and sixth person to pass through the door. This might be connected to the group formation through the corridor that in greater extent is shaped like a zipper compared to the two-line formation that is more common in the absence of a corridor.

4.3.3.3 *Starting distance from the door*

Occupant flow through the door is not affected by the walking distance before reaching the door in the performed experiments. The initial stage of passing through the door is partly connected to the walking distance. A short walking distance will affect the initial part of passing through the door in a negative extent. However, no difference is observed for scenarios with more than five meters walking distance before reaching the door.

4.3.3.4 Initial occupant density
No clear distinction is observed between comparable scenarios regarding the effect of initial occupant density on the flow through the door.

An observation of a more general nature is that participants rather quickly tend to settle in a queuing pattern with an occupant density of 2-3 p/m^2 when approaching the door. This phenomenon was observed unrelated to the initial occupant densities between the different scenarios.

4.3.3.5 Number of people
No clear distinction is observed between comparable scenarios regarding the effect of the number of people on the flow through the door.

4.3.3.6 Door configuration
The door opening force is not affecting the flow through the door or the initial stage of passing through the door in the performed experiments.

The door fittings affect the initial stage of egress in a negative way since the time to open the door increase with a two-step opening function.

5. Discussion

5.1 Purpose and goal
The evacuation experiments were conducted in accordance with the purpose and goal stated under section 1.2, i.e., to increase the understanding of situations where evacuation takes place through inward opened doors and to form a basis for assessment of safe evacuation from different types of premises with inward opened doors.

The goal related to the study's purpose is set to identify parameters that affect the risk of queuing and other aspects of evacuation conditions through inward opening doors.

The study has done this by evaluation of the defined research questions (section 1.3), given below:

- What factors influence the feasibility of evacuation through inward opening doors?
- Are there situations and room configurations where required safety-levels during evacuation can be met even if more than 30 people evacuate through an inward opening door?
- Under what conditions, if any, is the risk of queue formation and ability to open the door independent of its opening direction?
- How can a trade-off be achieved when conflicting interests arise regarding the opening direction of a door?

Regarding the first three research questions it can be stated that the evacuation experiments performed implies that there are situations and room geometries that facilitate safe egress even if the door is opened inwards and if the number of evacuees exceeds 30 persons. The trials were conducted with at maximum of 95 participating participants, a limited number of room geometries and without the "stress factor" that a real-life fire or evacuation alarm would evoke on the egress procedure. Far-reaching conclusions regarding evacuation through inward opening doors in cases with larger numbers of people should therefore be drawn with careful consideration of impact from the prevailing situation. Nothing, however, in the performed experiments points towards the number of people itself as a dimensioning factor in evaluating egress safety through inward opening doors. Factors that seem to be of greater significance are occupant density and room geometry (flow constrictions and walking distance) and maybe most significantly the conditions close to the door.

Further, in line with the conclusions drawn from the data analysis, there could be a risk with using inward opening doors in situations where a very high occupant density is expected to be present in the direct proximity to the door. Conclusions from this study, point towards a breaking trend at occupant densities exceeding 3 persons/m^2 close to the door, but the inward opening door was not blocked or more difficult to open even in the scenarios with 4 and 5 persons/m^2 close to the door. At such high occupant densities, a higher degree of cooperation between evacuees is needed to fully open the door and to reach the maximum people flow through the door opening. Further research is necessary to identify in what situations an inward opening door can no longer be opened due to crowding, and locally increased occupant densities in the direct proximity of the door as the data base for scenarios with occupant densities >3 persons/m^2 is quite small in this study. It should, for reference, be further noted that 3 persons/m^2 is the highest dimensioning average occupant density used in the Swedish building regulations (applies for occupancies such as pubs, bars and similar). However, it is important to point out that this constitutes the dimensioning occupant density for a room as a whole ("initial" or "global" occupant load in contrast to "resulting" or "local" occupant load) and is therefore not directly comparable with the occupant density in direct proximity of the door.

