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STUDENT REPORT

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Human errors during fire evacuations: a case-study
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ABSTRACT

To help minimize the effect of a fire event on the occupants within the building and the building itself, companies rely on fire contingency plans and safety management systems. These plans and systems are supported by procedures incorporated within the company's occupational health and safety system. These procedures are affected by the relevant rules, regulations, and standards for the company based on the daily activities within this company and the legal framework provided by the placement of this company. Previous research has indicated that the maintenance of fire safety equipment and the provision of information influence the evacuation process and the development of a fire event. This thesis provides an internal insight in the adherence with procedures within a production company. Based on both theoretical information and the current situation within the company, this thesis describes 10 different scenarios to investigate the impact of human errors on the evacuation process and the final evacuation time. These scenarios were simulated individually to illustrate the effect of these human errors separately from each other. Based on these simulations, it can be concluded that the human errors affecting the evacuation process and final evacuation time can be traced back to violation errors caused by non-compliance with company procedures, relevant regulations, or a combination of both.

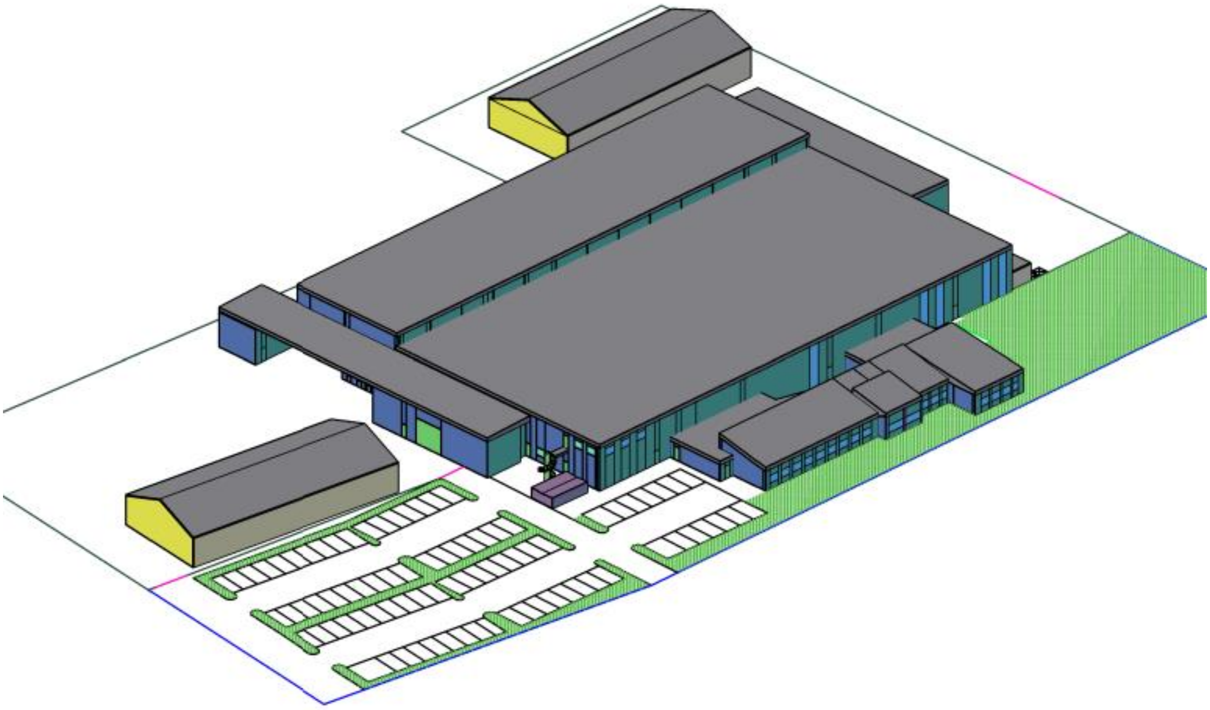
Printed Pages: [99] Pages: [44][1] Pages Appendix: [48] Pages Drawing Folder: [7]

By signing this document, each member of the group confirms participation on equal terms in the process of writing the project. Thus, each member of the group is responsible for all the contents in the project.

[1] 1 page = 4099 characters (including spaces)

Human errors during fire evacuations

A case-study



Master of Science and Technology in Risk and Safety Management

4^{th} Semester, Master Thesis

Aalborg University

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Preface

This thesis is written for the finalization of the master's degree in Risk and Safety Management at Aalborg University. This thesis aims to investigate the different human errors that occur in a company regarding the adherence with procedures impacting the safety management systems. The choice of this topic is made based on my personal background and previous experiences within the topic of fire and evacuation simulation. I have a bachelor's degree in civil engineering and have, therefore, gained a keen interest in modelling, simulations, and the preparation of technical drawings. Additionally, I performed similar simulations for my third-semester project and the mini-project executed during the course 'Simulation of Emergencies'. These previous experiences with this specific topic caused an interest in a more detailed and more practical application of the gained knowledge. I, therefore, chose a case-study of a production company where I had the possibility to observe the conditions within the building itself and the practical incorporation of the written procedures.

I hope that this case-study is not only interesting for my supervisors and external examinator but that the outcome is also relevant for the investigated company. Hopefully, some of the recommendations made in this report can be incorporated within the company's occupational health and safety system and the incorporated procedures.

Finally, I would like to thank everyone that supported and helped me complete this thesis to the best of my abilities. To my husband, thank you for providing me with emotional support and strength. To my son and my dog, thank you for providing me with smiles, hugs, and the possibility to take my mind off the task at hand. I would also like to thank Ronnie and Sandra for helping me find the necessary documentation, discuss the content of this documentation, and run the fire simulation. Lastly, I would like to thank my supervisors for providing me with support regarding the structure of this thesis and for answering my questions regarding the simulation.

Lisa Josan

Tistrup, January 2022

Abbreviations

Abbreviation	*Meaning*
3D	Three Dimensional
ABDL	Automatic Fire Door Closing System
AMO	Work Environment Organization
ASET	Available Safe Egress Time
ATEX	Explosive Atmospheres
BR	Building Regulations
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DKV	Operational, Control, and Maintenance
HRR	Heat Release Rate
IBU	Intrinsic Behavioural Uncertainty
ICE	Ingress, Circulation, and Egress
ISO	International Organization for Standardization
IT	Information Technology
NFPA	National Fire Protection Agency
OH&S	Occupational Health and Safety
PPBU	Perceptions and Preferences Behavioural Uncertainty
QA	Quality Assurance
QC	Quality Control
RSET	Required Safe Egress Time

List of Definitions

5S system: a system incorporated within the company's structure aimed at keeping the workspace and building itself clean and organized. The system is divided in 5 different steps that should be followed by the employees during the operational phase of the company. These 5 steps are illustrated in Figure 1.

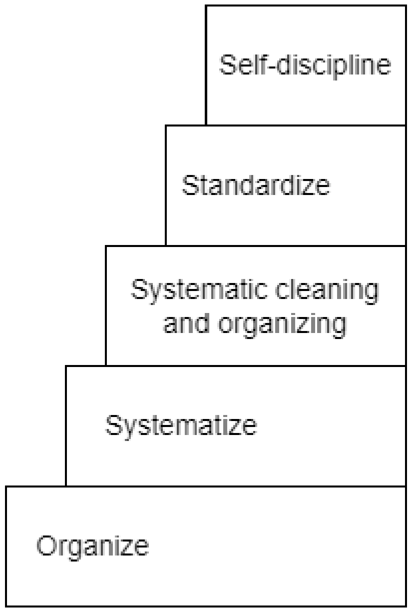


Figure 1: 5 steps of the 5S system (author's model)

Alarm time: time interval in which alarming actions are performed. The interval between the detection of the fire event and the alarming of the individual occupants.

ASET: the interval between the ignition of the fire event and the onset of untenable conditions for the occupants due to the spread of the fire.

Behaviour: actions that are performed by an individual as a reaction to an experienced situation and the perceived risk.

Cue: a signal that is created by the environment surrounding an individual. Everyone interprets this signal separately based on previous experiences and knowledge. The environment includes both the social environment (e.g., interactions with other individuals) and the building environment (e.g., placement of doors, indication of evacuation paths).

Detection time: time until the detection of the fire event.

Emergency door: a door indicated with an emergency sign that is used for emergency exit during a fire event.

Fire contingency plans: plans prepared by the company including an emergency floor plan and safety instructions. These plans are incorporated to minimize the risks experienced by individuals during a fire event.

Fire evacuation exercise: *"An evacuation drill (ED) is a pre-planned simulation of an emergency evacuation given a specific scenario"* (Gwynne, et al., 2020)

Fire safety equipment: components within the building inventory and structure that are actively used during the occurrence of a fire event to minimize the effect and the spread of this event. Examples of fire safety equipment are fire extinguishers, fire hose reels, fire doors, and fire gates.

Hazard-fighting behaviour: actions performed by individuals to try and contain the experienced emergency. These actions may cause injuries in that people usually have limited knowledge of hazards and incorrect assessment of emergencies and lack professional skills to fight the hazards. (Lin, Zhu, Li, & Becerik-Gerber, 2020)

Human error: a failure within the fire contingency plans caused by missing or lacking actions performed by the company's employees during the preparational phase for the execution of these plans. For this case-study, these actions include the completion of maintenance and the provision of information. Human behaviour due to social influence during the fire event is excluded due to limitations caused by lacking documentation within the company and the overall time frame of this master thesis.

Information-seeking: *"the purposive seeking for information as a sequence of a need to satisfy some goal"* (Lin, Zhu, Li, & Becerik-Gerber, 2020)

Inspection: investigation performed on the building inventory, the safety management systems, and the fire safety equipment for compliance with procedures and regulations.

Operational phase: the day-to-day functionalities of the company observed before and after the occurrence of a fire event.

Panic: *"In a fire situation, individuals tend to adopt a hysterical response, where people lose control of their actions. However, the panic in these situations, even when individuals see the fire and feel the smoke, refer to the attitude of shock, since they do not believe that something serious is actually happening"* (Bernardes, Rebelo, Vilar, Noriega, & Borges, 2015)

Perceived risk or perceived risk level: the subjective assessment of the probability to be affected by the emergency. This assessment is individual to each agent and does also consider the agents' perceived vulnerability and the coping mechanisms and resources that are available for the agent. (Lin, Zhu, Li, & Becerik-Gerber, 2020)

Pre-movement time/Reaction time: the time interval between when the occupant is alarmed of the fire event and the occupant's movement towards the evacuation assembly point.

Property protecting behaviour: actions performed by individuals that are aimed at protecting one's property from the perceived risk. These actions can cause fatalities and injuries due to stays in hazard-intensive areas and even delays in the wayfinding process. (Lin, Zhu, Li, & Becerik-Gerber, 2020)

Risk-taking behaviour: actions that are performed by individuals where potential threats caused by the external environment are overlooked e.g., jumping out of windows, protecting property, and retrieving property in hazard-intensive areas. (Lin, Zhu, Li, & Becerik-Gerber, 2020)

RSET: the total time until the completion of the evacuation process during the fire event. This time includes the detection, alarm, pre-movement, and travel time experienced by the occupants of the building.

Safety management system: a combination of operational instructions, and the building inventory and organization that are maintained through incorporated procedures during the operational phase of the company. This system is incorporated to minimize the effect and the spread of the fire event through active (fire safety equipment) and passive measures. Some examples of passive measures are evacuation paths, evacuation doors, maintenance instructions, and fire contingency plans.

Service: investigation and maintenance performed on the safety management systems and the fire safety equipment for compliance with the procedures and regulations.

Stress: *"Stress can be assumed as a generally uncomfortable emotional experience and it is often perceived by the biochemical, physiological and behavioural changes in human beings. It has been investigated that stress has a degrading influence on decision making."* (Bernardes, Rebelo, Vilar, Noriega, & Borges, 2015)

Travel time: the time it takes an occupant to escape from the building.

Contents

Executive summary

This thesis investigates the occurrence of human errors during an evacuation of employees from a building due to the inception of a fire event. The performance of this investigation is completed based on a company that is found in the city of Esbjerg in Denmark. This thesis, therefore, also considers regulations and standards imposed by the sector and the country in which the company operates. More precisely, this thesis describes the requirements provided by the Danish building regulations (BR18) and the International Organization for Standardization (ISO 45001).

The company is active in the metal industry. The company has subsidiaries in various countries such as the United Kingdom and Germany. This thesis, however, considers the company's headquarters in Denmark. At these headquarters the company designs, sells and produces bellows and expansion joints for various industries (e.g., shipping, chemical and energy). The investigated building does, therefore, consist of both an administration building and a production facility. Both parts are internally connected with each other through fire doors and fire gates. Additionally, the company's safety management systems include evacuation paths, emergency doors, emergency signalization, emergency doors and fire safety equipment (e.g., fire extinguishers and fire hose reels).

During the preparatory phase for the possible occurrence of a fire event, the company incorporates fire contingency plans within its occupational health and safety system. These fire contingency plans include safety instructions, emergency floor plans and operational procedures (e.g., maintenance of fire extinguishers, doors, and gates). The safety instructions provide the employees with information regarding the actions that should be taken during a fire event. Additionally, the emergency floor plans indicate the available safety management systems and the placement of fire safety equipment. The completion of the evacuation process using these safety instructions and emergency floor plans relies on the compliance with the described operational procedures. The preparation, discussion and implementation of these plans is organized through the company's work environment organization (AMO). This organization's tasks are to update fire contingency plans, divide roles and responsibilities, inform employees, and provide detailed maintenance procedures in compliance with BR18. This regulation states that employees must be informed yearly of the fire contingency plans. Additionally, adherence with this regulation leads to the requirement for an Operational, Control, and Maintenance (DKV) plan. This plan should provide time intervals for internal and external inspections and the description of what these inspections should investigate. Finally, the company must document all fire contingency plans for compliance with ISO 45001 and BR18.

To reveal and investigate the human errors occurring during this preparatory phase, this thesis uses the event tree analysis. This analysis is used to determine the various scenarios that can occur during an evacuation process based on the safety instructions, the emergency floor plans and the safety management systems. These scenarios focus on the occurrence of failure in one of the following components: fire extinguisher, manual fire alarm, closing windows/doors, fire gate/door, risk minimization system, evacuation/first response teams, evacuation paths, emergency doors and emergency signs. To determine the impact of failure in one of these components the scenarios are ranked in comparison with an ideal scenario where no component fails. This ranking is based on the expected value of each scenario. This value is defined as the product of the probability that the component fails and the total evacuation time. This evacuation time is calculated based on

the required and the available safe egress time (RSET and ASET) for each scenario. The probability that a component fails is based on the adherence of the company with its own procedures and a visitation of the building by the author of this thesis.

The ranking of the various scenarios is included in Table 1. This ranking shows the scenario with the lowest calculated risk at 1 and the scenario with the highest calculated risk at 9.

<table>
<tr><th>Ranking</th><th>RSET, ASET (component)</th><th></th></tr>
<tr><td>1</td><td>Fire doors and gates (scenario 7)</td><td rowspan="5">maintenance plan + emergency floor plans</td></tr>
<tr><td>2</td><td>Risk minimization system (scenario 6)</td></tr>
<tr><td>3</td><td>Evacuation doors (scenario 3)</td></tr>
<tr><td>4</td><td>Emergency signs (scenario 2)</td></tr>
<tr><td>5</td><td>Evacuation paths (scenario 4)</td></tr>
<tr><td>6</td><td>Doors, gates, and windows (scenario 8)</td><td rowspan="4">maintenance plan + emergency floor plans +safety instructions</td></tr>
<tr><td>7</td><td>Fire extinguishing actions (scenario 10)</td></tr>
<tr><td>8</td><td>Evacuation team (scenario 5)</td></tr>
<tr><td>9</td><td>Manual fire alarm (scenario 9)</td></tr>
</table>

Table 1: Ranking of scenarios (author's model)

The highest ranked scenarios include components that are affected by human errors occurring in the compliance with the maintenance procedures, the emergency floor plans and the safety instructions. The cause of the investigated human errors is revealed as violations of the company's own procedures, and the procedures described in regulations and standards. These violations lead to situations where employees present human errors such as mistakes, attentional failures (lapse) and memory failures (slip).

This thesis proposes certain actions that can be performed by the company to reduce these risks. These actions include the appointment of a person responsible for the follow-up of the fire contingency plans, the preparation of a DKV plan and the incorporation of a system that integrates both the information from the fire contingency plans, and the resulting inspection and maintenance reports.

While this thesis identifies the human errors based on the preparatory phase, the behaviour of the employees during an evacuation is not observed. Further research and the performance of a fire evacuation exercise is needed to investigate the inherent human behaviour during the evacuation process. Additionally, the calculation of the ASET should be refined with the inclusion of the simulation of the fire event until the onset of untenable conditions for the entire building. This simulation would, therefore, need to be performed with a longer calculation time.

1. Introduction

The necessity of contingency plans in case of a fire event is described in regulations and standards such as BR18 and ISO 45001. These contingency plans include the incorporation of emergency floor plans and safety instructions. Additionally, they include guidelines regarding the maintenance of fire safety equipment and the documentation of the various plans and instructions. The provision of documentation regarding these plans and instructions includes regularly informing the occupants regarding their content and possible updates to this content. A failure to provide information or to perform the required maintenance might increase the number of human errors that could be experienced during a fire event. Their impact might, furthermore, be higher. This thesis aims to investigate the impact of these human errors on the evacuation process experienced during a fire event. This impact is assessed through the simulation of various evacuation scenarios using modelling software. The investigation will, therefore, be performed through a case-study of a production company that produces expansion joints and bellows in Denmark. Based on the company's organizational structure, the various scenarios will be compared and discussed. Additionally, the discussion of the outcome includes a consideration towards the possible impact of the mentioned regulations and standards on the occurrence of the investigated human errors.

The outcome of this case-study is limited by the student's access to the required documentation. This includes the student's access to documents owned by the production company. Additionally, some company documents might be found to be out of date but if no adaptions or new versions could be found, the outdated documents were used. Due to the exponentially increased calculation time and the number of different scenarios, the effect of the ventilation system is not considered. This case-study aims to investigate the effect of human errors on the evacuation process individually. The scenarios do, therefore, not include any combined human errors.

This case-study and its outcome are assumed to be relevant for both the company itself and any people involved with the preparation, or the execution of the fire contingency plans. Both external and internal stakeholders can use the outcome of this case-study for the improvement of the processes that could affect some of the human errors during a fire event. For the company itself, the outcome of this case-study will, therefore, be most relevant for both the work environment organization (AMO) and the quality assurance (QA) department. The AMO is responsible for discussing fire plans and instructions. Additionally, this organization appoints different roles and responsibilities in the fire instructions to employees within different departments. The AMO is, therefore, responsible for incorporating different procedures within the day-to-day business. These procedures include the provision of information regarding the fire instructions and the follow-up of maintenance and monitoring systems. The AMO is tasked with keeping a log of all meetings and necessary documentation regarding its different tasks. In addition to the AMO, the QA department should be updated on the outcome of this document. This department is tasked with preparing the fire contingency plans for discussion by the AMO. The adaption of these instructions and plans based on the feedback from the AMO is also performed by this department. The QA department is, furthermore, responsible for obtaining and maintaining different ISO certificates. This department would, therefore, be interested in the different requirements from the relevant ISO standard and what changes must be made to obtain/maintain this certificate.

2. Procedural overview

This part of the document provides the reader with a general overview regarding the procedure that was followed to discuss this case-study. This procedure is illustrated on Figure 2.

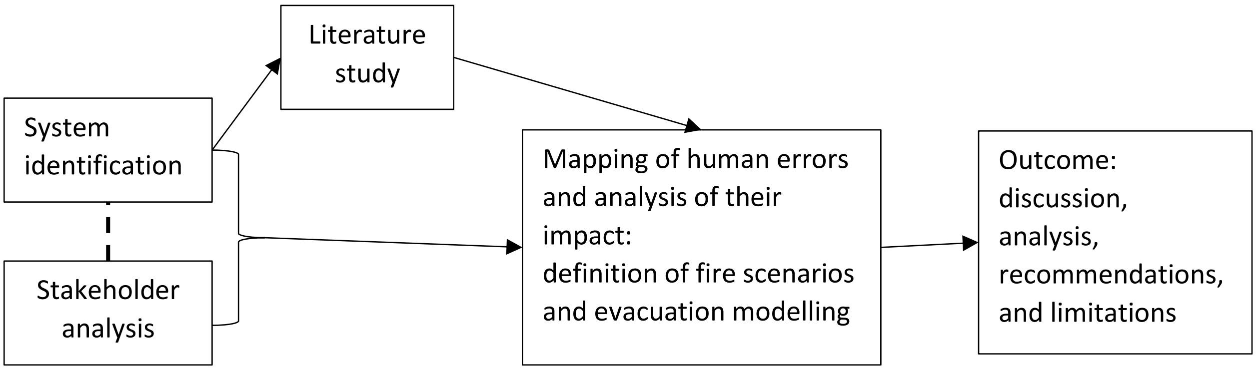


Figure 2: Schematic presentation of the general procedure (author's model)

Firstly, the system identification and the stakeholder analysis will be described to provide the knowledge basis regarding the company and its stakeholders. The system identification will describe the physical elements and main functionalities of the company. For the main functionalities of the company, both information regarding the daily business and the incorporated fire contingency plans (e.g., emergency floor plans and safety instructions) are considered. This part of the system identification includes a discussion of the company's preventive barriers and reporting systems relevant to fire events. The system identification also presents a clear overview of the rules, regulations, and standards relevant to this case-study. Additionally, the stakeholder analysis will provide information regarding the organizational structure of the company focused on the preparation for possible fire events and the implemented evacuation process. This analysis describes the internal organizational structure and its connection to external entities such as inspection agencies, governmental bodies and externally hired subcontractors.