The fourth research question, whether there are possible trade-offs between conflicting interests concerning the built environment and inward opening doors, was not studied quantitatively, but is rather covered in a general way in this discussion. In general, a holistic assessment needs to be made in relation to the balance of the specific building design, evacuation safety and historic and cultural value. However, the study implies that there are situations and options of room design that ensure evacuation safety even with the combination of inward opening doors and more than 30 persons in the premises. Observed results in this study indicate a reduced need for trade-offs between evacuation safety and preservation of build heritage.

In dense city environments, outward opening doors are often considered a problem due to the possibility that an opening door might hit a passing pedestrian. In many cases this problem is solved by placing the door in a niche. This certainly solves the problem, but in many cases is not a cost-effective, feasible or desirable solution. When applying the problem to buildings with high cultural value, as often is the case in older parts of larger cities, churches etc., fulfilment of the modern building legislations is in many cases in conflict with the protection demands of the buildings cultural value. The results of this study point towards the possibility to allow inward opening doors to a greater extent than what is acceptable in accordance with the Swedish building regulations (maximum 30 persons in premises with inward opening doors used for evacuation) under certain conditions. This conclusion is due to the fact that the number of evacuees does not seem to directly affect the possibility to open the inward opening door, but rather the occupant density and the room geometry (walking distance and flow congestions affecting the group formation).

5.2 Sources of error and improvements

Possible sources of error and improvements are discussed in the subsections below.

5.2.1 Extent of sourced data

To capture as many different variations in room geometry and population characteristics as possible, numerous parameters were identified and altered throughout the trials. This was done to make the results from the experiments as universal and applicable as possible. This approach resulted in the collection of a wide range of data results, but it also meant that data from each individual scenario is limited. Conclusions must, therefore, be made with care and only when clear trends in the quantitative data are visible.

With more repetitions of scenarios, a greater set of data could have been collected and clearer trends could possibly have been identified for some of the studied aspects. The performed scenario set-ups can, however, pose as a good ground for judgement of relevant parameters to further assess regarding the stated (or other) aspects.

5.2.2 Inductive bias

The experiments were conducted during one session where the same participants were used for all the conducted scenarios. This could possibly have resulted in learning effects to some degree (since the participants were made to pass through the used door approximately 60-65 times during the duration of a three-hour long session). No clear patterns could, however, be identified that imply that this fact had any effect on the results. The group of participants were also encouraged to mix between scenarios to avoid having the same single person opening the door in multiple trials. To remove any uncertainties, validating experiments could be performed for selected scenarios or parameters in future studies.

5.2.3 Demography of test cohort

As accounted for in section 2.2.2 the gender distribution of the trial population was rather even between men and women. The age distribution was, however, slightly weighted towards a younger cohort with an elevated representation of the age range of 25-35 years (corresponding to ~39 % of the total group). This could possibly have some effect on the group's overall walking speed and agility, but such effects are deemed negligible in this context with regards to the mainly studied aspects (relating to opening the door rather than people flow through it) and the formulated research questions.

5.2.4 Group behavior

The experiments were carried out in the form of walking experiments without external influencing factors that might influence human behavior when evacuating. Such factors can be, e.g., additional stress caused by a fire, or other danger, is in the vicinity of the evacuees, a loud evacuation alarm, etc.

"Panic" behavior and its effects on the evacuation process is further discussed in section 5.3. It is stated that evacuees tend to act rather rationally in an evacuation situation [52]. However, "rationally" might differ depending on the person and the situation of the fire. With a greater number of persons evacuating, possibilities of communication in the queue reduces due to greater difficulties to overview the situation. An evacuation alarm might also affect the possibilities of communication due to the loud noise. With lacking communication, rational behavior of evacuees further back in the queue might be to push forward trying to evacuate as fast as possible making the opening of the door harder. Variation of human behavior depending on communication possibilities in the queue is not fully covered by the performed study. The results of this study would, thus, benefit of validating unannounced evacuation experiments with the presence of an evacuation alarm.

5.2.5 Limitations of the premises

In the design of the evacuation experiments, the prerequisites and physical limitations of the used premises inevitably set the framework to some extent. As can be seen in Figure 1 there was a wall perpendicular to the door on the inward opening side. The arrangement was such that the wall extended about two meters out from the egress door and was situated on the hinge-side of the door, as illustrated in Figure 28. There were also vertical ventilation ducts on either side of the door on the outward opening side and on the lock-side as shown in Figure 28, Figure 7 and Figure 9. These obstacles could have affected various studied aspects such as resulting occupant density and group formation to some extent for scenarios without the short corridor present.

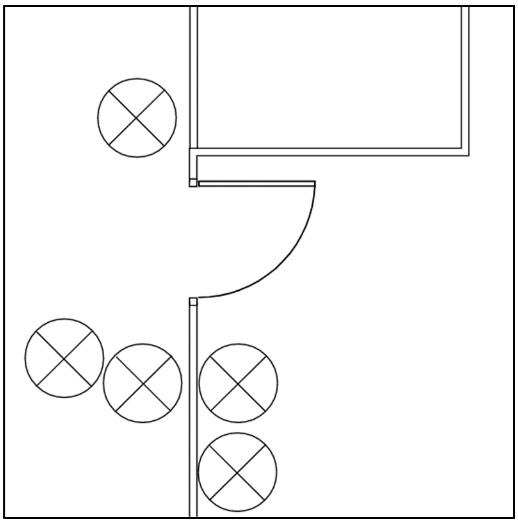


Figure 28. Schematic illustration of obstacles surrounding the studied egress door.

The ventilation ducts and the wall could have acted as flow constrictors and could have facilitated the egress procedure. This could have occurred through imposing an organizing effect on the group formation, forcing the evacuees into more of a “line“ or “zipper” formation rather than a cluster just as they pass through the door.

The presence of the wall part could also possibly have affected the possible “pressure profiles” working on the door leaf from a group of evacuees pushing forward, see Figure 29.

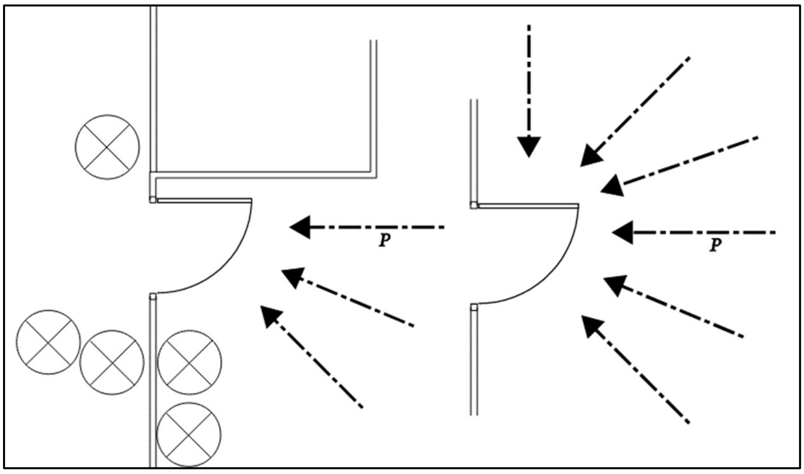


Figure 29. Schematic illustrations of theoretical "pressure profiles".

It is not possible, from the results in this study, to judge whether the presence of the wall imposes unambiguously positive or negative effects on the evacuation process. The physical obstacles could facilitate the possibility to open the door in the initial evacuation stage through “cutting” away half of the possible pressure profile obstructing opening of the door. Its presence could, however, also lead to the complete opposite, i.e., making it more difficult to open the door, this is due to the fact that people could get "stuck" between the door and the wall and, thus, prevent the door from being opened. The latter was to some extent observed in scenario 5.2 and 5.3 where participants had some difficulties moving out of the space created between the door leaf and the wall and, thus, obstructed the door opening maneuver.

Further studies are necessary to clarify the effects of physical objects in the immediate vicinity of an egress door, especially in combination with high initial occupant densities and short walking distances.