Afterwards, a literature study is incorporated to investigate and describe the methodology that will be used as a basis for structuring the modelled fire events. This basis includes both the approach used to define various evacuation scenarios and the approach used to model the agents and their behaviour. The definition of these evacuation scenarios will be based on their ability to illustrate the effect of human errors within the company's contingency plans. Additionally, the literature study provides information regarding researched or observed human errors and human behaviour.

The information from the literature study, the stakeholder analysis and the system identification are, subsequently, combined to map the components that could be affected by human errors. These components are mapped to determine different fire evacuation scenarios that will be modelled to analyse their individual impact on the evacuation process. This analysis is completed based on a fire simulation using Pathfinder and Pyrosim.

Finally, based on the mapped fire evacuation scenarios and the simulation results the outcome of this case-study is discussed. This outcome includes a discussion and analysis of the results, and recommendations regarding the mitigation of the revealed human errors and the relevance of the compliance with regulations and standards. As several limitations can be experienced during the process of this case-study, the outcome also includes the discussion of the limitations and their possible effect on the outcome from the fire evacuation simulation.

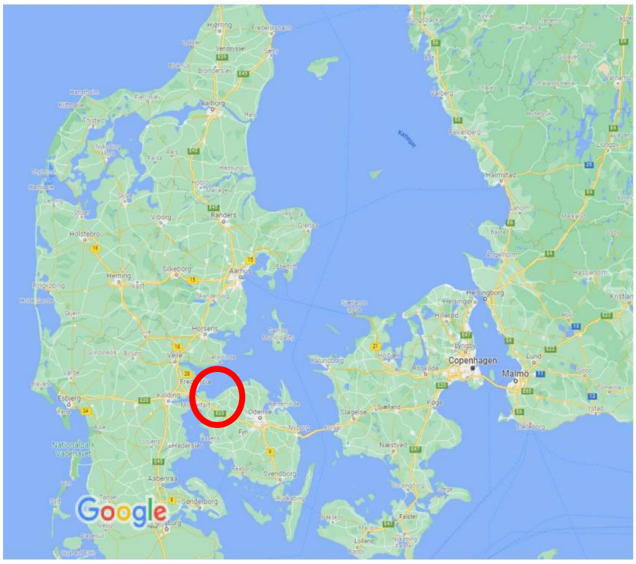
3. Knowledge basis

3.1. System identification

3.1.1. Boundaries

The case-study is performed on a company that produces and supplies bellows and expansion joints for both on- and offshore industries such as the shipping industry, the chemical industry, and the energy industry. According to Eurostat classification standards the company can be classified as a medium-sized company based on the number of employees they employ (European Commission Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW), 2019). At its headquarters the company currently employs 75 to 80 individuals including temporary workers and student workers.

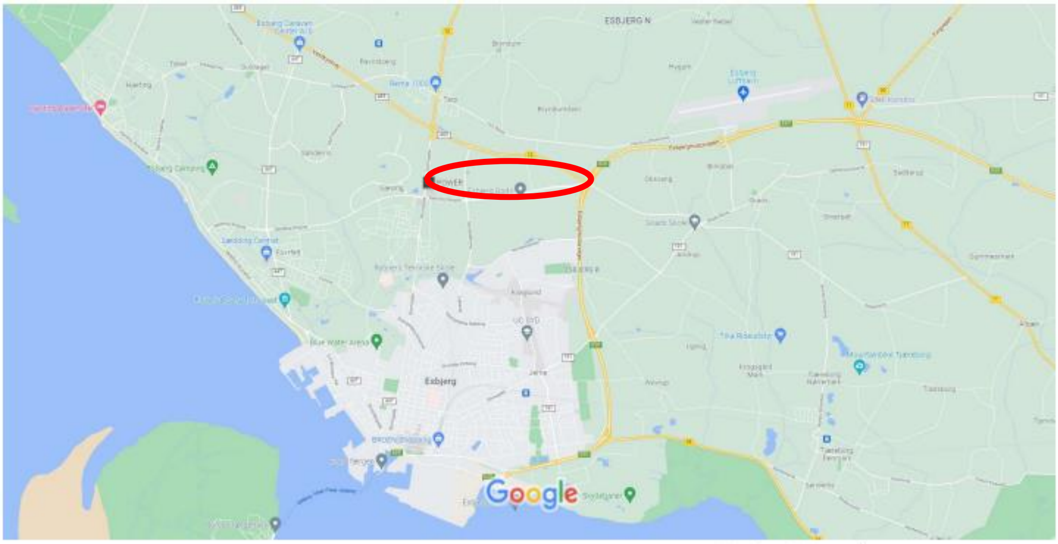
The company has various subsidiaries worldwide, but their headquarters are in Denmark. At the headquarters, both a production facility and an office can be found. Most of the products that are sold, are, therefore, designed, quoted, and produced in Denmark. This case-study will only consider the described headquarters. These headquarters are in Esbjerg. Esbjerg is a city that can be found on the western coast of Denmark as shown in the red circle on Figure 3.



Map data ©2021 Google, GeoBasis-DE/BKG (©2009) 20 km

Figure 3: Map of Denmark (author's model using Google Maps)

Since the company fulfils an industrial position within Esbjerg, it is placed in a designated industrial area. This area is indicated in the red circle on Figure 4. The area surrounding the company does, therefore, not contain any domestic buildings.



Map data ©2021 1 km

Figure 4: Detailed map of Esbjerg (author's model using Google Maps)

The construction of the first part of the building was completed in 2002. Due to the growth of the company since its inception, the building was expanded. The last expansion on the building was added in 2014. The original building and its expansion were designed in accordance with the Danish building regulations that were in effect in 2002, i.e., BR10. The fire safety equipment and safety management systems are, therefore, in accordance with BR10. Some examples of fire equipment are alarm systems, smoke detectors and fire extinguishers. Additionally, some examples of safety management systems are evacuation routes and exercises. However, the new building regulations (BR18) state that all existing buildings that do not have an approved operation, control, and maintenance (DKV) plan in connection with their building permit, must follow the regulations described in BR18 (Mailund, 2021). Since the company does not have a DKV plan that was approved in connection with any of the approved building permits, they must follow the regulations stated in BR18.

Since the company's headquarters are in Denmark, the company must adhere with the fire regulations defined by the relevant Danish jurisdictions. Additionally, if no specific documentation is provided by the Danish documents, the European jurisdiction should be complied with. Finally, since the company aims to obtain the 45001 certification from the International Organization for Standardization (ISO), they should incorporate the requirements presented within this standard.

3.1.2. Main functionalities

3.1.2.1. Day-to-day business

As mentioned previously, the company has both a production facility and an office at the headquarter building in Esbjerg. The building itself is, therefore, divided as illustrated on Figure 5. The area indicated with the red shape is the office where the administrative side of the business is conducted. This includes IT support, quality assurance and quality control (QA/QC), sales, and finance. The area indicated with the blue shape is the production facility, in this facility the units are produced and assembled. Additionally, all finished units are shipped to the client from this facility. Within the production facility and in the surrounding area several storage places can be found. Some of these storage spaces are indicated with the orange shapes on Figure 5. These storage spaces are used by all departments within the production facility. They are, therefore, solely accessed for storage purposes of parts and units. No employees are expected to stay in these areas for longer than necessary as they should perform their tasks within the area designated for their department.

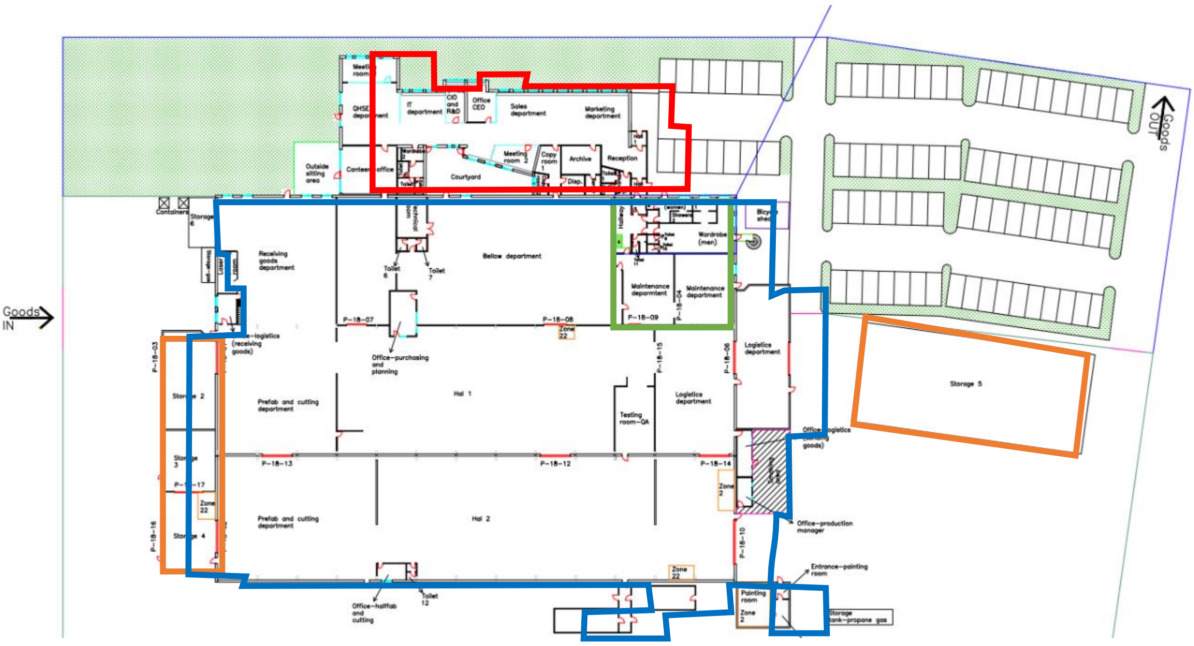


Figure 5: Illustration division headquarter building-extract from drawing 1.01, 12. Drawing folder, p. 2 (author's model)

Although the building is mainly constructed with only a ground floor, a first floor is added above the changing rooms as indicated by the green shape on Figure 5. This first floor contains a small meeting room and the canteen for the employees within the production facility. The first-floor plan can be found on drawing 1.02 (12. Drawing folder, p. 3).

The surrounding area on Figure 5 also shows the parking lot where all employees park their vehicles and the green area in front of the building. The parking lot is used as an evacuation assembly point, the placement of this assembly point is indicated on drawing 3.01 (12. Drawing folder, p. 6). The green area in front of the building is a grassy area. In between the parking spaces a green area is also indicated (Figure 5). This green area comprises small bushes. These small bushes have a maximum height of 1.0 m, and they can, therefore, be crossed if needed. Finally, since goods are shipped to and from the production facility, the surrounding area also includes road for truck access. These roads are indicated with arrows on drawing 1.01 (12. Drawing folder, p. 2).

Both the production facility and the office are divided in smaller departments. They are indicated on drawing 1.01 (12. Drawing folder, p. 2). These departments handle various parts of the day-to-day business within the company. Additionally, each department has its own representation within the AMO. This division in departments is, furthermore, used for organizing evacuation procedures and evacuation teams. More information about the role of the different departments in the AMO and the evacuation teams can be found in the stakeholder analysis (section 3.2).

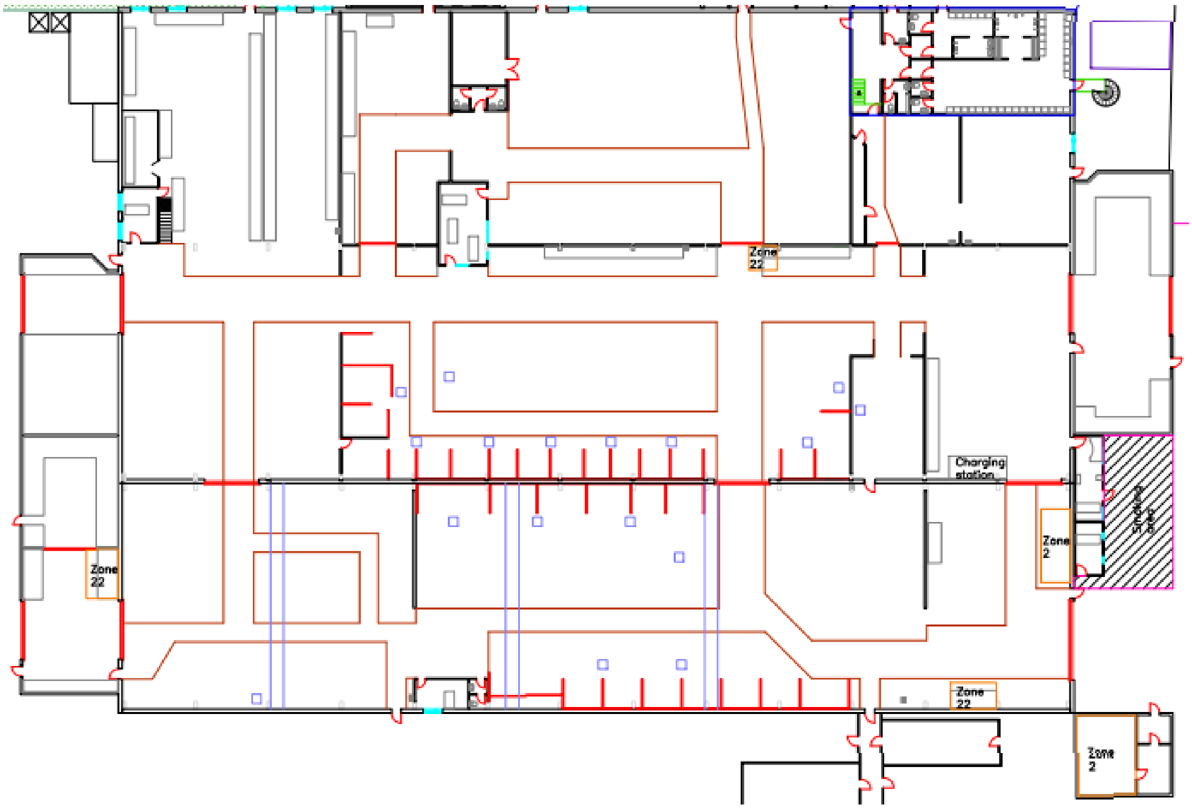


Figure 6: Pathways and zones production facility-extract from drawing 2.01, 12. Drawing folder, p. 4 (author's model)

Within the production facility, both working stations and storage areas are included. These storage areas contain both finished bellows and components to produce them. The placement of both storage areas and cranes for lifting heavy parts are indicated on the floor plan (drawing 2.01, 12. Drawing folder, p. 4). Since employees need to have access to these storage spaces, the office and the different departments within the production facility, pathways are indicated with yellow tape on the floor. These pathways are indicated with the brown lines on Figure 6 and drawing 2.01. They must be kept free of any obstacles to allow employees to move unhindered, also during emergency situations. The drawing (drawing 2.01) also shows the ATEX (explosive atmospheres) zones that are designated within the facility. These zones are used to indicate areas where explosive atmospheres such as gasses and vapours could be present. The facility has both zone 2 and zone 22 indications. Zone 2 indicates the infrequent or short occurrence of hazardous gas, vapour, or mist. Zone 22, however, indicates the infrequent or short occurrence of a cloud of combustible dust (Klinge Corporation, 2020).

To ensure that all safety procedures are adhered with, the company's procedures describe the performance of both internal and external checks. These checks should be performed in accordance with the plan decided on by the AMO. Additionally, quarterly work environment meetings are held by this organization. These meetings are held to discuss the implications of the workplace assessment. The discussion should, therefore, include reported accidents and safety issues, fire evacuation procedures, the planning of fire evacuation exercises, and the maintenance of the workplace and the building equipment (gates and doors). Finally, the AMO decides on the necessary courses (such as first aid and management courses) for the employees. More information regarding this organization and the different participants in the meetings can be found in the stakeholder analysis (section 3.2.1).

The company is also subjected to planned fire inspections performed by the fire brigade. These inspections aim to find any issues or shortcomings where the building itself is not in accordance with the relevant fire laws.

3.1.2.2. Emergency events (fire event)

In case a fire event occurs, the employees in the company are provided with fire safety instructions and the presence of fire safety equipment. Fire safety instructions are a part of the safety management systems that are adopted by the company. The fire safety instructions are given to the employees whenever they start working within the company. These instructions are available in both English and Danish. The safety instructions provide a detailed description of the tasks that must be performed by the employees. The instructions are, therefore, divided in 3 different parts. The first part consists of a general description of the tasks that all employees in both the office and production facility must follow. The second part details the tasks that the person from the reception is responsible for. These tasks focus on providing a list of all visitors and employees that are present in the building at the time of the fire event. Finally, the last part describes the tasks that should be performed by the responsible work environment representative at the evacuation assembly point. These tasks include organizing all employees at the assembly point and performing a rollcall. Additionally, this person is tasked with receiving the rescue crew and providing them with information regarding the fire event and any missing employees. The current safety instructions (with the redaction of personal information) are included in the appendix (11. Appendix, section 11.1.1).

The performance of the safety instructions is supported by evacuation groups. These groups are chosen by the AMO, and they are composed of employees with first aid and/or fire courses. More information about these evacuation groups and the work environment organization can be found in the stakeholder analysis (section 3.2).

The placement of the fire safety equipment is shown on the emergency floor plan. This plan shows the position of emergency signalization, hazard containment equipment (fire extinguishers, fire hose reels and activation buttons for smoke hatches), first aid equipment (fire aid kits and eyewash stations) and evacuation plans. These evacuation plans show both the emergency floor plan and a summary of the safety instructions. The emergency floor plan is included to aid the employees in orientating themselves during the fire event. The emergency floor plans can be found in the drawing folder (drawing 3.01 and 3.02, 12. Drawing folder, p. 6-7).

3.1.3. Relevant rules, regulations, and standards

3.1.3.1. ISO standard (ISO 45001)

Within the documentation of their fire contingency plans, the company references ISO 45001 (ISO, 2018). The company does not currently have the certificate for this ISO standard. However, since the company is preparing its procedures and documentation for obtaining this certificate, the incorporation of this standard is relevant for the discussion of possible measures and their impact on the simulated fire event.

The ISO 45001 standard describes requirements and guidance for the implementation of occupational health and safety (OH&S) systems.

For fire events specifically, the standard describes the implementation of emergency preparedness for the operational phase of the company. This preparedness is supported by the planning of occupational health and safety actions and objectives, the management and leadership within the company and continuous improvement with the inclusion of performance evaluations. This support is illustrated in Figure 7.

Figure 7: Support systems for fire emergency preparedness based on ISO 45001 (author's model)

For the planning of actions and objectives, the standard describes the need for hazard identification processes. These processes aim to define and describe both current and future hazards that could cause a fire event or impact the evacuation process during an emergency. Based on the outcome of these processes, the company must prepare a fire contingency plan detailing the actions that must be taken to address the risks caused by the fire hazard. This plan must adhere with the legal requirements from the building regulations (BR18). Finally, it must be integrated within the current OH&S system. The company must, therefore, consider the needed actions for its integration and implementation within this system. This integration can include other actions such as keeping emergency exits/pathways free and providing clear guidance regarding the storage of flammable materials.

After the plan's integration within the OH&S system, it is necessary to perform an evaluation of the effectiveness of this plan during fire events. The standard defines different methods for this evaluation. For the fire contingency plans, these methods include an internal audit, a management review, and the evaluation of the compliance with the legal requirements. Additionally, the fire contingency plans and their integration within the OH&S system can be evaluated through a performance evaluation. This evaluation can be obtained through the performance of fire evacuation exercises or the investigation of incidents and near-misses. This evaluation should lead to the continual improvement of the OH&S system and the fire contingency plans.

The planning, and improvement and evaluation of fire contingency plans is supported by the managerial framework. This managerial framework is provided through the AMO in accordance with the ISO standard. This organization consists of managers, workers' representatives and workers that have different functions and positions within the company. This participation should ensure that employees from different levels can provide their input regarding the actions described in the safety instructions. It is the organization's responsibility to incorporate and evaluate these plans. The organization also assigns relevant roles within this plan to trained employees. The AMO, therefore, provides the necessary resources for the training of these employees. This training can be both fire emergency training and first aid training. Finally, the organization is tasked with the documentation of information and the communication with employees. This communication should provide all employees with the relevant knowledge regarding their role in the fire contingency plans. For future reference, the relevant information from both AMO meetings and the fire contingency plans must be documented.

The ISO standard also describes different tasks that must be performed by the company for emergency preparedness. These tasks were divided over the three supporting elements described above. The tasks and their division are illustrated in Table 2.

Planning	Improvement and evaluation	Management and leadership
- Establish a fire contingency plan (include provision of first aid)	- Periodical testing and fire evacuation exercises - Evaluation of performance - Revision of fire contingency plan (after exercise or fire event)	- Provide training - Communicate and provide relevant information (duties and responsibilities) - Consider needs and capabilities of all stakeholders - Maintain documentation of information (fire contingency plan and meetings)

Table 2: Emergency preparedness tasks in accordance with ISO 45001 (author's model)

3.1.3.2. Building regulations (BR18)

The information that is added to this part of the document focuses on the fire safety equipment and the safety management systems that are present at the headquarters of the company. All information that is inserted in this part of the document is based on (Bolig og planstyrelsen, 2021)

The operation, control and maintenance of all systems and equipment needed for the fire safety in and around the building should be performed with the goal of ensuring the safety of the employees for the total lifespan of the building. All equipment must, therefore, be installed so these tasks can be performed easily. For the planning and performance of these tasks, a DKV plan detailing the different roles and responsibilities should be made by a certified fire consultant. This plan must adhere with the maintenance and inspection instructions that are provided by the supplier. All documentation prepared for the performance of the DKV plan must be kept for a minimum of 5 years. The performed actions and logs must also be reviewed once a year.