The experiments were carried out in lighted rooms during daytime, meaning that the visibility in the premises was good. During a fire, there is a risk of power loss or lighting malfunction, not to mention that smoke may obscure the visibility. In dark spaces, the opening maneuver of the door could be affected since people do not see how the door handles, door knob or other locking functions work. When the door is opened inwards, a delay of opening the door might result in an occupant density build-up similar to the results observed in scenarios with a door knob (scenario 4.5.A and 4.5.B). This affects the possibility to open the inward opened door in a negative sense. Thus, intuitive and easy maneuvered door fittings are especially important in darker spaces.

5.3 Real-life evacuation procedures and previous research

Further, the representability of the evacuation experiments performed is a matter that should be addressed with regards to how well the set up and scenarios used were able to capture the prerequisites and nuances of real-life evacuation situations and human behavior. One aspect that is judged to differ markedly between the experimental setup and a real fire evacuation is the fact that all participants in the experiments are instructed to start their movement momentarily on the signal from the trial management. This fact eliminates any effects of *Awareness time* and *Pre-movement time* which typically are significant parts of evacuation procedures. In practice, these parts of the evacuation procedure differ quite a lot between individuals, which results in a more scattered event where people start their movement towards the exits less unison, see e.g., Forssberg & Kjellström [53], Forssberg et.al. [54] and Lovreglio et.al. [55] regarding distribution of pre-movement times. In this matter the performed experiments might overestimate the resulting occupant density in direct proximity of the door somewhat. The approach was, however, deemed to be the most suitable for the study's purpose and the most manageable way to conduct evacuation trials without imposing further uncertainties concerning diversification of starting times for individual participants. In real-life evacuations, there might be situations with a quite homogenous pre-movement time. An example might be fire scenarios with a very rapid fire development. A situation like the performed experiments is, however, quite unlikely. The legitimacy of the experiments performed, and the results are not judged to be affected by the above in any significantly negative sense.

The representability of human behavior in the performed trials in relation to a real-life evacuation scenario is a matter that can be discussed. In the experiments performed, the participants were encouraged to walk "with a clear goal, such as having decided to evacuate", and no "irrational" or stressful behavior was encouraged. This was done with respect to the results of previous research performed on human behavior in fire and the conclusions performed that evacuees tend to act rationally and cooperate to a great extent, to facilitate a smooth egress procedure. This contrasts with many anecdotes about people behaving irrationally, and making wrong decisions, i.e., showing what is interpreted by an observer as a panic behavior [52]. The irrational or panic behavior is not seen in research or in investigations after tragic events. Overall, in the experiment, the group behavior and walking speeds of the participants is deemed to be representative to a typical evacuation procedure as observed and described in available reports and research, even though more stressful situations might appear e.g., in scenarios with rapid fire development or high risk of crowding.

It is, however, clear that there are tragic fires with a lot of fatalities reported. Cases in which inward opening doors have been present, see section 3.4. Analyzing these events, has shown that there are a few aspects that are common. The first is that, in almost all cases, the fire development has been very rapid, with a very short time for the persons to decide to evacuate. In some cases, like in the fire in the Cocoanut Grove fire in Boston, some of the patrons were found sitting at their tables after the fire was extinguished. Obviously, they did not have time to realize the eminent danger and died without trying to escape. In this case the layout was such that it was very difficult to find the way out. A rapid fire development situation also occurred at the Dupont Plaza fire, indicating that this is an important aspect to consider when applying inward opening doors for evacuation in crowded premises. Another factor mentioned in several of the investigation reports is that it was suspected that some doors were potentially locked, preventing the doors to be opened at all. In the Dupont Plaza fire people were found inside of an inward swinging door in their attempt to evacuate, i.e., they showed a logical behavior but were hindered to evacuate by a door that was reported to be locked. In this case, it would not have helped if the door was opening in the direction of travel. The number of fatalities in some of these cases were not exactly reported, but in the Dupont Plaza case 35 persons were found inside the inward swinging door. Together with the results of this study, this further highlights the importance of intuitive and easy managed door fittings when using inward opening doors for evacuation.

It is also necessary to mention the church fire in Norway which was reported to have resulted in over a hundred fatalities, all found behind a door swinging inwards. This is a fire that occurred 200 years ago, and it is not known if there were other factors that also may have contributed to the tragic event. It is known that several hundred church goers managed to escape and therefore survived. As the fire occurred so long ago, the conclusions can be questioned whether the tragedy can be explained only by the doors.