The building regulations describe different requirements for both the fire safety equipment and the safety management systems. A diagram illustrating the different subjects that will be discussed for those requirements can be found in Figure 8.

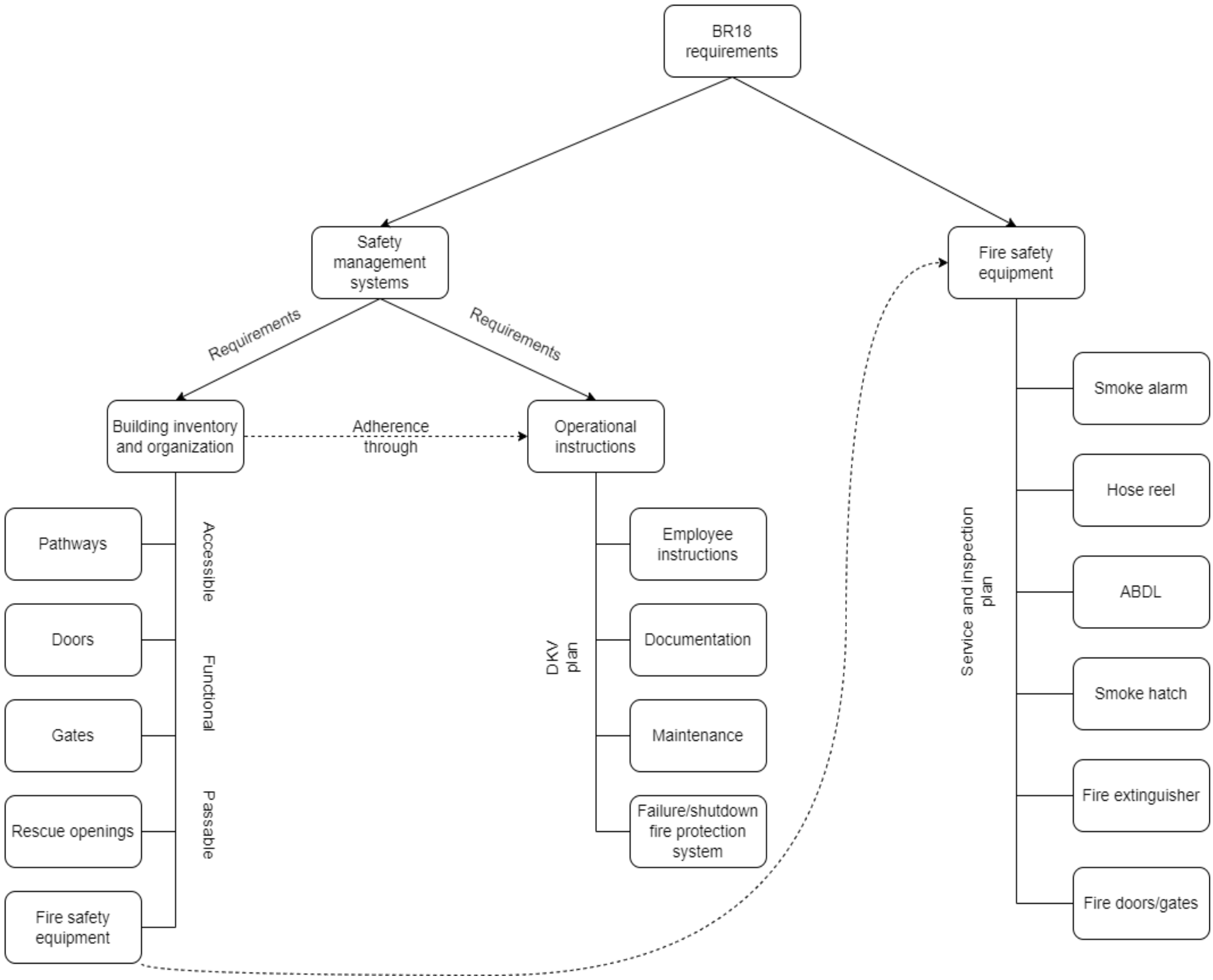


Figure 8: Systematic representation of subjects for BR18 requirements (author's model)

3.1.3.2.1. Requirements for safety management systems

Building inventory and organization

All evacuation pathways must be accessible and usable. Loose furniture, storage spaces and parts should, therefore, be placed outside of the indicated evacuation pathways. Along evacuation pathways, doors and gates are included for evacuation from the building. These doors and gates must always be functional and accessible. Doors can, therefore, not be covered or blocked. Additionally, all gates must open automatically and remain open when the building is operational (during working hours). The functionality of both doors and gates should be checked regularly to ensure that the self-closing mechanism is activated and that they are not propped open. Finally, rescue openings (such as the indicated windows in the office (drawing 3.01, 12. Drawing folder, p. 6)) must be accessible and easy to open without any keys or tools.

For firefighting purposes access to all hose reels and fire extinguishing equipment must be unobstructed for both the employees and the rescue crew.

Operational instructions

The operational instructions are detailed in the DKV plan. These instructions should include consideration for adherence with the above-mentioned requirements regarding building inventory and organization. The DKV plan also provides information regarding the responsible person for following-up on the maintenance of equipment, the organization of documentation and the procedure regarding failure or breakdown of fire protection systems. Additionally, this person must ensure that all employees (also interns and temporary workers) receive the necessary information, instructions, and training for both fire safety and evacuation in case of a fire event. These instructions must be done immediately after employment, and they must be repeated yearly. The instructions should include at least the points included in Table 3. Finally, all updates regarding instructions and plans (emergency floor plan, space allocation plan) must be communicated with all employees.

Instructions for employees
- Fire and evacuation instructions - Warning system in the building and how it sounds - Placement of space allocation plans, inventory layout plans, electrical safety certificates and evacuation instructions - Location and instructions for use of fire-fighting equipment (e.g., fire extinguisher) and fire safety installations (e.g., smoke hatch, fire gates/doors) - Close doors during evacuation to minimize fire and smoke damage - Self-closing doors must not be propped open - Furniture and storage must not be placed in escape pathways, stairwells, and corridors (in and around building) - Role and responsibility during evacuation/fire evacuation instructions

Table 3: Yearly instructions for employees (author's model)

All the above-mentioned requirements are relevant for both the production facility and the office. The building regulations do, however, mention additional requirements for this production facility. These additional requirements also include a consideration for the performance of hot work such as welding within this facility. They can be found in Table 4. To evaluate the relevance and compliance with these instructions, fire evacuation exercises can be held at timed intervals according to the fire strategy or the interval pre-determined by the municipal council.

Additional instructions for employees (production facility)
- Parking of trucks can only be done where specific space is allocated - Fire doors and gates must be closed at the end of the working day - Welding workplace must be monitored, and work must be stopped at least 1 hour before the facility is closed - Employees (working with welding tasks) must have completed a course in firefighting techniques - Option to alert emergency services directly

Table 4: Additional yearly instructions for employees-production facility (author's model)

3.1.3.2.2. Requirements for fire safety equipment

To minimize the probability of failure or issues arising during an evacuation, fire safety equipment must be regularly checked, inspected and function tested. These investigations are initiated to attempt to identify and rectify any damages or faults. Additionally, the goal of these inspections it to ensure that the equipment is functioning as desired if a fire event occurs. The different types of fire safety equipment and the frequency of service and inspections for them are shown in Table 5. More detailed information regarding the requirements for these services and inspections can be found in the appendix (11. Appendix, section 11.1.2.).

Fire safety equipment	Monthly	Quarterly	Yearly	2-yearly	5-yearly	10-yearly
Smoke alarm		x	x		x	
Hose reel	x		x		x	
Automatic fire door closing system (ABDL)		x		x		
Smoke ventilation (smoke hatch)			x			
Fire extinguisher	x		x		x	x
Passive fire protection			x			

Table 5: Frequency of service and inspection for fire safety equipment (author's model)

3.2. Stakeholder analysis

The stakeholders relevant for this case-study are dependent on the phase of the emergency. The different phases and the connected stakeholders are shown in Figure 9. The phase 'during a fire event' can also be the execution of a fire evacuation exercise since this exercise aims to simulate the evacuation process that occurs during a fire event.

Before and after the fire event, the AMO is responsible for the work environment. This organization is, therefore, tasked with discussing the fire contingency plans and providing feedback to the QA department regarding changes that must be made to these plans. The AMO must, also, provide instructions, courses, and information regarding these plans to all employees within the company. The organization, furthermore, determines which employees have a roles and additional responsibilities within the contingency plans. These employees should receive additional instructions and courses through the AMO.

During a fire event, the relevant stakeholders are detailed in the safety instructions (11. Appendix, section 11.1.1.). As mentioned previously, some of these stakeholders are chosen by the AMO.

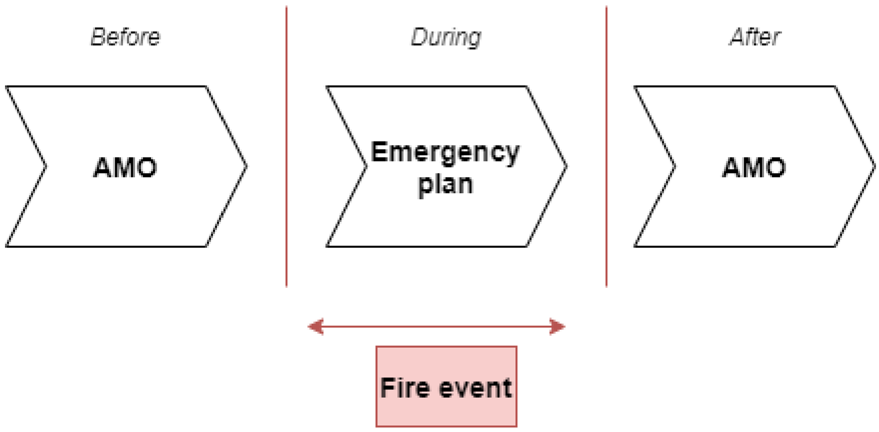


Figure 9: Stakeholders for different phases of an emergency (author's model)

3.2.1. Stakeholders relevant before and after the fire event

As stated previously (section 3.2), the stakeholders relevant before and after the fire event are found in relation with the AMO. The various stakeholders and their relationship with the AMO are illustrated in the appendix (11. Appendix, section 11.3.1.1.).

The QA department is responsible for preparing and adapting the fire contingency plans based on the feedback received from the AMO. This department assigns a person to this task. This person must ensure that the plans are adapted and kept up to date before the next AMO meeting. Since the AMO should discuss these plans at the quarterly meetings, this person has the possibility of delaying this task if there are more important tasks that must be completed within a stricter deadline.

The AMO is responsible for ensuring a safe and secure work environment and workspace for all the employees within the company. This organization discusses the fire contingency plans and gives feedback to the responsible person from the QA department. Additionally, the AMO organizes the provision of instructions and courses to the employees. This is accomplished through a yearly training program that is organized by the AMO. Participants within the AMO are representatives from different levels such as supervisor and management representatives. The representatives within the AMO are divided between the production facility and the office as shown in the stakeholder map (11. Appendix, section 11.1.3.1.). It is, therefore, assumed that the feedback provided by these representatives is influenced by and targeted at the conditions and the community within the production facility and the office respectively. Especially since all employees know each other personally, the representatives might experience a higher pressure to keep these employees satisfied. The different members and their roles/input are discussed below. All members discussed below should have the necessary knowledge regarding the evacuation procedure and they are, therefore, considered as back-up members for the evacuation team. More information about this team can be found later in this part of the document (section 3.2.1).

- **Managing director and chairman**
  The chairman of the AMO is a member of the upper management (board of directors) that can make decisions regarding how to act in relation to issues within the work environment. The chairman of the AMO is also the managing director of the company. They are, therefore, tasked by the board of directors with establishing the AMO. This establishment is required to ensure the needed cooperation between representatives to provide and maintain a safe and secure work environment for all employees. The managing director has the power to make decisions regarding the day-to-day business within the company. However, bigger decisions regarding the company, its goals and opportunities are discussed in planned meetings with the board of directors. The decisions made by the managing director are, therefore, influenced by the desires of the board of directors. Finally, after the occurrence of a fire event the managing director is responsible for all communication regarding the event and its consequences with the media.
- **Management representative**
  The management representative is the production manager. This person is responsible for the day-to-day business within the production facility. They can, therefore, make decisions regarding the incorporation of changes to the work environment and the planning of tasks. Additionally, they are supposed to have knowledge regarding audits and internal/external inspections of fire safety equipment and management systems for the production facility. Finally, the production manager has the decision power over the supervisors i.e., he makes decisions on what they can and cannot do and implement.
- **Supervisor representative**
  The role of supervisor representative is appointed to a supervisor that is chosen to represent all supervisors within the AMO. This person is, therefore, responsible for communicating feedback regarding the fire contingency plans experienced by the supervisors. The supervisors have direct knowledge regarding the status of the

work environment as they are in the workspace daily. They, also, have an opinion about the status of the implementations (i.e., what works, what does not work) and about which implementations could possibly improve these contingency plans.

- **Safety representative**
  There are two safety representatives included within the AMO. One representative for the office and one representative for the production facility. These persons act as work environment representatives, and they represent the employees within the AMO. These representatives, therefore, receive feedback regarding issues experienced by the employees. They, additionally, have an opinion regarding how the employees will react to certain implementations regarding the fire contingency plans. Finally, as safety representatives these persons receive a yearly course in first aid and fire-fighting techniques. They can, therefore, provide relevant input regarding the positioning and usefulness of fire safety equipment.
- **Moderator**
  The moderator leads the discussion and makes sure that the meetings proceed as planned. The moderator is an employee from within the QA department. This person must stay neutral during the meetings. It is, however, possible that this person is influenced by different factors. These factors are the managing director being a member of the AMO and the QA department being responsible for adapting and preparing the fire contingency plans. Since all employees in the office work within the same space and they all know each other, it is assumed that personal interests and influences will impact the judgement of the moderator.

The members of the first response team and the evacuation team are appointed by the AMO. The members of the first response team are all employees with a first aid certificate and/or a fire education. This team is tasked with initiating response actions during the occurrence of a fire emergency. This first response could include providing first aid to injured employees or attempting to stop/minimize the spread of the fire through fire-fighting techniques. The members of the evacuation team do not necessarily have a first aid certificate and/or a fire education. This team's responsibility is, therefore, organizing and facilitating a safe evacuation of all employees from the building to the evacuation assembly point. There are 5 main persons that are appointed to this evacuation team, they are the supervisors responsible for hall 1, hall 2, logistics and the bellow department, and the work environment representative for the office. Each person is responsible for organizing the employees within their department at the assembly point and for notifying the person responsible at this assembly point of any missing persons. The AMO also appoints a back-up person in case the responsible person is not available or present. Furthermore, in cases where both the responsible person and his back-up are not available, the members of the AMO will act as the evacuation team.

The employees of the company are informed by the AMO regarding the safety instructions and emergency plans. The company's procedures assume that all employees can perform first aid, firefighting, and evacuation actions, even though they are not a part of the first response or the evacuation team.

Both employees that are appointed to teams and employees that are not, are stated to provide feedback to their representatives within the AMO regarding the safety instructions, emergency floor plans and the fire safety equipment. All employees do, however, perform their daily tasks within the company. These daily tasks must be performed within the delivery and production deadlines set by both the client and the production planner. A combination of these daily tasks and the lack of incentives such as feedback deadlines, leads to decreased participation and feedback from the employees. Additionally, since no fire event was ever registered and the last fire evacuation exercise was performed in 2018, it could be assumed that employees are not attentive to or aware of issues with safety instructions, emergency floor plans and fire safety equipment. Finally, since all employees know each other due to the size of the company it could be a possibility that personal preferences and disagreements impact the participation of certain employees.

The external auditors include all companies and persons that visit the company to either perform inspections and service on the fire safety equipment or to investigate the adherence with the relevant regulations and standards. These auditors work within the legal framework provided by the relevant Danish regulations and the relevant ISO standards. The Danish regulations are enforced by the Danish workforce agency. For the inspection of fire safety equipment, these regulations mention that the suppliers' maintenance manual must be complied with. The suppliers can, therefore, affect the external auditors through the inspection requirements that are written within this manual. Additionally, for inspections that do not require an external audit, the AMO is responsible for adhering with the inspection requirements during the internal maintenance procedures. The inclusion of inspection requirements and regulations can provide legal security for the supplier of fire safety equipment in case of failure during a fire event. This does, however, mean that the company must assure that maintenance plans for internal and external audits comply with both the suppliers' inspection requirements and the relevant regulations.

The board of directors was mentioned previously within this section of the document. This board has several meetings yearly to discuss the company strategy, goals, and opportunities for the future. Since the managing director is part of this board, the points discussed during these meetings will influence their decision-making processes. This influence will mainly be observed through compliance with company strategies and goals to keep the board satisfied.

The fire brigade is informed regarding their role and responsibilities within the safety instructions by the AMO. The fire brigade, therefore, provides feedback regarding the fire safety of the building and its equipment through the performance of a fire inspection. This fire inspection is performed every 2 years in accordance with the emergency preparedness act (Danish Emergency Management Agency, 2016). This act also describes that the municipalities are responsible for the local fire prevention and fire mitigation. The municipalities, therefore, set the desired goals and provide a budget for the fire brigade. Finally, the act provides the legal framework for the participation of the fire brigade before and after the occurrence of a fire event

The training centre includes all services that are hired through the AMO to train its employees in first aid and/or firefighting. The centre is responsible for providing the relevant information to employees in first response team so they can fulfil their role within the safety instructions. The training centre is paid by the company and will, therefore, aim to satisfy the goal set by the AMO.

3.2.2. Stakeholders relevant during the fire event

The stakeholders that are relevant during a fire event in the company are described in the safety instructions (11. Appendix, section 11.1.1.). Since these instructions make a division between a fire event in the production facility and a fire event in the office, two different diagrams were made to illustrate the stakeholders for both events separately. These diagrams can be found in the appendix (11. Appendix, section 11.1.3.2.).

The employee that notices the fire must call for emergency assistance using the information described in the safety instructions. This person should also inform the work environment representative of the fire event and their immediate supervisor. The immediate supervisor is only contacted if the fire starts in the production facility, since this supervisor is also part of the evacuation team. Additionally, the employee that notices the fire must warn all nearby guests and employees that a fire event is happening and that they must evacuate the building. If the fire starts in the office, this person should send an email to all employees in both the production facility and the office informing them to evacuate the building. Finally, this employee should try to extinguish the fire if possible or limit the spread of the fire by closing windows and doors.

As described above, the employee that notices the fire needs to perform several tasks to facilitate the evacuation of the building. These tasks rely on the information and instructions that are provided by the AMO before the occurrence of the fire event. More information regarding these instructions and the involvement of the AMO can be found in section 3.2.1. Additionally, only employees involved in the first response team are instructed in firefighting techniques. This means that the employee that notices the fire relies on their previous experience or personal knowledge regarding firefighting techniques if they are not part of this team.

The employees and guests present within the building are warned of the fire event by the employee that notices the fire or by the evacuation team. They are required to evacuate the building using their knowledge of the building layout, and the present emergency signs and floor plans. Most of the employees are assumed to have the needed knowledge about the building and its layout to be able to escape the building with minimal help. Additionally, all employees are informed of safety instructions and emergency floor plans by the AMO before the occurrence of the fire event. Guests are, however, assumed to have little to no knowledge regarding the building layout. They are, therefore, reliant on the information provided by the emergency signs and floor plans. Additionally, guests will require guidance from the evacuation team to find an evacuation path to escape the building since evacuation paths are not indicated on the floor plans.

As mentioned previously, the evacuation team's role during a fire event is the guidance of evacuation actions. The members of this team must warn employees and guests that did not get notified by the person that noticed the fire. Additionally, they are tasked with helping the employees and guests find the evacuation paths and emergency exits. The members of the evacuation team are informed of their specific roles and responsibilities during a fire event by the AMO. They should, therefore, have extensive knowledge regarding the evacuation procedures. More information regarding this can be found in section 3.2.1.

The first response team is tasked with initiating firefighting actions and providing first aid to injured employees and guests. The members of the first response team are also informed of their roles and responsibilities by the AMO. They do, however, receive a yearly first aid course unlike the members of the evacuation team. Within the company, there is only one person that has a fire education certificate. This person has their office in the production facility, and they are therefore only assumed to help with firefighting if the fire starts near their office. As mentioned previously, all other employees must rely on previous experience or personal knowledge for the performance of firefighting actions.

At the assembly point, the production manager is responsible for organizing all employees and guests, and for gathering information regarding the fire event and possible missing persons. If this person is not available, the work environment representative from the office takes over. The organization of the employees at the assembly point is facilitated by the evacuation team. The members of this team must each organize their own department, so the work environment representative has a clear overview of all people that are present. To establish any missing persons, the work environment representative uses the lists provided by the supervisors and the person responsible for the reception. These lists should include information regarding guests that are present and employees that did not come to work that specific day. The work environment representative is the main contact person for relaying the gathered information to the rescue crew. Since this person is part of the AMO, it could be assumed that they have detailed knowledge regarding the safety instructions and their responsibilities during the fire event.

The rescue crew is sent by the emergency assistance service based on the information that was provided by the employee that noticed the fire. Additionally, the fire brigade is informed of the company's layout and their role within the safety instructions through the AMO as described in section 3.2.2. Based on this information, the rescue crew's composition is decided on. This composition can include health care personnel and the police in addition to the fire brigade.

3.2.3. Conclusion and recommendations: communication structure for stakeholder mapping

The communication structure is based on the designed stakeholder maps (11. Appendix, section 11.1.3.). This structure is different before/after the occurrence of the event, and during the fire event due to the involvement of different stakeholders.

3.2.3.1. Communication structure before/after the fire event

The communication structure before the fire event is heavily dependent on the AMO. The AMO is responsible for providing information and instructions to all employees, also employees with responsibilities during the fire event. They must, therefore, ensure that all necessary information is provided and updated regularly. Additionally, the AMO must give a clear and understandable explanation of each employee's tasks and responsibilities especially if this employee is a member of the first response or evacuation team. All information provided to the employees must be clear and detailed. Examples of the information that must be provided is what should be relayed to the emergency assistance when making an alarm call and the necessity of having a cell phone or telephone available. Additionally, all supervisors and the person responsible for the reception should be clearly informed that they need to have a list of absentees and guests for detailed identification of missing persons. Since no course in rudimentary firefighting techniques is included by the AMO, they must consider this when providing information. All employees must, furthermore, be reminded and updated yearly about the provided information and instructions. The AMO must ensure that changes are communicated with all employees especially in case of changes to responsibilities and roles.

The AMO is also tasked with providing a maintenance schedule for all fire equipment. This maintenance schedule should be updated regularly and the person that is responsible for documenting this maintenance should be informed. This information should be detailed in regards of what type of maintenance is expected and the time intervals between the maintenance. Furthermore, the relayed information must provide the responsible person with details about who should perform the maintenance, i.e., can the maintenance be performed through an internal investigation or should an external specialized company be contacted.

Additionally, the AMO is responsible for the communication with the fire brigade. This communication includes providing information regarding the role of the fire brigade during a fire event. This information should include the building structure, building elements and the activities that are performed within the production building. This information will aid the fire brigade in determining their approach to minimizing the consequences of a fire event. Additionally, the fire brigade performs a fire inspection every two years. This inspection will provide additional information regarding the building and its activities. This additional information can include the storage places of trash and flammable material and changes to the building layout. Communication with the fire brigade should, therefore, ideally include floor plans showing the placement of flammable material (ATEX zones) and the positions of fire safety equipment.

Finally, if a fire event occurs all communication afterwards should focus on providing information regarding the event. This includes feedback from the stakeholders relevant during the fire event (11. Appendix, section 11.1.3.2.). Since this feedback is relevant for determining the weak points within the fire safety equipment and the fire management systems, the communication must be clear, detailed, and truthful. This communication will provide valuable information about what happened during the different phases of the evacuation process in different parts of the building. All feedback is received by the members of the AMO. This organization must, therefore, stay impartial and provide a secure environment in which the stakeholders can come forward with their (unfiltered) experiences. If there is any media coverage after the occurrence of a fire event, all communication with them is done by the managing director. This communication must be general to protect both the company, its image, and the personal information of any affected employees.

3.2.3.2. Communication structure during the fire event

During the occurrence of a fire event, employees rely on their knowledge regarding the safety instructions, emergency floor plans and their responsibilities. As mentioned previously, this knowledge is obtained through communication provided by the AMO during the preparatory phase. Members of the first response/evacuation team must be attentive to the situation and be able to react accordingly. If a fire breaks out, they must start with first aid or evacuation actions. Even though all employees are assumed to be able to aid in evacuation actions, it is assumed that members of these teams are instructed in what information to provide. They are, therefore, assumed to be the primary provider of communication for both guests and employees. All communication during the event must, therefore, be clear and concise. The relayed information should focus on the position of the fire, the closest emergency exit, and the placement of the evacuation assembly point. This focus is especially important for the safe evacuation of guests as they are assumed to rely on information and instructions provided by the employees.

Since the emergency services are contacted by an employee, all necessary information described in the safety instructions must be provided. It is, furthermore, important that this employee stays calm and provides only what is described in these instructions. This will help the emergency services gain an overview of the situation as quickly as possible. Based on this information the composition of the rescue crew is chosen. Furthermore, detailed information regarding the current situation, what happened and possible missing/injured persons is provided by the work environment representative upon arrival of the rescue crew. This communication must focus on providing only the information that is relevant to either rescue attempts or fire extinguishing actions. Since the work environment representative is responsible for both communication with the rescue crew and organization of the employees, this person must stay calm and perform well in stressful situations.

The person that noticed the fire is also responsible for informing their immediate supervisor and the work environment representative. Since they have an assigned role and responsibilities during the evacuation, this information should be similar to what is provided to the emergency services. This internal communication can, however, include more detailed information regarding who exactly is missing, the situation at the time of the fire outbreak and possible fire extinguishing attempts.

4. Literature study

4.1. Generation of fire evacuation scenarios

4.1.1. Methodology: event tree analysis

The discussion of the various human errors that can affect a fire evacuation within the investigated company is based on different fire scenarios. These fire scenarios are defined to illustrate how failures within different components of the fire contingency plans can affect the evacuation time. These components include all systems or installations that are in place for the minimization of the fire risk.

Based on research performed by (Kong, Lu, & Ping, 2017) and (Albrecht C., 2014), an event tree approach was chosen to determine the different fire scenarios. This approach enables that author to include the different types of fire safety equipment and safety management systems. Additionally, this approach includes the possibility of assigning a failure or success condition to each component separately. The probabilities needed for the branches of the event tree will mainly be extracted from inspection reports and procedural descriptions. An example of an event tree for the generation of a fire scenario can be found in Figure 10.

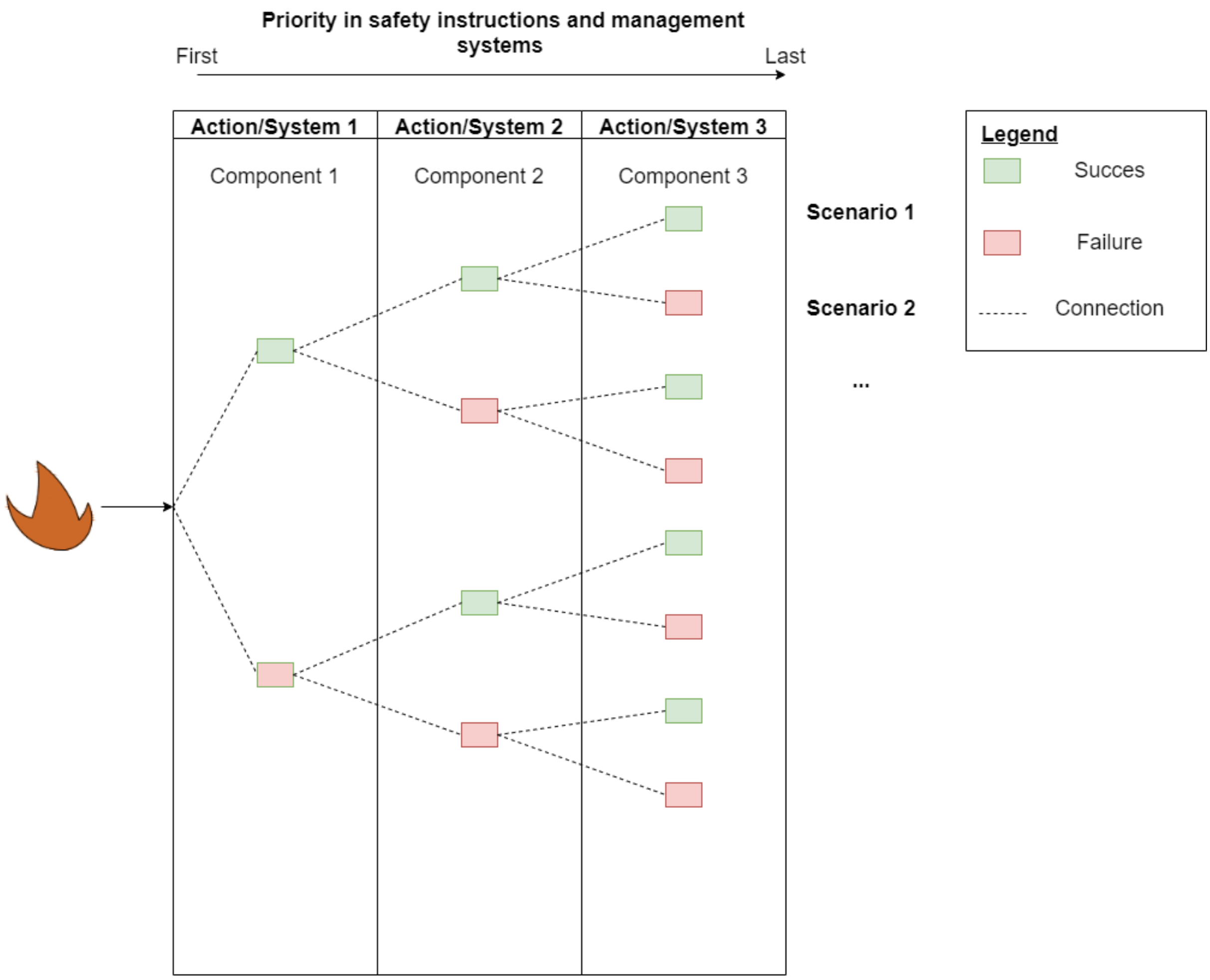


Figure 10: Illustration of the event tree approach

The event tree analysis will only include failure due to human error. This includes failure due to incorrect installation, lacking maintenance and inspection. The effectiveness and failure probability of the equipment in perfect circumstances are excluded for the discussion of this case-study.

4.1.2. Effect of obstructed emergency paths and doors

The main objective of emergency plans is the reduction of the time that occupants use to reach the exit of a building during emergencies (Shariff, Yong, Salleh, & Siow, 2019). This reduced time will give the occupants a bigger chance of survival. Since obstructed emergency routes increase the time occupants need to reach the exit, they will have a higher risk to get injured or to be unable to escape the building. (Shariff, Yong, Salleh, & Siow, 2019) performed a simulation with four different scenarios where each scenario had either no, one, two or three blocked exits. This simulation was based on a fire event where a high fire risk was registered due to blocked pathways. These blocked pathways were caused by items left along the egress route by the occupants of the building (Woo & Hwang, 2014). The research showed that the number of blocked exits linearly influences the mean evacuation time. A higher number of blocked exits will cause a slower mean evacuation time, whereas a lower number of blocked exits will lead to a faster mean evacuation time. Additionally, the effect of blocked exits is noticed most during peak times when the biggest occupational load is registered. In these scenarios, even a scenario with no blocked exit is shown to carry the risk of creating a situation that could majorly harm the evacuating occupants.

4.1.3. Effect of safety management systems and fire safety equipment

Both safety management systems and the use of fire safety equipment affect the propagation of a fire event. An investigation of a fire incident with lacking functional fire systems and fire safety equipment was done by (Shakib, Pirizadeh, Dardaei, & Zakersalehi, 2018). They identified that the rapid fire spread in the building was caused by the impeded operational state of the building and the non-compliance of the building with the relevant guidelines and building codes. Both factors are described to be a consequence of non-standard maintenance, and lacking inspections and checks of the building and its installations. The above-mentioned issues affected the condition of the electrical installations in the building. The electrical installations revealed substandard wiring, a lack of inspections and checks, and changes caused by repairs, displacements, and manipulation by unqualified workers. The building, therefore, lacked an automatic fire detection and suppression system. This system could have aided in minimizing the spread of the fire. Additionally, defect fire extinguishers meant that attempts to manually contain the fire spread could not be made. The findings from this investigation are also backed up by (Woo & Hwang, 2014).

Finally, the state of the building and its non-compliance with regulations also affected the evacuation process. (Shakib, Pirizadeh, Dardaei, & Zakersalehi, 2018) determined that the execution of the evacuation process was hindered by lacking emergency evacuation maps, evacuation instructions and coordinating protocols. Additionally, a lack of public awareness regarding fire events meant that the occupants did not realize the importance of timely evacuation during an actual fire event. This lack of public awareness can lead to occupants piling up combustibles and propping open smoke doors (Woo & Hwang, 2014), (Albrecht C., 2014).

4.2. Agent modelling

4.2.1. Methodology: multi-layered modelling approach

The input in the model is discussed based on a multi-layered modelling approach. The different layers included within this approach are shown in Figure 11.

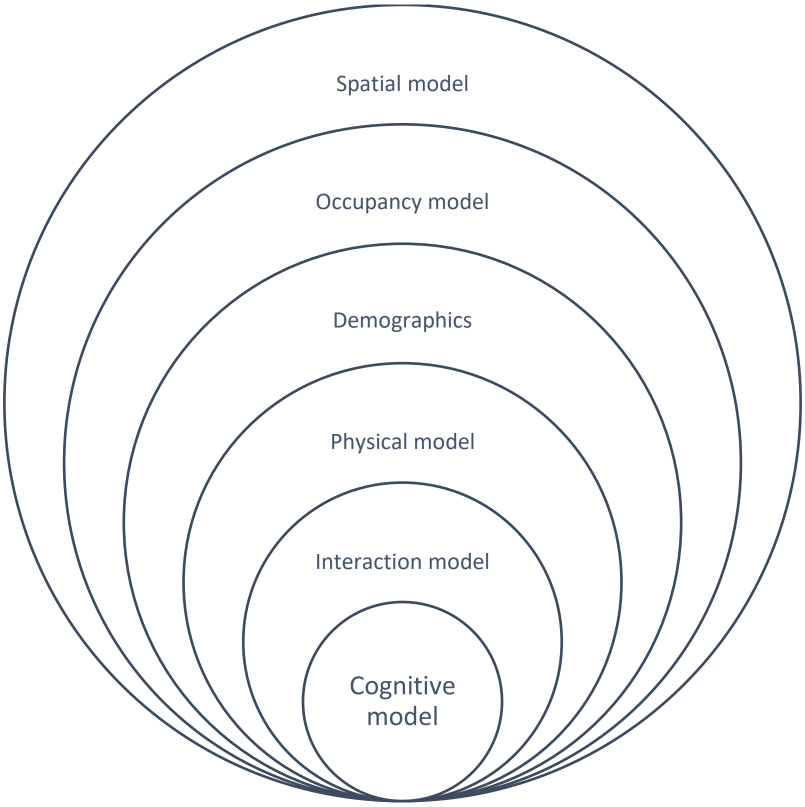


Figure 11: Multi-layered modelling approach (based on (Rangel-Ramirez, Faber, & Nielsen, 2021 forthcoming))

4.2.1.1. Spatial model

The spatial model defines the space for which the evacuation and fire simulation are performed. This part of the model describes the layout and the inventory of the building. This description includes the orientation of doors, gates, windows and building inventory.

4.2.1.2. Occupancy model and demographics

The demographics describe the occupants within the modelled space. This description divides the occupants in groups based on their age and gender. Based on these groups the occupancy model is developed. This model allocates the various groups to the different departments in the company based on the distribution of employees within them.

4.2.1.3. Physical model

The physical model describes the speed, shape, and height parameters for the occupancy model developed in the previous part of the model (section 4.2.1.2).

4.2.1.4. Interaction model

The interaction model describes the occupant's interactions within the spatial boundaries defined in the spatial model (section 4.2.1.1). This model, therefore, focuses on the actions described in the safety instructions and the interactions of the occupants with the spatial components. This includes their movement along the evacuation paths and their usage of the staircases. Additionally, this model also describes the fire-fighting actions.

4.2.1.5. Cognitive model

The cognitive model introduces the effect of decision-making on the behaviour of the occupants. This model, therefore, describes the selection of evacuation paths, emergency doors and the pre-movements times experienced by the occupants, dependent on the constraints provided by the spatial and the occupancy model.

4.2.2. Effect of human behaviour on the interaction and cognitive model

The interaction and the cognitive model included within the multi-layered modelling approach (section 4.2.1.4 and 4.2.1.5) describe how occupants behave and move in fire emergency simulations. This part of the simulation is, therefore, determined by interactions with the shared environment and with other occupants i.e., human behaviour. The human behaviour exhibited during fire events is determined by the perceived risk of the agent (Lovreglio, Ronchi, & Nilsson, 2016). This perceived risk can be defined as "*the interpretation of sensations generated by the experience and the expectations of the individual.*" (Bernardes, Rebelo, Vilar, Noriega, & Borges, 2015). Since perceived risk is an associative and emotional process, human behavioural responses can vary from protective (evacuation behaviour) to non-protective (ignoring behaviour). Situations with a high perceived risk can cause agents to experience responses such as panic and stress (Bernardes, Rebelo, Vilar, Noriega, & Borges, 2015).

There are 3 main components that affect the risk perceived by an agent: personal characteristics, social cues, and environmental cues. The influence of perceived risk on human behaviour is illustrated in Figure 12.

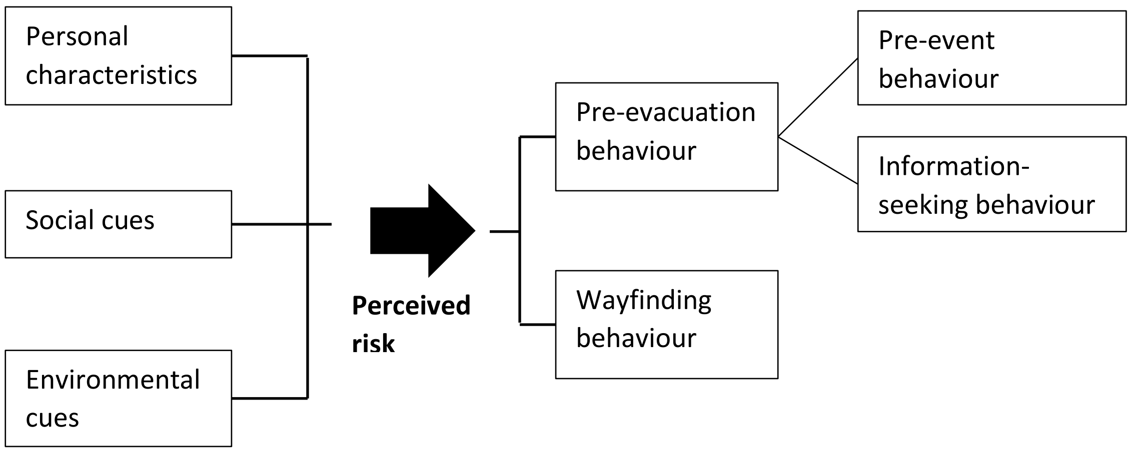


Figure 12: Human behaviours (based on (Lin, Zhu, Li, & Becerik-Gerber, 2020) and (Lovreglio, Ronchi, & Nilsson, 2016))

Investigations in emergency behaviour show that both familiarity with the environment and the other occupants influence how agents behave (Hu, Wang, & Wang, 2018). It is, therefore, important to consider the distribution of the occupants, their familiarity with the available routes and their activities at the time of the emergency (Gwynne & Boswell, 2010). These elements are included within the personal characteristics for the determination of the perceived risk experienced by the agent. Furthermore, past experiences with either fire events or evacuation exercises can affect the knowledge of the agents regarding escape routes, emergency plans, reactions to safety management systems and the use of fire safety equipment (Bernardes, Rebelo, Vilar, Noriega, & Borges, 2015). According to (Bernardes, Rebelo, Vilar, Noriega, & Borges, 2015), agents with previous knowledge of the available escape routes are more likely to have a low perceived risk. Additionally, the personal characteristics also include considerations towards the behavioural uncertainty. This uncertainty is caused by the impossibility to fully understand how one specific agent will behave in an emergency. There are 2 different sources of uncertainty, i.e., Intrinsic Behavioural Uncertainty (IBU), and Perceptions and Preferences Behavioural Uncertainty (PPBU) (Lovreglio, Ronchi, & Nilsson, 2016). IBU accounts for the difference in initial behavioural states depending on the agent or depending on the situation that the agent experiences. Additionally, PPBU considers that different agents have varying perceptions and preferences. Agents will, therefore, make different estimates and allocations of importance of the same factor.

Social cues received by the agent are dependent on the social influence that is present during the emergency. This social influence can be divided in informational social influence and normative social influence (Lovreglio, Ronchi, & Nilsson, 2016). Informational social influence is defined as the information that is received from other agents, whereas normative social influence describes the desire of the agent to conform to the expectation of other people. Both components of social influence are affected by the role of the agent within the organization during day-to-day business (role rule theory) and the relationship between the different agents (affiliative theory) (Lovreglio, Ronchi, & Nilsson, 2016). Affiliative theory states that agents belonging to the same personal group could have a bigger impact on the perceived risk.

Finally, environmental cues are different depending on the environment surrounding the agent i.e., different rooms might present different cues. There are 2 types of environmental cues: constant and non-constant intensity cues (Lovreglio, Ronchi, & Nilsson, 2016). Constant intensity cues are cues that do not change depending on the time and the position of the agent, examples of such a cue are a fire alarm or emergency signage (Lovreglio, Ronchi, & Nilsson, 2015) . Non-constant intensity cues do, however, change depending on the time and the position of the agent. Examples of non-constant intensity cues are the presence of smoke and smell or the visual feedback of the fire itself.

4.2.2.1. Pre-evacuation behaviour

Pre-evacuation behaviour is the behaviour that is shown by the occupants before the decision to evacuate or to perform evacuating actions is made. This behaviour can, therefore, be defined as the reaction time of the occupants to the fire event. The reaction time of occupants includes both pre-event behaviour and information-seeking behaviour (Lin, Zhu, Li, & Becerik-Gerber, 2020). Pre-event behaviour is defined as the normal state of the occupants (Lovreglio, Ronchi, & Nilsson, 2015). In this state the occupant continues performing their pre-emergency actions as they do not realize that a fire event is happening. Afterwards, when the occupant realizes that a fire event is happening, they show information-seeking behaviour. During information-seeking behaviour occupants are in an investigating state where they perceive both environmental cues and instructions/behavioural cues from other occupants (social cues) (Lovreglio, Ronchi, & Nilsson, 2016). The information-seeking behaviour is, therefore, influenced by the perceived risk, the complexity of the task itself and the time pressure (Lin, Zhu, Li, & Becerik-Gerber, 2020).