5.4 Comparability of scenarios

Scenarios that are deemed as directly comparable have been identified and are categorized as “green-scenario-combinations” in section 2.2.5 and in the matrix of comparison (Table 2). These are selected and cross-compared dependent on the scenario set-up and the varied parameters. The starting point of the assessments has been that in order for two or more scenarios to be directly comparable to each other only one parameter (the one that is assessed) is allowed to differ between the compared scenarios. In exceptional cases alteration of two parameters was accepted, but only in such cases where the alteration of the second (not assessed) parameter was small and could be deemed as irrelevant regarding influence on the obtained data.

Nevertheless, as an inherent challenge in designing and performing field experiments there is always the possibility of the presence of factors and unforeseen consequences of adjusting certain parameters that can affect the outcome of one or more of the studied aspects. The matrix of comparison shown in Table 2 was created to address and avoid such issues with internal validity caused by methodological issues (confounding factors or similar) in the way of clearly limiting the possible comparisons of different scenarios. It cannot, however, be completely excluded that unknown consequential effects of parameter variation may have influenced results in some scenarios. Still, no cases where these set of assessment principles impose contamination of data or conclusions have been identified during the analysis phase.

“Yellow-scenario-combinations” have been used for reference and were not assessed in depth or separately accounted for in this report. Observations and parallels have, however, been drawn from the data analysis and loose comparison and intuitive conclusions regarding influence of the different parameters on the studied aspects have been made throughout the data processing and analysis phase. These secondary data have partly been used as assessment grounds for the more direct comparable scenarios.

Nonetheless, there is still a great potential for further studies and assessment of “yellow-scenario-combinations” on a more qualitative basis, and additional patterns could likely be identified leading to added conclusions. This is, however, considered to fall outside of the stated scope of this study.

Regarding the evacuation experiments with a door knob, no directly comparable scenarios were conducted. The effects of more challenging door fittings on outward opening doors are therefore not studied and could not be directly compared to the effect on inward opening doors. A high occupant density close to the door does, however, affect the opening of an inward opening door more than an outward opening door. This indicates that measures to avoid an occupant density build-up close to the door, such as the introduction of intuitive and easy door fittings, is of greater importance when the door is opened inwards.

5.5 Application in Swedish regulatory environment

According to the Swedish building regulations (see section 3.2.1), inward opening doors are not explicitly prohibited, but it is clearly stated that they may only be used if queues are not expected to occur in front of the door. Examples of how this can be achieved are presented as general recommendations. The performed evacuation experiments confirm previous studies on the subject of inward opening doors for evacuation [7, 8]; that evacuation through inward opening doors is neither impossible nor unproblematic, and rather affected by occupant density in proximity of the door than the number of persons in the premises. In the experiments presented as part of this study, several aspects have been studied that affect the possibility to open the door, the risk of queue formation and other aspects of evacuation safety. Based on the results of this and previous studies of the subject, knowledge is now available to further support design of premises to hinder queues from occurring and thereby assist in fulfilling the regulatory requirements. In addition, the results also support regulatory development. It is deemed possible to accept evacuation through inward opening doors to a greater extent than the current Swedish building regulations allow and still maintain a satisfactory evacuation safety. By assuring that current aspects are controlled within the framework of building legislation, safe evacuation when using inward opening doors can be facilitated.

Premises where the risks related to evacuation through inward opening doors are considered lower in:

- Premises with multiple evacuation exits in which a spread of evacuees between different routes of egress can be ensured.
- Premises with a possibility to ensure a low occupant density close to the door (no problems to open the door was observed with an occupant density below 3 persons/m^2 in the experiments).
- Premises with evacuation exits located in the end of an evacuation corridor or a staircase (at the bottom of a staircase, similar group formations can be expected as when evacuating through a corridor) ensuring well-structured group formations and lower occupant density.

Premises where the risks related to evacuation through inward opening doors are considered higher in:

- Premises in which a low occupant density cannot be ensured directly in front of the door.
- Premises and occupancies with risk of rapid fire spread and a short time until critical conditions appear.