4.2.2.2. Way-finding behaviour

Whenever agents make the decision to evacuate or to perform evacuating actions during an emergency, they start exhibiting way-finding behaviour. Some examples of evacuating actions are actions that are described in the emergency plan such as calling a certain number, performing first aid, and attempting to extinguish the fire. The decision-making process is influenced by the perceived risk of the agents. This perceived risk is, as stated previously, dependent on personal characteristics, social cues, and environmental cues (Lin, Zhu, Li, & Becerik-Gerber, 2020), (Lovreglio, Ronchi, & Nilsson, 2016).

Some examples of personal characteristics are visual impairment of the agent, familiarity with the building, and the agent's care for and attachment to their personal belongings (Lin, Zhu, Li, & Becerik-Gerber, 2020). When an agent is familiar with their environment, it is observed that they prefer to follow familiar routes. This can lead to longer travel distances and a possible increased exposure to risks such as injuries obtained due to fire or smoke exposure (Lin, Zhu, Li, & Becerik-Gerber, 2020). Additionally, the high time pressure and high stress experienced by the agent due to the fire event can affect the decision-making process both positively (higher efficiency) and negatively (higher error rate). The combination of high time pressure and high stress can cause agents to experience attentional narrowing, where agents make irrational or random decisions based on momentary stand-out characteristics of certain choice alternatives (Meng & Zhang, 2014).

Additionally, some examples of environmental cues are the perception of the spatial characteristics, and the assessment of the distance and the direction of the path leading to the agent's desired destination. These environmental cues can be affected by fire safety equipment such as emergency signage and lighting. The role of emergency signage during an emergency is decreasing the evacuation time of agents by providing orientation guidance (Fu, Cao, Song, & Fang, 2019). Emergency signage, therefore, affects the walking speed of the agents. The interaction with this signage is, however, dependent on each individual agent. It is investigated that there are four different processes this agent must follow: the visibility of the sign, the registration of the sign by the agent, the understanding of the sign and the usage of the information provided by the sign (Fu, Cao, Song, & Fang, 2019). These processes are, therefore, affected by the visibility due to smoke and illumination, and the ability to influence the agent based on the design and placement of the sign. This placement includes the surrounding environment around the sign, cluttered areas can lead agents to dismiss the information provided by the emergency sign (Ribeiro, et al., 2012).

Finally, social cues can be presented by the presence of leaders or the herding phenomenon. The herding phenomenon occurs when agents imitate the wayfinding behaviour of others (Lin, Zhu, Li, & Becerik-Gerber, 2020). During experiments it was registered that in evacuation scenarios agents adhere to spontaneous leader and follower roles (Ribeiro, et al., 2012). This proves that there is a certain amount of social influence that can impact the wayfinding process. During experiments it is shown that both verbal and non-verbal communication of other agents influence this process (Ribeiro, et al., 2012). Because of social influence, the appointment of a person in charge is extremely important. This person must make fast decisions based on the emergency scenario and the potential evacuation strategies (Mirahadi & McCabe, 2021). It is, therefore, necessary that this person is familiar with the building and its occupants. Additionally, the person in charge must have the ability to stay alert and the improvise solutions whenever unexpected situations occur.

The decision-making process during wayfinding can lead to interaction behaviour with both the environment and other agents. When agents exhibit these behaviours, they actively perform a certain action. Some examples of interaction behaviour with the environment are risk-taking, property-protecting and hazard-fighting behaviour (Lin, Zhu, Li, & Becerik-Gerber, 2020). Additionally, some examples of interaction behaviour with other agents are grouping, competing, helping, queuing, and waiting behaviour (Lin, Zhu, Li, & Becerik-Gerber, 2020). All the previous behaviours can have a significant impact on the response process of the agents and the outcome for each individual emergency (Lin, Zhu, Li, & Becerik-Gerber, 2020). Interaction behaviours such as grouping, and queuing can affect the efficiency of the evacuation as they might lead to an unbalanced use of the available exits. Queuing can, furthermore, affect the walking speed of the agents as their velocity will decrease when the near the formed queue and when they try to locate another available route/exit. Additionally, competing behaviour will generally have a negative impact on the evacuation as it can lead to agents getting injured (Fang, Song, Zhang, & Wu, 2010).

4.2.2.3. The impact of familiarity (fire evacuation exercises)

The impact of familiarity on the evacuation process can be shown through fire evacuation exercises. Fire evacuation exercises are generally conducted regularly within an organization to train the agents how to act correctly and how to avoid any possible hazards (Marzouk & Mohamed, 2018). Evacuation exercises are usually completed to fulfil two different objectives. These objectives are the improvement of the agent's performance during evacuations and the assessment of the effectiveness of the safety instructions and emergency floor plans (Gwynne, et al., 2020). This incorporation of 2 different objectives does, however, have an impact on the assessment of the outcome of the evacuation exercise. The impact of the exercise on the population can be investigated through debriefing sessions, whereas the assessment of the emergency procedure and plans can be done through gathering data. This gathering of data is accomplished through the usage of monitoring equipment such as cameras and sensors. Including both assessment methods mentioned previously will have a negative effect on the outcome of the exercise since its organization will be difficult to manage and the overall exercise will be disruptive to the work environment within the company (Radianti, et al., 2015). Additionally, the assessment will require significant effort and resources (Gwynne, et al., 2020).

There are two main types of evacuation exercises that are currently used. These types are traditional evacuation drills and teaching-based approaches such as workshops and videos (Gwynne, et al., 2020). There are some shortcomings that are registered with both types of evacuation exercises. These shortcomings are the exclusion of sub-populations, the 'cry-wolf' effect and overall organizational inconsistency. The exclusion of sub-populations means that certain types of evacuation techniques such as assisted evacuation are not performed. The 'cry-wolf' effect, furthermore, might undermine the compliance of the agents with the alarm system. In this situation, some agents might start seeing the fire alarm as an afterthought where the alarm going off just indicates another exercise or a false alarm (Bernardes, Rebelo, Vilar, Noriega, & Borges, 2015). Finally, the overall organizational inconsistency causes the fulfilment of the exercises to be different across different organizations, building types and jurisdictions (Gwynne, et al., 2020). The shortcomings that are registered for each individual type are inserted in Table 6.

Traditional evacuation drill	Teaching-based approach
Safety challenges (e.g., crushing)	No requirement of engagement
Physical/emotional consequences (discomfort, impacted health, loss of interest)	Solitary completion
Loss of functionality (downtime, extra costs, reputational damage)	No physical evacuation experience
Difficulties keeping the exercise unexpected	

Table 6: Shortcomings individual types (based on (Gwynne, et al., 2020))

The most used type of evacuation exercise is the traditional evacuation drill (Gwynne, et al., 2020). This type is preferred since it creates the opportunity to observe the behaviour of the agents. Additionally, the drill also has the possibility of creating uncertainty and randomness within the behaviour of the agents. It is, however, difficult to establish reliable data as the drill is only an 'one-off' event. Additionally, the gathered data focuses on the total evacuation time and the fulfilment of success criteria. This does exclude detailed information about the behaviour of the occupants during the evacuation procedure. This exclusion also means that the adherence of the agents with the different steps described within the evacuation procedure cannot be assessed. Some steps within the evacuation procedure such as how to use a fire extinguisher are usually excluded from evacuation drills since no actual fire is present. These steps are, therefore, taught using teaching-based approaches such as videos. Research on the retention of information regarding the use of a fire extinguisher indicated that about 40% of the public knows how the correctly use a fire extinguisher (Lovreglio, Duan, Rahouti, Phipps, & Nilsson, 2021). Further research based on this statement investigated the retention of this information based on an experiment. The outcome of this experiment can be seen in Figure 13.

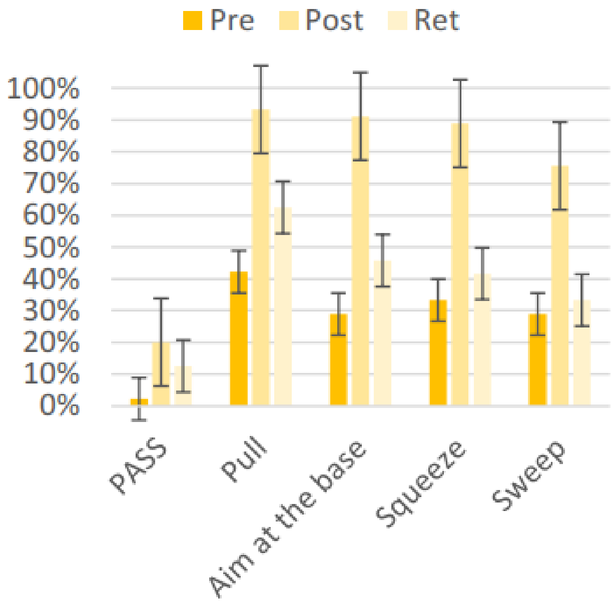


Figure 13: Knowledge (pre, post and retention) of participants (Lovreglio, Duan, Rahouti, Phipps, & Nilsson, 2021)

5. Representation of relevant fire evacuation scenarios

This part of the thesis describes the basis that is necessary for the development of the fire and evacuation simulation. Firstly, the hazardous condition is described. This condition is the cause for the fire evacuation and the start of the events described in the different fire scenarios. These fire scenarios are determined based on an event tree analysis where the different components of the safety instructions and management systems are prioritised. These different components are assumed to be dependent on human errors such as lacking emergency signalization, lacking knowledge regarding fire extinguishing actions and outdated safety instructions and floor plans. Finally, the agent-modelling is described. This modelling describes the actions performed by the employees within the constraints of provided by the system and its stakeholders (section 3).

5.1. Fire event (hazardous condition)

The last fire inspection report (April 2018) described a hazardous condition where pressurized gas containers were placed near flammable material in a shed outside the production facility. Additionally, the last monthly inspection round regarding organization and cleanliness of the workspace in the production facility was performed in March 2021. It is, therefore, assumed that a general lack of organization and cleanliness in this workspace will cause similar hazardous conditions in various parts of the production facility.

The hazardous condition describing the origins of the fire for the fire simulation is, therefore, based on the condition in the production facility at the time of visitation (19/11/2021). During this visitation, a transport pallet with a wooden crate was placed on the evacuation path near a welding cabin. This placement and the picture of the pallet itself can be found on Figure 14. Due to this placement, it is assumed that the sparks created by welding activities landed on the transport pallet and ignited the fire. This assumption is made since welding is one of the leading causes of fires in industrial buildings. In 2004, 17 % of all industrial fires in Denmark were caused by welding actions (Beredskabsstyrelsen, 2004). Additionally, the National Fire Protection Agency (NPFA) registered that 33% of structural fires in industrial buildings was caused by welding activities between 2014 and 2018 (Ahrens, 2021).

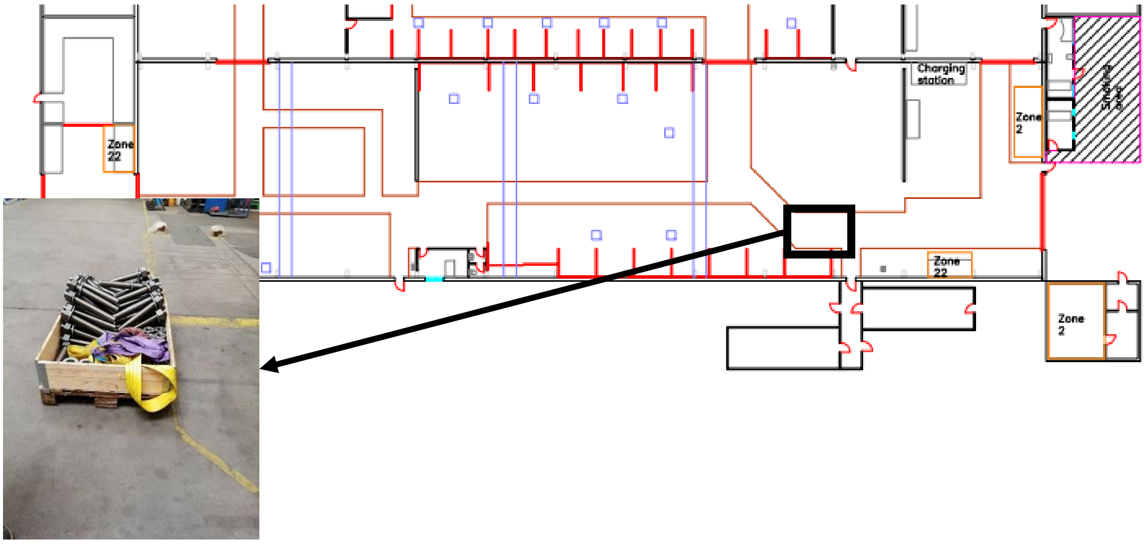


Figure 14: Extract from drawing 2.01, 12. Drawing folder, p. 4 (author's model)

The heat release rate (HRR) of the pallet is based on an experiment of 2 stacked pallets described in (McGrattan, 2020). The HRR curve is inserted in Figure 15.

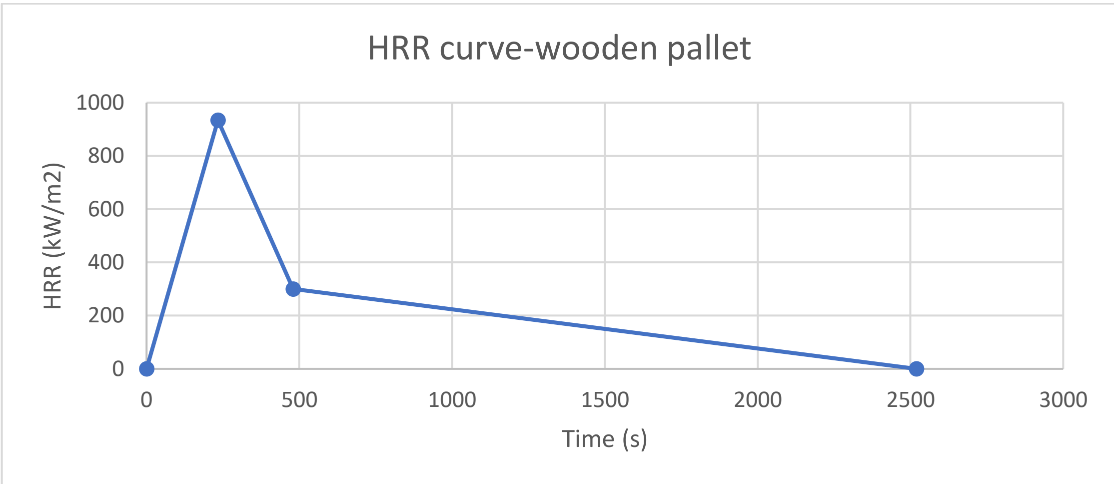


Figure 15: HRR curve based on (McGrattan, 2020) (author's model)

Additionally, the pallet is assumed to be a standard Euro pallet with a height of 144 mm, a width of 1200 mm, and a length of 800 mm (iContainers, 2020). The HRR per m^2 was, therefore, calculated to be equal to 972,9 kW/m^2. Furthermore, the experiment also indicated the yield of both CO and soot. These values can be found in Table 7.

CO Yield	**Soot Yield**
0,038	0,0035

Table 7: CO and soot yield based on (McGrattan, 2020)

5.2. Fire evacuation scenario (event tree analysis)

5.2.1. Definition of fire scenarios

The approach to define the different fire scenarios is described in the methodology (section 4.1). Since this report aims to determine the impact of human errors on the individual components of the evacuation process, only scenarios where one or no component fails are considered. The different components are divided according to the action or system within the instructions or evacuation process that they are relevant for. The progression of these actions and systems from the start of the fire until the people escape from the building is determined based on the safety instructions and emergency plans provided by the company (11. Appendix, section 11.1.1 and 12. Drawing folder, p. 6-7). The various components and their relevance during the progression of a fire event are illustrated in Figure 16.

Figure 16: Safety instructions and evacuation process for event tree analysis (author's model)

As described in the safety instructions, fire extinguishing actions are started after the occurrence of a fire event is noticed by an employee. These actions include all attempts made by the employees to extinguish the fire using a fire extinguisher or a hose reel. Since both the fire extinguisher and the hose reel are used for the same purpose, they are described within the component 'fire extinguisher' (Figure 16). After the fire extinguishing actions are performed, the person that noticed the fire is supposed to perform alarming actions. These actions provide the signal for other employees to start the evacuation process. The company does not have an automatic or button-activated alarm system in the production facility. This alarm is, therefore, initiated by the employee warning each department individually. The safety of employees during the evacuation process is, furthermore, dependent on the impact and the consequences of the fire itself. To minimize both the impact and the consequences, fire management systems are incorporated within the emergency plans and the safety instructions. The fire management systems within the production facility include actions that are described in the safety instructions such as closing all doors and windows, and systems to manage the spread of the fire. The systems that are incorporated within the building structure and organization to minimize the fire spread are the fire control system (fire doors and gates) and the storage organization system (ATEX zones and waste storage-risk minimization system). Finally, the evacuation process is facilitated using evacuation escape systems. These systems are incorporated within the building design, the safety instructions, and the emergency plans. The safety instructions provide guidance and first aid responsibilities for the evacuation and first response teams respectively. Additionally, evacuation paths and emergency doors are incorporated within the building design to provide unobstructed escape opportunities. The indication of emergency doors is done through emergency signs that are placed in accordance with the emergency floor plans.

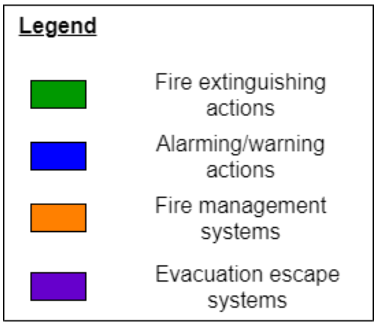


Figure 17: Legend for Figure 16

The completed event tree analysis based on the above described and illustrated progression (Figure 16) can be found in appendix (11. Appendix, section 11.3.1.). This analysis indicates ten different scenarios that are relevant for the simulation of the fire event. These scenarios are shown in Table 8, each scenario includes the possible component (Figure 16) that fails. Scenario 1 defines the base case scenario where no component fails. Additionally, a description of each scenario with a failing component can be found in the following sections (section 5.2.2.1-5.2.2.9).

Scenario	**Failing component**
1	None
2	Emergency signs
3	Emergency doors
4	Evacuation paths
5	Evacuation/first response team
6	Risk minimization systems: recycling system and ATEX zones
7	Fire door/gate
8	Closing windows and doors
9	Manual fire alarm
10	Fire extinguisher

Table 8: Scenarios for the fire simulation based on the event tree analysis (author's model)

The comparison of the different scenarios is performed using the calculation of the expected value for the specific branch in the event tree. This expected value is calculated using the formula $P_1 * C_1 + P_2 * C_2 + \cdots + P_9 * C_9$ where P describes the probability of the component failing and C describes the consequence of that failure. Since the calculation of the expected value is based on the fire simulation, this consequence is stated to be the difference in evacuation time between the base case and the investigated scenario. The probability of failure is estimated based on a combination of information extracted from reports and an investigation of the general conditions in the production facility. The considered reports contain both internal and external reports regarding maintenance and inspections, and documentation regarding the provision of safety instructions and updated plans from the AMO. The investigation of the conditions in the production facility focuses on finding obstructions and components that are not conforming with the incorporated contingency plans. For the calculation of the expected value, increased reaction times due to human errors influencing the human behaviour of all employees are excluded.

5.2.2. Detailed description of the events affected by human errors within the defined scenarios

All calculations for the probabilities described for the different scenarios can be found in the appendix (11. Appendix, section 11.3.2).

5.2.2.1. Scenario 2

As detailed in Table 8, scenario 2 describes fire scenarios where the emergency signs fail. The events leading to the success or failure of this component are illustrated on Figure 18.

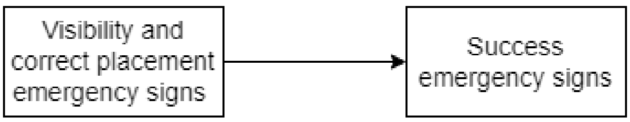


Figure 18: Scenario 2-events (author's model)

The success of the emergency signs component is dependent on the visibility and the placement of emergency signs (section 4.1.3, 4.2.2.2). These emergency signs include both signs indicating emergency doors and fire safety equipment. The placement of these signs is indicated on the emergency floor plans that can be found in both the production facility and the administration building. These plans illustrate the advised emergency routes for the employees in case of a fire event through the indication of emergency doors. Additionally, they also provide an indication of the placement of fire safety equipment such as handheld fire extinguishers for the employees. Since all employees must sign for reading and understanding these plans and the safety instructions, it is assumed that following these routes should facilitate the evacuation process.

During the visitation of the company, all emergency signs were clearly visible. The placement of some of the signs was, however, indicated incorrectly on the emergency floor plans. These plans were last updated in 2019. It is, therefore, assumed that all newly hired employees are informed regarding the fire contingency plans using these emergency floor plans. The probability that the emergency signs fail is consequently dependent on their indication on these plans. From a total of 35 emergency signs, 20 were indicated incorrectly on these plans. This gives a probability of 57,1% that the emergency signs component will fail.

5.2.2.2. Scenario 3

Scenario 3 describes a fire scenario where the emergency doors do not function as required for the evacuation process. This scenario includes the malfunctioning of the door mechanism itself and the obstruction of the doorway. During the inspection no emergency doors were found to be malfunctioning. Several doors were, however, found to have an obstacle hindering the passage through the doorway. For the production facility, this failure to function is described as emergency doors that are obstructed. The events leading to success for the emergency doors component are indicated on Figure 19.

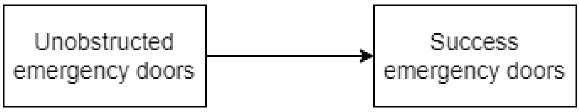


Figure 19: Scenario 3-events (author's model)

The updated emergency floor plans (executed by the author) indicate 16 different emergency doors. After an inspection of the emergency doors in both the office building and the production facility, three of these doors were found to be blocked by materials and finished products. The obstructions are indicated with the blue squares on Figure 20. The two obstructions on the left side of the drawing are due to the storage of components as illustrated with the pictures. This storage of components includes the possible placement of heavy and/or sharp objects such as sheet metal on top of the moveable tables. These obstructions are, therefore, assumed to be immovable. The obstruction on the right side of the drawing is due to the placement of finished parts that are ready for shipment to the costumer.

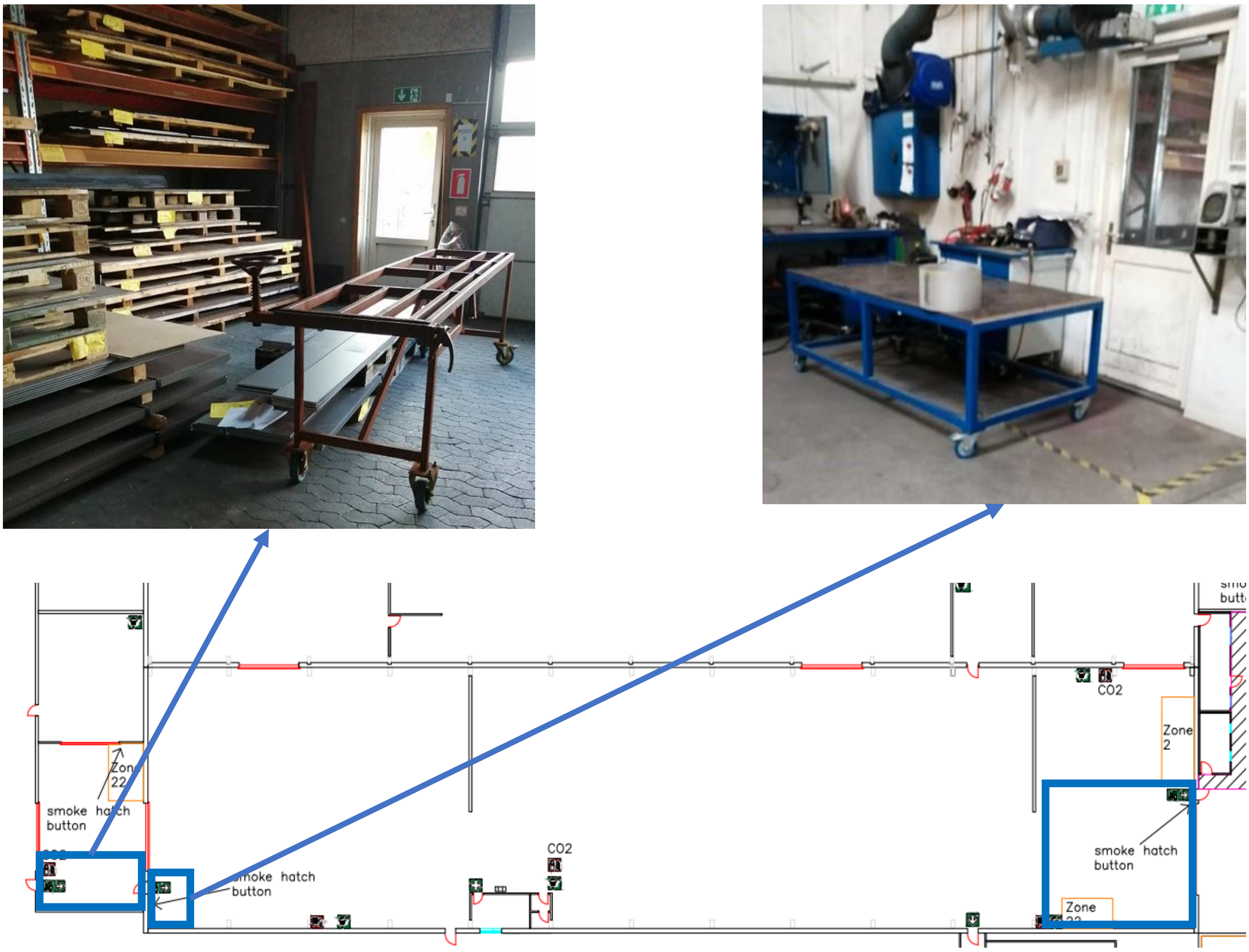


Figure 20: Obstructed emergency exit doors (drawing 3.01, 12. Drawing folder, p. 6)

Based on the experienced obstructions and the total number of indicated exit doors, the probability that an exit is blocked is 13,3%. Additionally, this probability is increased by the number of missed monthly inspections. During these monthly inspections, the evacuation paths and emergency exit doors are checked for obstructions. The last monthly inspection was performed in March. The probability of failure is, therefore, increased with 75%. This gives a total probability for an obstructed emergency exit door of 23,3%.

5.2.2.3. Scenario 4

For scenario 4, the failing component is the evacuation paths. These paths are shown with the brown lines in drawing 3.01 (12. Drawing folder, p. 6). Since the failure of emergency doors is described for scenario 3 (section 5.2.2.2), this scenario does not consider those components. The events leading to the success of the evacuation path component are illustrated in Figure 21.

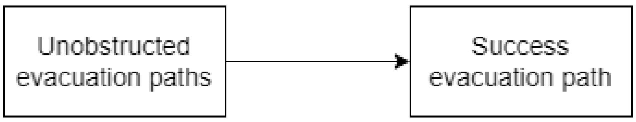


Figure 21: Scenario 4-events (author's model)

The obstructions found on the evacuation paths were registered during a company visit. The total number of obstructions at that point was seven. These different obstructions and their placement within the production facility are indicated and illustrated on Figure 22. Additionally, Figure 22 also shows the numbering of the different evacuation paths. These evacuation paths are numbered depending on the different routes that can be used to escape each department.

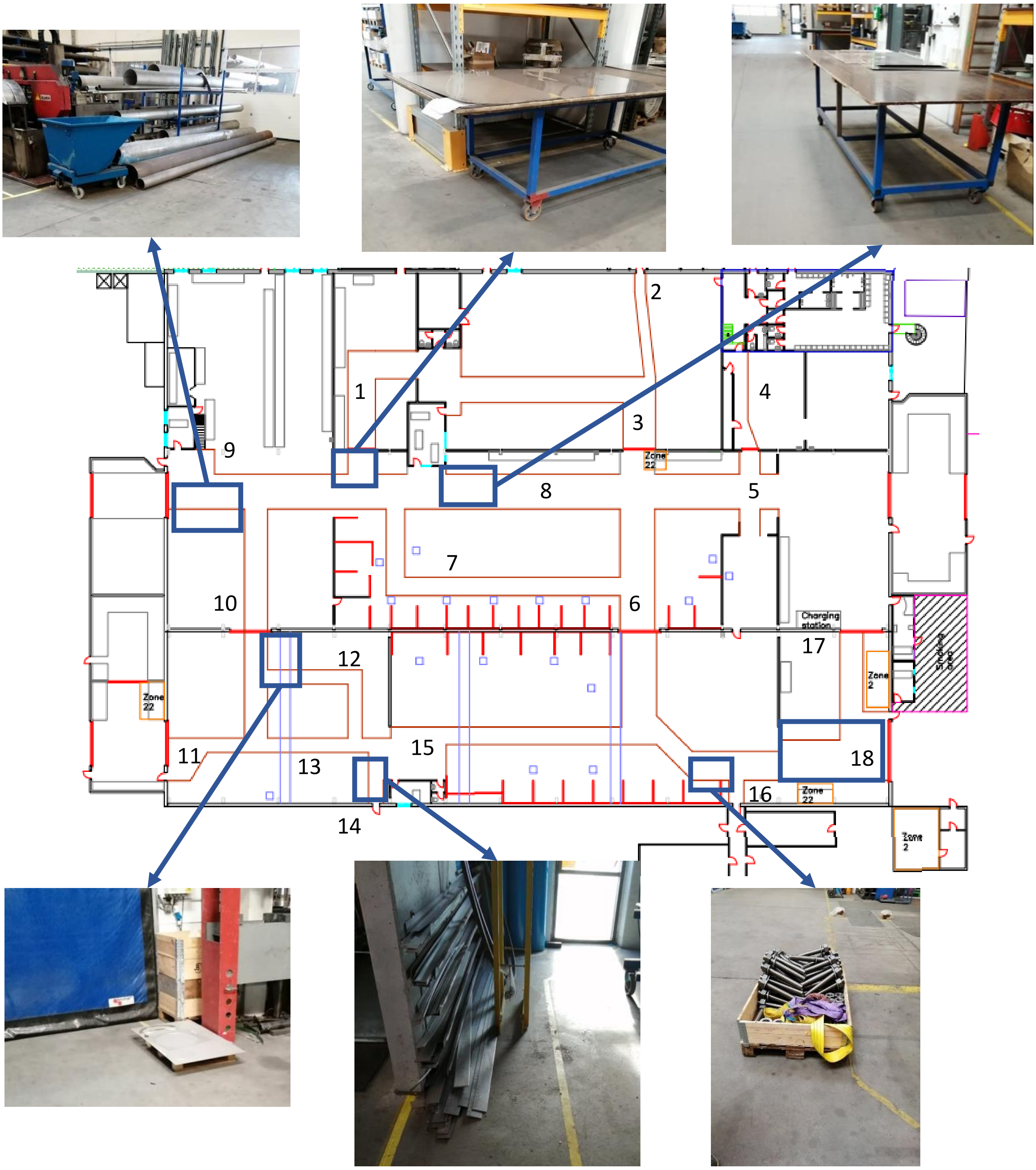


Figure 22: Indication and illustration of obstructions (drawing 2.01, 12. Drawing folder, p. 4)

Based on the number of obstructions and the total number of evacuation paths, the probability that a pathway is blocked is equal to 38,9%. Additionally, this probability is increased due to number of missed monthly inspections. These monthly inspections are performed by the company to reveal obstructed pathways and unconformities with the marking of these pathways. An example of a pathway with missing markings is found on Figure 23. The last monthly inspection was performed in March. The probability of failure is, therefore, increased with 75%. This gives a total probability for an obstructed emergency exit door of 68,1%.

Figure 23: Pathway with missing markings (author's picture)

5.2.2.4. Scenario 5

As described in Table 8, scenario 5 describes a fire scenario where the evacuation team component fails. This component is dependent on the knowledge of the evacuation team and the employees regarding the safety instructions. The members of the evacuation team must know their allocated role and the connected responsibilities within the safety instructions. Additionally, the employees must know the instructions to be able to facilitate the rollcall at the assembly evacuation point. These events are illustrated on Figure 24. This scenario does not include the first response group since the influence of this group will not be modelled during the evacuation and fire simulation. This exclusion is based on the lack of an action describing the provision of first aid in the safety instructions.

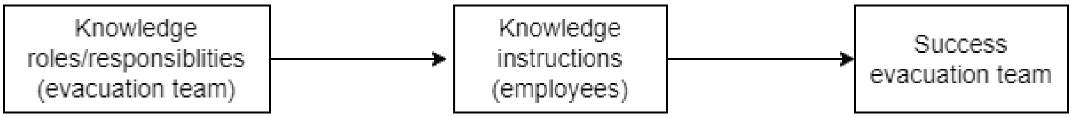


Figure 24: Scenario 5-events (author's model)

The probability that a member of the evacuation team does not know their role and responsibilities is calculated based on the number of lacking members in the allocation of the evacuation teams. The evacuation teams are supposed to have 10 people in total, one primary and one back-up member. At this point, only five people from these evacuation teams are appointed by the AMO. There is, therefore, a probability of 50% that a person will know their role and responsibility in case of a fire event.

Additionally, the number of employees that knows the updated safety instructions is dependent on the provision of this information by the AMO. Based on a general enquiry regarding this, it can be assumed that only newly hired employees and members of the AMO structure are updated regarding these instructions. Employees that are not involved with the AMO or the safety instructions were only informed of the contingency plans at the start of their employment. They had to sign for reading and understanding these plans. They do, however not receive yearly updates regarding them. The members of the AMO structure should discuss and update these plans in accordance with the company's procedures as described in the stakeholder analysis (section 3.2.1). Additionally, all members of the evacuation teams and the person from QA that is responsible for updating and preparing these plans, are updated through their involvement with the discussed contingency plans. The number of employees that know the safety instructions is, therefore, calculated to be 18. The total number of employees that is employed within the company is set to be 77. More information regarding the total number of employees can be found in the agent modelling part of this document (section 5.3.1.2). The probability that an employee will be updated regarding the safety instruction is, therefore, 23,4%.

5.2.2.5. Scenario 6

Scenario 6 describes a fire scenario where the risk minimization system fails. The company uses the 5S system to minimize risks related to organizing and cleaning the workspace. The 5S system provides the framework that is implemented to ensure that the workspace is organized and cleaned regularly. The functioning and regular review of this system is, therefore, required to obtain a successful risk minimization system. This is illustrated in Figure 25.

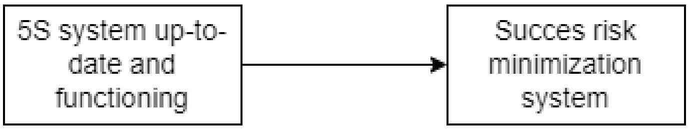


Figure 25: Scenario 6-events (author's model)

The company requires the completion of monthly inspection rounds for the compliance of the employees with the 5S system. The last recorded inspection round was performed in March. The assessment of the condition of the workspace and the compliance with the 5S system was an average of 2,4 points out of 5. This assessment method is dependent on the person that performs the assessment and the assessment system where 1 is the best and 5 is the worst score. Additionally, the performance of the assessment is carried out for each department individually. The assessment team is composed of the production manager and the supervisor of the investigated department. The assessment is, therefore, subjective and the impact of a different assessment must be investigated with a sensitivity analysis. This analysis will be performed in the discussion part of this document (section 6.3.3). Based on the provided assessment, the probability that the 5S system is not adhered with is 48%. Additionally, this probability is increased since no inspection rounds where performed in the last 9 months. This gives a total probability of 84%.

5.2.2.6. Scenario 7

Scenario 7 describes a fire scenario where the fire doors and/or gates fail. Since the hazardous condition occurs in the production facility (section 5.1), the fire gates are the first barrier to stop the spread of the fire. Additionally, the fire doors are incorporated to limit the fire spread to the administration building. The placement of both the fire gates and doors can be found on drawing 3.01 (12. Drawing folder, p. 6). The different events leading to the success of the fire doors/gates component are illustrated on Figure 26.

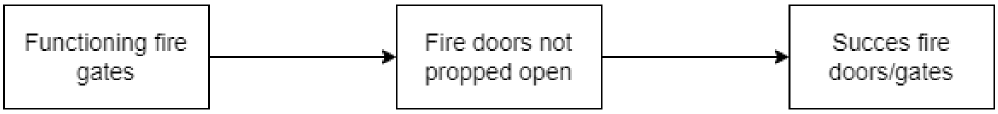


Figure 26: Scenario 7-events (author's model)

The three fire gates in the production facility are inspected and serviced once a year. The last inspection was performed by an external company in May 2021. During this inspection, the closing mechanism and the integrity of the gates was investigated. One of the fire gates was found to have a damaged door leaf and an issue with the door pump. This door pump was repaired by the inspector. All doors were afterwards stated to fulfil the legal requirements. Since this damage could impact the resistance of the fire gate in case of a fire event, the probability that the fire gates will fail is set to 33,3%.

The fire doors are not operated by an automatic closing system. During the visits of the company no fire doors were found to be propped open or broken. The probability that the fire doors will fail is, therefore, set to the value of 0,1%. To investigate the impact of this probability a sensitivity analysis will be done (section 6.3.3).

5.2.2.7. Scenario 8

As described in Table 8, scenario 8 investigates a fire scenario where the closing of windows and doors fails. This component can be divided in two different events. Firstly, the person needs to know the safety instructions as this component is described as an action within these instructions. Afterwards, the doors and windows must be functioning as required. The different gates within production are also included in this event as they are operated using an automatic door pump. The different events are illustrated in Figure 27.

Figure 27: Scenario 8-events (author's model)

The probability that an employee knows the updated safety instructions is set to a value of 23,4%. This probability is explained in the description of scenario 5 (section 5.2.2.4).

There is no record regarding damaged or malfunctioning double glass pane windows and/or doors. Additionally, during the visits none of the doors or windows were found to be defect. The probability of any defects to the function of the windows and doors is, therefore, assumed to be 0,01%. To investigate the impact of this probability as sensitivity analysis is performed in the discussion part of this document (section 6.3.3). As explained previously, the possible malfunctioning of the self-closing gates is also included for this event. Since fire gates are included in scenario 7 (section 5.2.2.6), they are excluded for this scenario. The inspection and service of the gates is performed yearly by an external company. The last inspection was performed in May 2021. This inspection investigated all 15 gates. Out of these 15 gates, two were found to not fulfil the legal requirements to pass the inspection. Additionally, two other gates were approved but they both had a broken window. The probability that these gates function as desired is, therefore, equal to 73,3%. Consequently, the total probability that the windows, doors, and/or gates function as required is equal to 73,2%.

5.2.2.8. Scenario 9

Since the company building does not have an automatic alarm system or fire alarm in the production facility, alarming all employees of the fire event is done manually. Scenario 9 describes a fire scenario were this component fails. The failure of this component is dependent on three different events. Firstly, the person that notices the fire and provides the manual alarm must know the safety instructions. These instructions in combination with the emergency floor plans and fire evacuation exercises provide the employee with information regarding the system that is used to alarm everyone in case a fire event occurs. Additionally, this person must know the building layout to be able to warn all different departments in both the production facility and the administration building of the fire event. Finally, the person that is being warned must know the safety instructions to react accordingly to the fire alarm. These different events are illustrated on Figure 28.

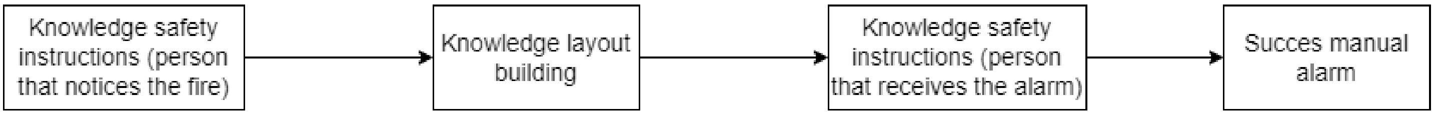


Figure 28: Scenario 9-events (author's model)

The knowledge of the safety instruction for both the person that performs the manual alarm and the person that receives the alarm is equal to 23,4% as explained for scenario 5 (section 5.2.2.4).

The knowledge of the building layout for the person that performs the manual alarm is dependent on that person's familiarity with the building. It is assumed that newly hired employees, and students within the different departments are not familiar enough with the building to optimally perform the manual alarm. This assumption is based on information provided by the employees in both the administration building and the production facility. Additionally, since the fire event occurs in the production facility (section 5.1) it is assumed that an employee in the production facility is tasked with performing the manual alarm. There are 6 newly hired people and 3 students based on the information provided by the company. The total number of employees within the production facility is set to 47. The probability that a person employed in the production facility knows the building layout is, therefore, equal to 80,9%.

5.2.2.9. Scenario 10

The last scenario (scenario 10) describes the failure of the fire extinguisher component as described in Table 8. Firstly, the person that is supposed to use the fire extinguisher must know the safety instructions. Afterwards, it is important that this person knows where to find a fire extinguisher and how to use this extinguisher. Lastly, the fire extinguisher should be functioning as needed. Through regular maintenance, the probability that a fire extinguisher will function is increased. The different events leading to the successful use of a fire extinguisher are illustrated in Figure 29.

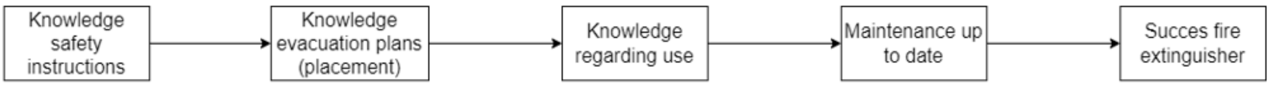


Figure 29: Scenario 10-events (author's model)

The knowledge of the safety instructions for the person that is supposed to use the fire extinguisher is equal to 23,4% as explained for scenario 5 (section 5.2.2.4).

The probability that a person will know the placement of the different fire extinguishers is dependent on the correct indication of these extinguishers in the production facility. It is assumed that this correct indication is based on the indication of these extinguishers on the original evacuation floor plans. This assumption is made since these floor plans supplement the safety instructions. Additionally, these floor plans are present within the administration building and the production facility to aid the evacuation process. The placement of these floor plans can be found on drawing 3.01 (12. Drawing folder, p. 6). There are a total of ten fire extinguishers distributed across the company building, three of them were not included or not indicated correctly on these evacuation floor plans. The probability that a person will know the placement of a fire extinguisher is, therefore, equal to 70%.