6. Conclusions

Based on the observed results from the evacuation experiments performed in this project, the following conclusions are drawn:

- The study concludes that there are possibilities for safe evacuation through inward opening doors given that certain prerequisites are fulfilled.
- The initial stage of egress is slower when evacuating through an inward opening door compared to an outward opening door, and more persons need to interact with each other to open the door.
- Occupant density affects the possibility of opening an inward opened door. A high occupant density, >3 persons/m^2, in direct proximity of the door makes it more difficult to open the door. No problems to open the door was observed for lower occupant densities independent of starting distance from the door.
- The initial occupant density did not affect the possibility to open the door in scenarios with more than five meters walking distance before reaching the door. For shorter walking distances, a high initial occupant density, >3 persons/m^2, might affect the possibility to open the door.
- Participants tend to settle in a queuing pattern rather quickly with an occupant density of 2-3 p/m^2 when approaching the door if unobstructed (i.e., no corridor). This phenomenon was observed unrelated to the initial occupant density, except for scenarios where participants start in direct proximity of the door.
- A corridor in front of the inward opened door results in a somewhat lower people flow through the door. The group formation reaching the door was, however, organised as a zipper, which might favour the opening of the door in an initial stage of evacuation.
- A longer walking distance before reaching the door results in a lower occupant density in the very front of the evacuating group of people. This makes the opening of the door easier since there is less crowding close to the door and fewer people must interact.
- No difference regarding the opening of the door or the people flow through the door was observed depending on the number of people.
- The door fittings will affect evacuation through inward opening doors. More difficult handles, such as a door knob extend the time it takes to open the door and could, thus, impose a negative effect on the egress procedure if combined with high occupant densities.
- The door opening force did not affect the results in this study. However, a bigger variance of door opening forces needs to be studied to draw further conclusions.

Based on the observations above, the assessment is made that evacuation through inward opening doors could be acceptable for higher number than 30 persons provided that:

1. The door fittings provide a fast and easy opening manoeuvre.
2. An occupant density of approximately 3 persons/m^2 or lower, can be ensured close to the door.

The second point can, for example, be achieved by ensuring an increased walking distance before reaching the door, or by constraining the flow of people through the introduction of physical obstacles in the proximity of the door.

7. Further research

Since the available scientific basis regarding inward opening doors is quite scarce, this study has a wide scope. This means that many different parameters were varied trying to identify parameters affecting the possibility of evacuation through inward opening doors rather than focusing in depth on a single parameter. Thus, some of the results are based on a limited number of observations that needs to be verified by additional experiments. Further, some parameters which might affect the results were excluded from the scope of the study. The following parameters could, based on experiences from the conducted experiments, benefit from further research:

- Effects of door width on the possibility to open the door and people flow in the initial stage of egress.
- Effects of even higher door opening force than studied in the performed experiments. In Sweden, 150 N is the upper allowed limit regarding door opening force in new/changed buildings. Further, possible impact of automatic door openers could be a point of assessment.
- Effects of various kinds of door fittings and their impact on the ability to open the door and time to complete the opening manoeuvre.
- Effects of people with movement impairment on the possibility to open the door, group formations and the flow through the door.
- Effects of variations of the flow constraint (corridor or staircase) in terms of placement in relation to the door opening and geometric design.
- Validating evacuation experiments to extend the available data set regarding all or some of the studied parameters.
- Further studies on effects of occupant density in direct proximity to the inwards opening door, and if possible, identification of generic threshold-values for determining dangerously high levels of crowding.
- Effects of physical objects in the immediate vicinity of an egress door and relationship between wall and door placement (e.g., corner vs. straight wall), especially in combination with high initial occupant densities and short walking distances.
- Effects of lighting in the premises.
- Extended analysis of previous fires where inward doors were present and the consequences of these fires (larger data set).
- Effects of the pre-movement time on the occupant density close to the door in early parts of the evacuation process.
- Alternative measures of engineering on doors of cultural value or its surroundings to enhance the possibilities of evacuation without changing the appearance of the door.

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