Additionally, the probability that a person will know how to use a fire extinguisher is equal to 40% as described in the literature review (section 4.2.1.5).

Finally, the maintenance of fire extinguishers should be done through internal and external inspections and services. The internal inspections should be done on a monthly and a yearly basis as described in BR18 (section 3.1.3.2). The external inspections must be done every year. The completion of the yearly internal and external maintenance can vary within an accepted period of 1 month compared to the date of the previous inspection (Firesafe). The base failure rate for a fire extinguisher is 0,90% (National Association of Fire Equipment Distributors, 2010). This failure rate is, however, increased due to the number of missed and delayed inspections and services. The last monthly check is assumed to be performed in March 2021 when appointed employees did a visual inspection of the production facility. The last internal yearly check was performed 1 month too late for 50% of the fire extinguishers and the last external yearly check was performed 6 months too late. The planned and completed inspection dates for both the internal and the external yearly inspections can be found in Table 9.

	Planned	**Completed**
Internal yearly maintenance	6 January 2021/16 March 2021	16 March 2021
External yearly maintenance	25 May 2020	8 December 2020

Table 9: Planned and completed dates for internal and external yearly inspections (based on maintenance documentation)

Since the yearly external inspection includes the approval of the fire extinguisher for the next year, the effect of a delayed inspection is increased with a factor of 2. The total increased probability of failure for the fire extinguisher based on the maintenance intervals is, therefore, calculated to be set at 2,44%. A sensitivity analysis will be performed to investigate the impact of the base failure rate and the weighted probability due to a delayed external yearly inspection (section 6.3.3).

5.3. Agent-modelling

The discussion of the input regarding agent-modelling focuses on the multi-layered model that is used for the simulation of the base case (scenario 1). Afterwards, the adaptations that are made to this model for the input in the alternate scenarios (scenario 2-scenario 10) are illustrated. The description of the multi-layered modelling approach and the different layers included in this model can be found in the methodology section of this case-study (section 4.2.1).

5.3.1. Discussion of the input (scenario 1)

5.3.1.1. Spatial model

The spatial model of the building is based on the floor plans that were provided by the company. Some changes were, however, made to the layout in both the office building and the production facility after the completion of these plans. These floor plans were, therefore, adapted by the author to fit with the current layout. The development of the 3D model for the simulation was performed using measurements taken from the building itself. The height of all windows and doors found on the 3D model was based on the measurements taken from one window and one internal door in meeting room one (drawing 1.01, 12. Drawing folder, p. 2). The height of different types of furniture, such as desks, shelfs, toilets and cabinets, was derived from industry standards and similar articles of furniture online. Additionally, some shelving units especially in the storage and logistics areas in the production facility were modelled as floor to ceiling shelves.

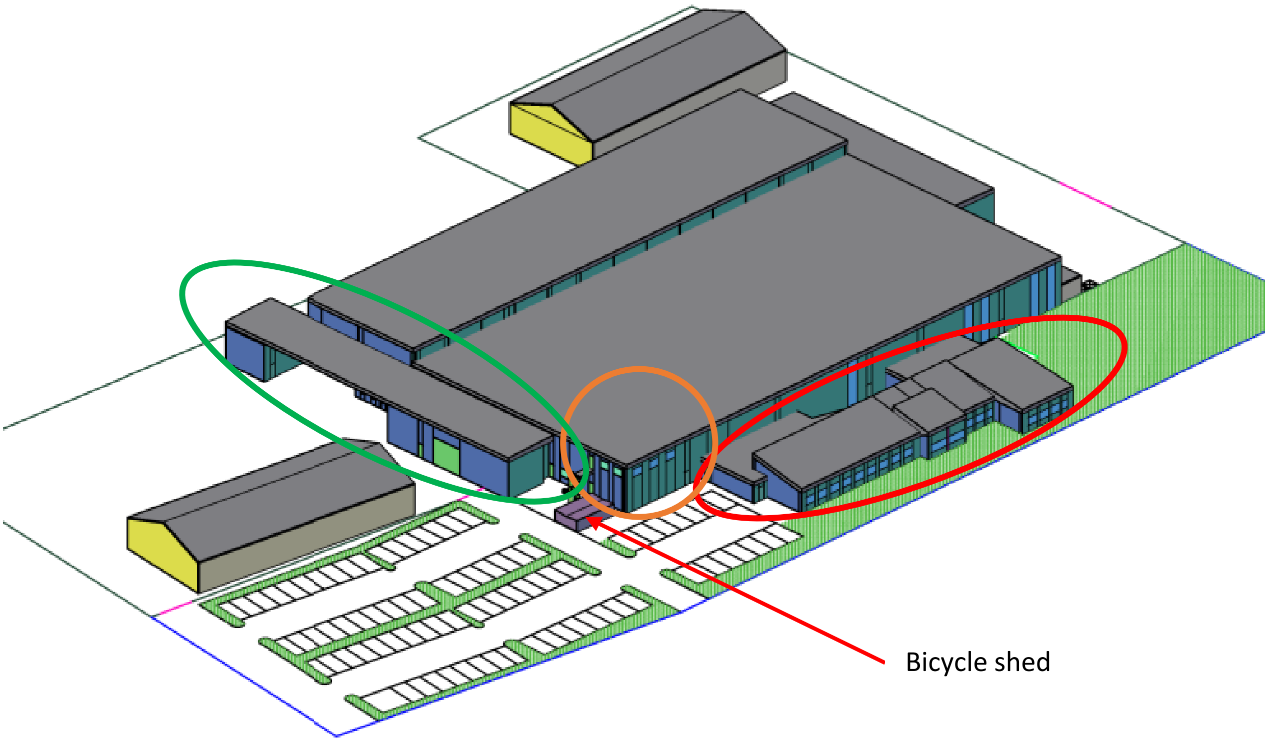


Figure 30: 3D model building and surrounding plot-NE view (author's model)

Figure 30 shows the developed 3D model. The building itself is as mentioned previously split up in an office building and a production facility. The office building is indicated with the red shape on Figure 30. This part of the building consists only of a ground floor level. As illustrated on Figure 30, some parts of this office have a slanted roof, whereas other parts have a flat roof. This flat roof can be found above the toilets, the washrooms, and the canteen for the office employees. The areas where office employees and managers are seated can be found under the slanted roof. Most of the ceilings in these areas are, therefore, also slanted. The only exceptions are the area where the IT department is seated and meeting room 1, both areas have a lowered ceiling in one level.

The other part of the building is the production facility. Most areas within this facility consist of only a ground floor level. The canteen for the production employees and a meeting room can, however, be found on the first level above the changing rooms. This floor can be reached through both an internal and an external staircase. This external staircase is a spiral staircase. The placement of this first floor is illustrated with the orange shape on Figure 30. The other areas of the production facility are open floor areas with dividing walls, shelving units and tall ceilings with a height between 6 and 9 m. Additionally, toilets, washrooms, and offices for the foremen of the different departments and the production manager are separated from these open floor areas using enclosed structures with lowered ceilings. Furthermore, storage areas can be found on either side of the production facility. These storage areas have a lower ceiling in comparison with the production facility itself. The ceiling heights in these areas are approximately 5,5 m. One of the storage areas and the connected covered smoking area is indicated with the green shape on Figure 30.

On the building plot itself, there are two tents that are used for storage. These tents are the structures with yellow walls on Figure 30. Additionally, the 3D model also shows the placement of the bicycle shed, the parking lot and the green area adjacent to the office building.

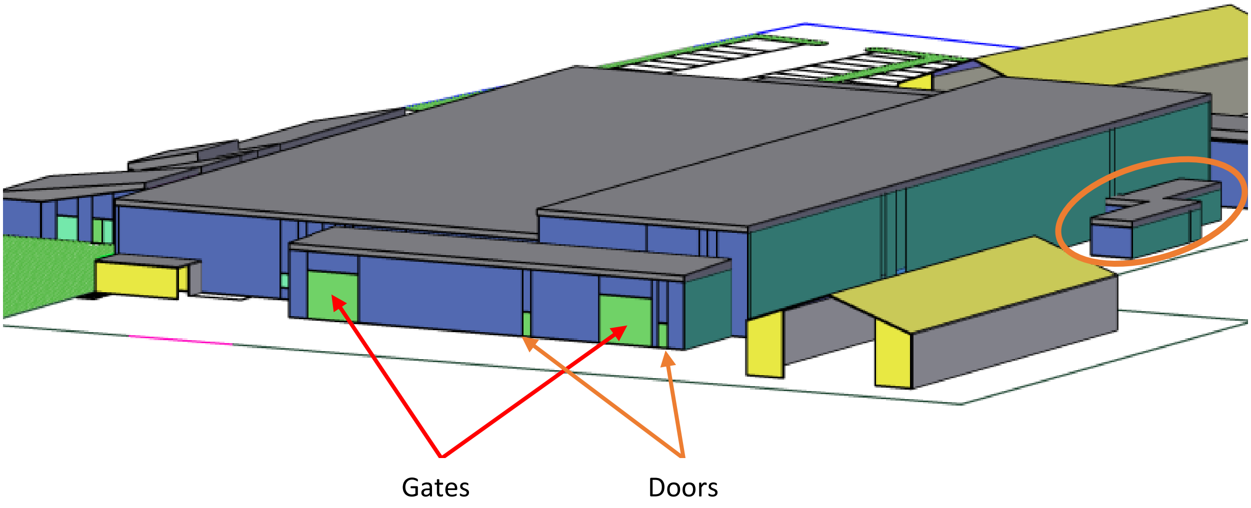


Figure 31: 3D model zoomed-in on the production facility-SW view (author's model)

Figure 31 shows the south-western view of the production facility. Since the activation of smoke hatches is not described in the safety instructions (11. Appendix, section 11.1.1.), it is assumed that these hatches will not be activated when a fire event occurs. The impact and usage of the smoke hatches is, therefore, excluded from the simulation. The arrows indicated the gates and doors that can be used to escape the building. Additionally, the orange shape shows the additional changing rooms that can be used by the employees in the production facility. These changing rooms also have an emergency exit door that employees can use to exit the building.

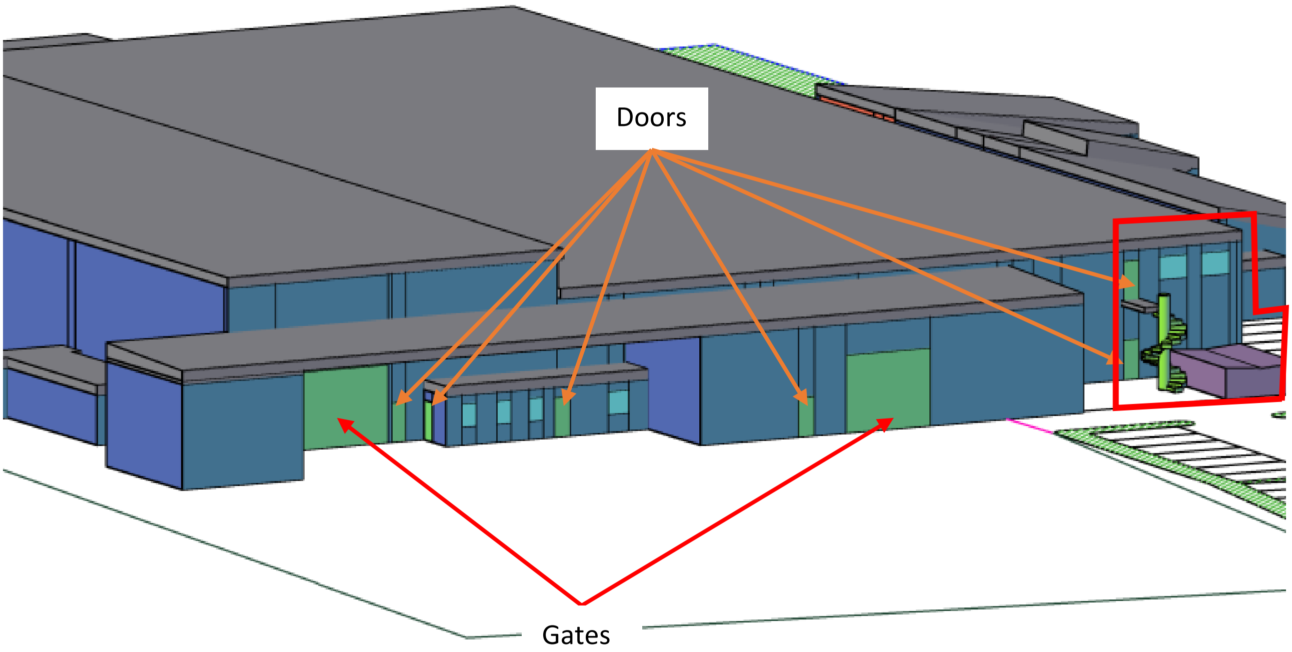


Figure 32: 3D model zoomed-in on the production facility-SE view (author's model)

The south-eastern view of the production facility is shown on Figure 32. This view shows the placement of gates and doors that can be used to exit the building. Additionally, this view also shows the windows within this part of the production facility. The windows are the teal-coloured rectangles found on the external walls of the facility. The red shape on Figure 32 shows a more zoomed-in view of the part of the production facility where the first floor can be found. This shape also illustrates the external staircase and the bicycle shed.

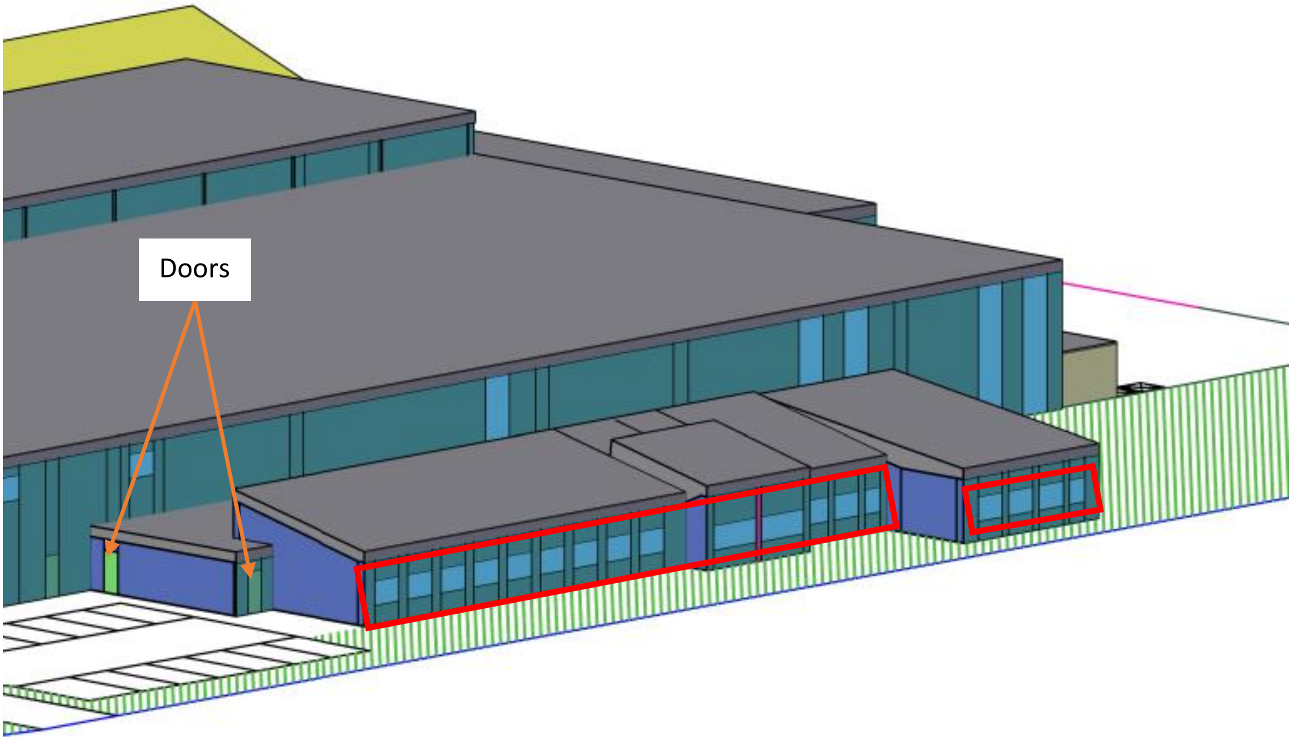


Figure 33: 3D model zoomed-in on the office building-NE view (author's model)

The north-eastern view of the office building inserted in Figure 33 shows the placement of the emergency doors. Additionally, all windows indicated with the red squares can be used as an emergency exit. This view also shows the slanted and the flat roofs more clearly.

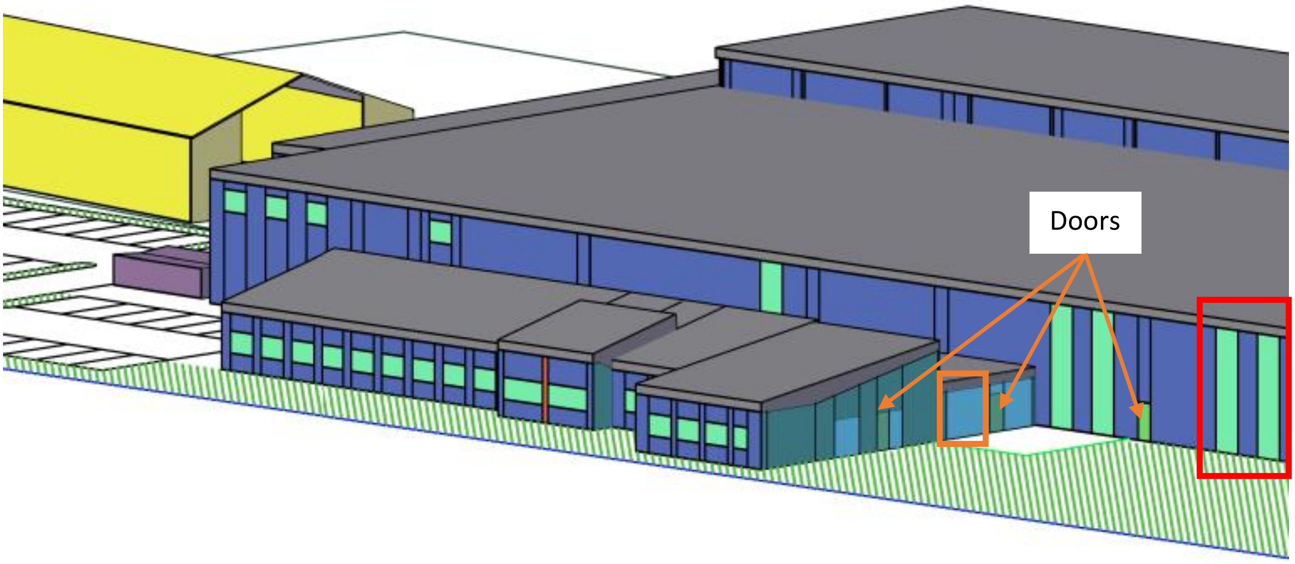


Figure 34: 3D model zoomed-in on the office building-NW view (author's model)

The north-western view of the office building can be found in Figure 34. This view shows emergency doors in both the office building and the production facility. Additionally, this view also shows floor to ceiling windows in both the production facility (red square) and the office facility (orange square). These windows cannot be opened.

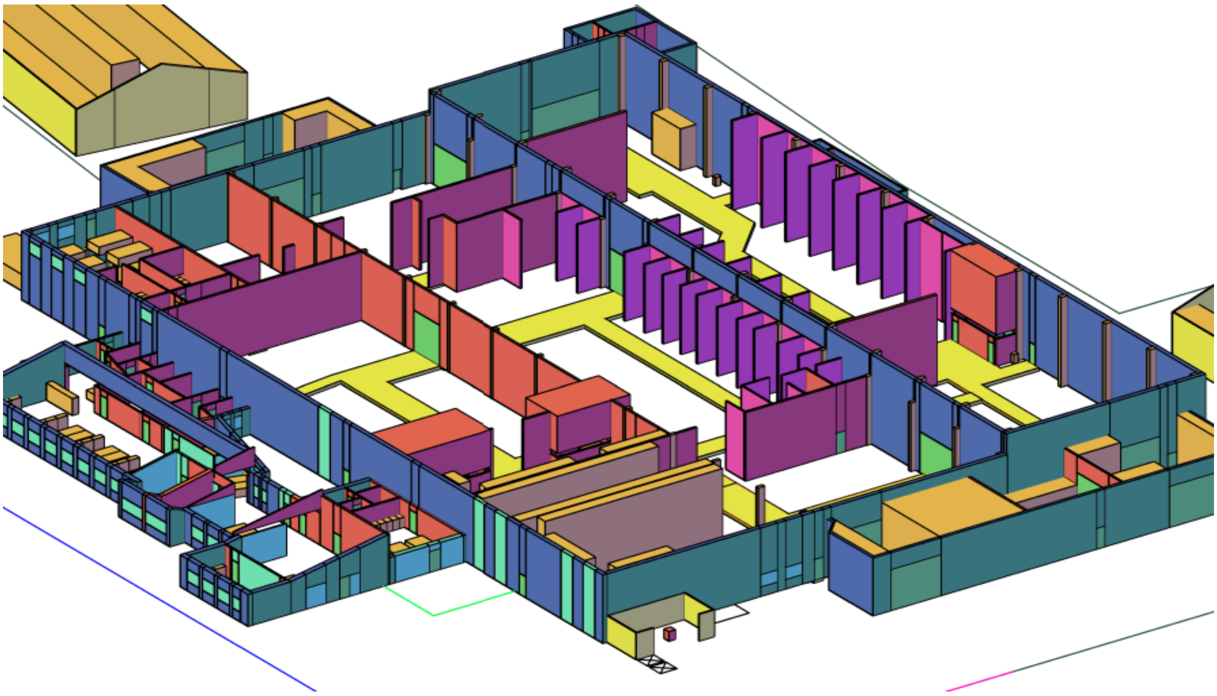


Figure 35: 3D model internal layout-NW view (author's model)

More details regarding the placement of internal stairs, external and internal gates and doors, and windows can be found on drawing 1.01 and 1.02 (12. Drawing folder, p. 2-3). These drawings also indicate the different departments and rooms, and their orientation within the building layout. An illustration of the internal layout of the building can be found in Figure 35. This model shows internal furniture (orange), internal walls (red), welding cabins (pink) and evacuation pathways (yellow). This internal layout is entirely based on the adapted floor plans, these floor plans can be found on drawing 1.01, 1.02, 2.01 and 2.02 (12. Drawing folder, p. 2-5).

The placement of evacuation equipment and signs is shown on the floor plans (drawing 3.01 and 3.02, 12. Drawing folder, p. 6-7). These floor plans are adapted from the floor plans provided by the company to reflect the current placement of both the emergency equipment and signs inside the building.

5.3.1.2. Occupancy model and demographics

Due to collaboration between the author of this case-study and the company, it was possible to determine a detailed occupancy distribution. This distribution divides the employees within the company based on the department they are employed in, their gender and their age group. The different departments and their orientation inside the building can be found on drawing 1.01 (12. Drawing folder, p. 2). At the time of writing, a total number of 77 employees is stated to work in the company. Of those employees, 30 work in the administration building and 47 work in the production facility. The occupancy distribution for the administration building and the production facility can be found in Figure 36 and Figure 37. For the simulation, it is assumed that no guests are present inside the building at the time of the fire event.

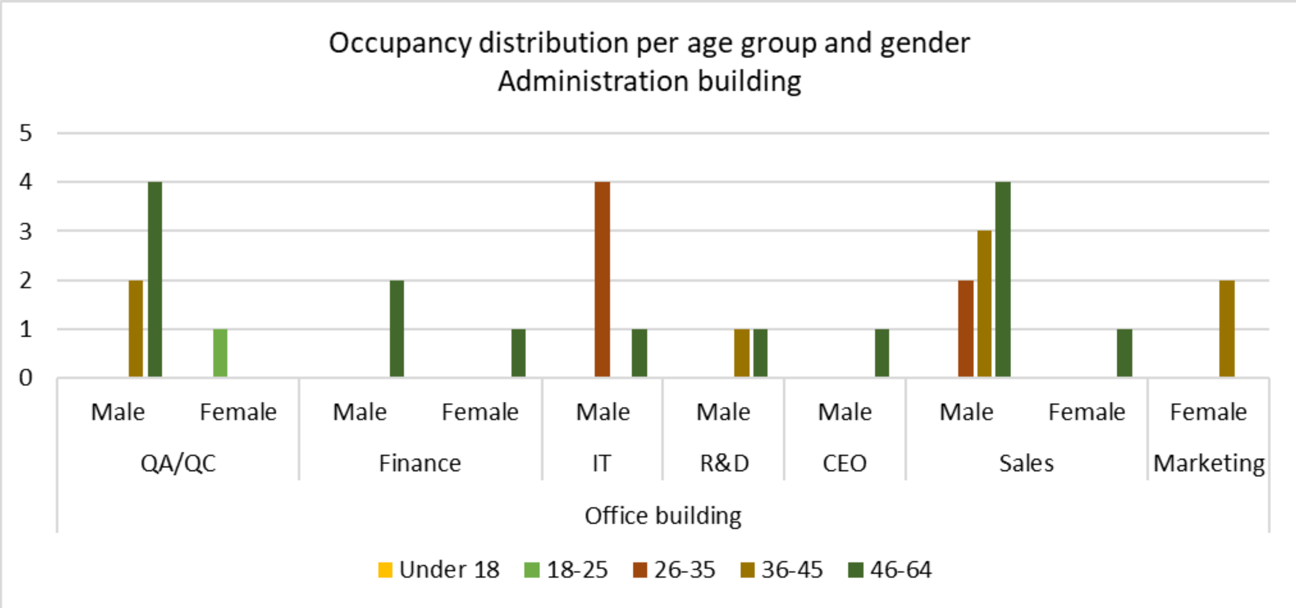


Figure 36: Occupancy distribution-administration building (author's model)

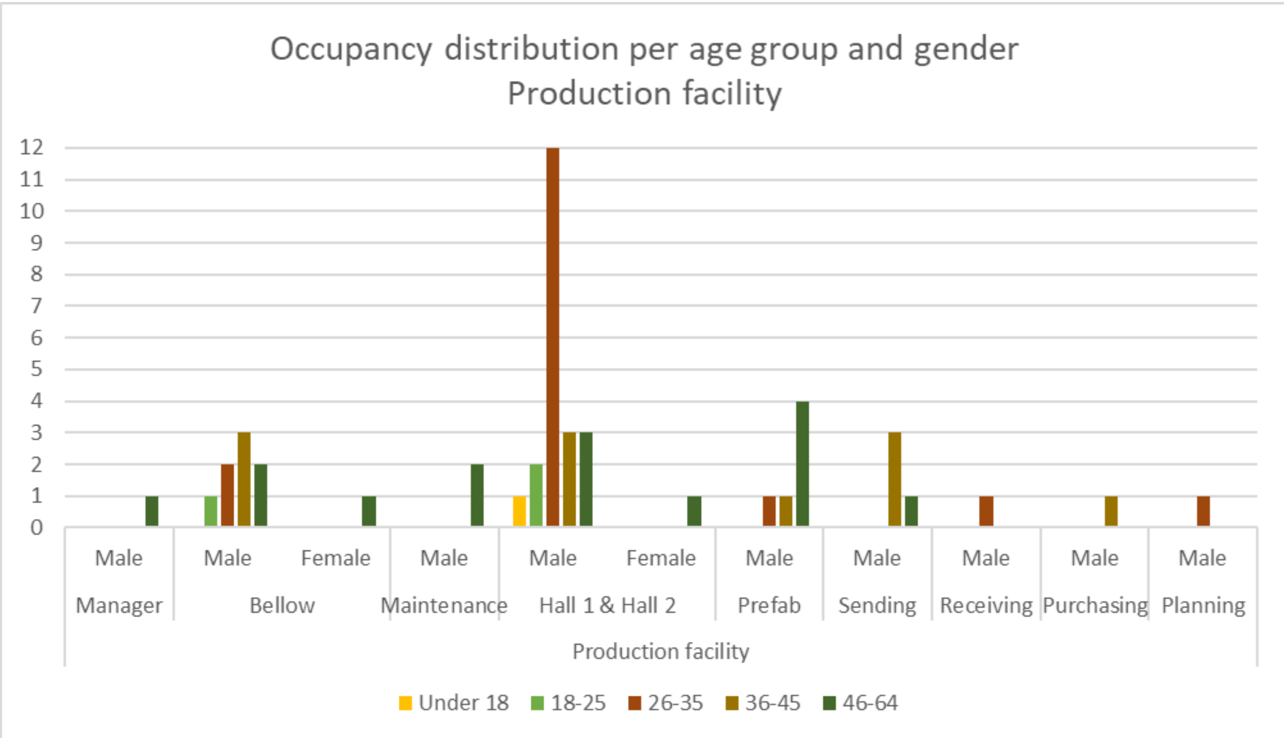


Figure 37: Occupancy distribution-production facility (author's model)

5.3.1.3. Physical model

The physical model describes the occupants based on their speed, shape, and height. The information regarding the speed and shape was defined based on (Korhonen, 2018). The height of the adult occupants was extracted from (WorldData.info, n.d.). Additionally, the height of the adolescent occupants was based on the growth curves discussed in (Tinggaard, et al., 2013). The minimum and maximum speed and shape parameters were based on the 99% confidence interval where both the minimum and the maximum values were calculated according to the following formula: $\mu \pm 3\sigma$ with $\mu = location$ and $\sigma = scale$. The final input values for the physical model are shown in Table 10.

Age groups	Sex	Speed					Shape					Height
		Distribution	Min	Max	Location μ	Scale σ	Distribution	Min	Max	Location μ	Scale σ	
13-17	Men	LN	0,7	1,3	1	0,1	LN	33	51	42	3	1,7
	Women	LN	0,7	1,3	1	0,1	LN	33	51	42	3	1,64
18-25	Men	LN	0,75	2,0	1,35	0,2	LN	42	66	54	4	1,82
	Women	LN	0,75	2,0	1,35	0,2	LN	36	60	48	4	1,69
26-35	Men	LN	0,85	1,8	1,3	0,15	LN	42	66	54	4	1,82
	Women	LN	0,85	1,8	1,3	0,15	LN	36	60	48	4	1,69
36-45	Men	LN	0,6	1,8	1,2	0,2	LN	42	66	54	4	1,82
	Women	LN	0,6	1,8	1,2	0,2	LN	36	60	48	4	1,69
46-64	Men	LN	0,2	2,0	1,1	0,3	LN	42	66	54	4	1,82
	Women	LN	0,2	2,0	1,1	0,3	LN	36	60	48	4	1,69

Table 10: Input values for the physical model (author's model)

5.3.1.4. Interaction model

The interaction model describes the different steps that will be taken by the employees during the evacuation process. These steps are based on the safety instructions that are provided to the employees by the AMO. The currently used safety instructions can be found in the appendix (11. Appendix, section 11.1.1.). The different steps are illustrated on Figure 38.

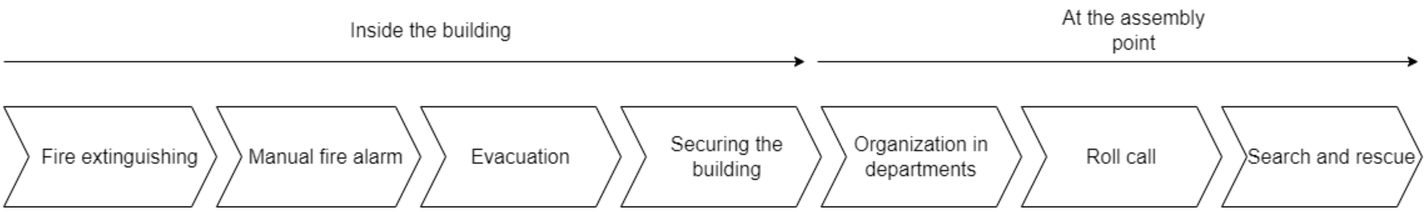


Figure 38: Steps to be taken during an evacuation based on the safety instructions (author's model)

After the occurrence of the fire, the person that notices the fire should perform fire extinguishing actions. These actions are performed using a hand-held carbon dioxide (CO_2) fire extinguisher. The fire extinguisher model that is used has a discharge time of 17 seconds (Falck, 2017). Additionally, it takes the person a total of 5 seconds to operate the fire extinguisher (Howcast, 2010). Afterwards, the person must alarm all employees present within the company building. Since no buttons could be found during the visitation of the building and no actions to trigger a fire alarm were described in the safety instructions, it is assumed that this person must manually warn the employees of the fire event. This person must, therefore, go to all different departments to warn the employees in each department. It is assumed that screaming will not alarm all employees in the production facility due to the noise created by welding activities, reach trucks and machinery. Additionally, the fire alarm in the administration building can only be triggered by the installed smoke detectors. The person performing the fire alarm must, therefore, enter the administration building to warn the employees. After the employees are alarmed of the fire event, they will evacuate the building using the indicated emergency doors (drawing 3.01, 12. Drawing folder, p. 6). The last person to leave an area will close the windows and doors. All gates and emergency doors in the production facility are self-closing. Additionally, the fire gates are manually closed by a button-operated door pump. These gates are, therefore, assumed to be closed by the last person that leaves the area. The members of the evacuation team are the last employees that leave the building as they are required to ensure that everybody left the building. The evacuated employees assemble at the evacuation assembly point that is indicated on drawing 3.01 (12. Drawing folder, p. 6). At this assembly point the employees will be organized in groups depending on the department they are employed in. This organization is facilitated by the members of the evacuation team. Afterwards, the production manager performs a roll call. If any employees are registered as missing, one of the members of the evacuation team will perform search and rescue.

Additionally, the interaction model describes the interaction of the employees with building components such as staircases, doorways, and pathways. As illustrated in the spatial model (section 5.3.1.1), the building has two staircases to reach the first level. The internal staircase is split in two parts with a landing as illustrated in Figure 39.

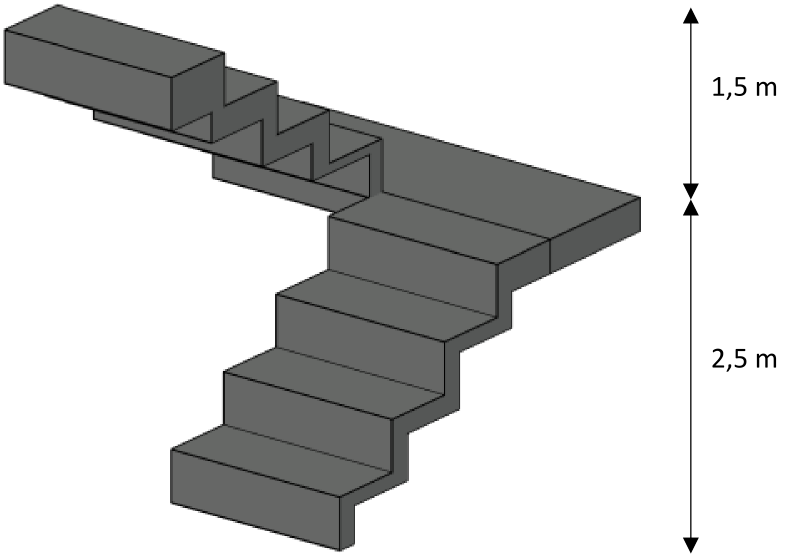


Figure 39: Illustration internal staircase (author's model)

The lower part of the staircase is calculated to have 14 steps with a riser of 17,8 cm and a thread of 28,4 cm. Additionally, the upper part of the staircase has 9 steps with a riser of 18,9 cm and a thread of 32,2 cm. The external spiral staircase has a riser of 18,9 cm and a thread of 32,3 cm. The calculation of the specific flow on the internal staircases is based on the values found in (Gwynne & Rosenbaum, pp. 2124-2128). The calculated flow rates can be found in Table 11.

Staircase	Width (cm)	Boundary layer (cm)	Effective width (cm)	Specific flow (pers/s)
Internal lower	106,2	15	76,2	0,72
Internal upper	133,7	15	103,7	0,97
External	85,2	15	55,2	0,52

Table 11: Values for calculation specific flow-staircases (based on (Gwynne & Rosenbaum, pp. 2124-2128))

Finally, the specific flow on the evacuation paths is calculated since it is assumed that the workspaces surrounding these paths contain several obstacles such as cranes, moveable tables, and welding equipment. The different sections of the evacuation paths are illustrated on Figure 40.

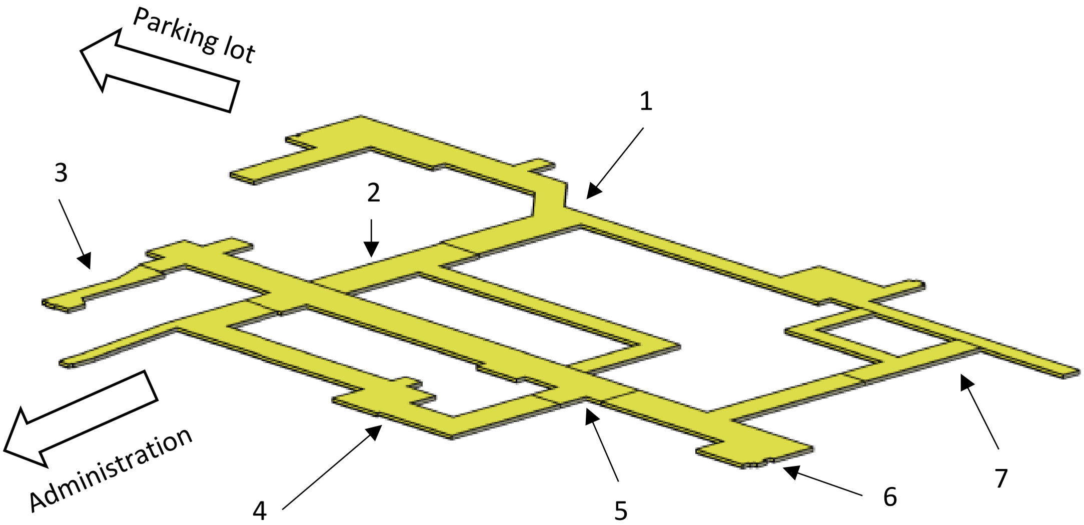


Figure 40: Indication of different evacuation paths (author's model)

Each section is assumed to be defined by its smallest width. The width of each section and the specific flow rate are inserted in Table 12.

Evacuation path	Width (cm)	Boundary layer (cm)	Effective width (cm)	Specific flow (pers/s)
1	155	10	135	1,76
2	200	10	180	2,34
3	150	10	130	1,69
4	120	10	100	1,30
5	220	10	200	2,60
6	250	10	230	2,99
7	155	10	135	1,76

Table 12: Values for calculation specific flow-evacuation pathways (based on (Gwynne & Rosenbaum, pp. 2124-2128))

5.3.1.5. Cognitive model

The cognitive model describes the pre-movement time and the delay at the assembly point. The pre-movement time describes the delay of the employees before they start performing evacuation actions. Firstly, the employees within the building are split up in two different groups. The first group contains employees that can see the fire itself or the smoke it creates. Due to the placement of the fire near the welding cabin in hall 2, all employees present in this department are part of this first group. The employee that notices the fire and performs fire extinguishing and alarming actions is, therefore, also included with this group. As illustrated in the stakeholder analysis (section 3.2.2), this person will warn their immediate supervisor (team leader from hall 2) first. The pre-movement time for this first group is equal to 3 minutes (CFPA Europe, 2009). The second group includes all employees that are not able to see the fire or the smoke it creates. This group, therefore, includes both employees in the production facility and in the administration building. Employees that are present in the first-floor canteen or the meeting room are also included in this second group. The pre-movement time of this second group is dependent on the time it takes the person that performs the manual fire alarm to reach each department. The employees in this group are, therefore, assumed to start evacuating the building 3 minutes after they are alarmed. This time is added to account for the time it takes employees to stop with their previous actions. This includes putting the equipment they are using down and stopping the machine they are operating. Persons in the administration building and the production facility that are not present in the general space (e.g., they are on the toilet or in the changing rooms) will not be alarmed by the manual fire alarm. The responsible member of the evacuation team will facilitate their evacuation from the building. Lastly, the production manager is present within his own office. This office is indicated with the red circle on Figure 41. Since this office can only be entered through an external door, the production manager is assumed to be warned by the team leader responsible for hall 2.

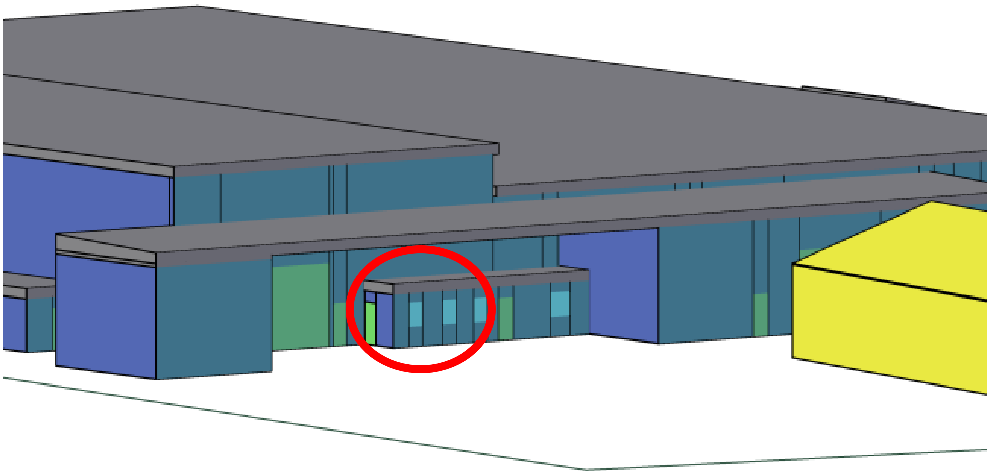


Figure 41: Placement office production manager-SE view (author's model)

The employees are stated to assemble at the evacuation assembly point. This assembly point is indicated with the red shape on Figure 42. Since there are only six newly hired employees, it is assumed that most employees know how to reach this assembly point since it is indicated with a visible sign in the parking lot. All employees cross this parking lot before entering the building itself. Additionally, most of the employees in both the administration building and the production facility are familiar with their environment, they will, therefore, choose an evacuation route based on their familiarity with the layout of the building (section 4.2.2 and 4.2.2.2). Newly hired employees are assumed to follow their co-workers. Due to the placement of the assembly point, employees from the production facility are assumed to prefer the emergency doors on the eastern side of the building. This assumption is made since the employees must follow the path indicated by the black arrow (Figure 42) if they exit the building from the western side. Additionally, employees are assumed to prefer using visible emergency doors with emergency signs (drawing 3.01 and 3.02, 12. Drawing folder, p. 6-7). Emergency doors at the changing rooms are, therefore, only used by employees that were already present within these areas at the time of the fire event. Any employees present on the first floor will be using the internal staircase instead of the external staircase to reach the assembly point. This assumption is made since they use this internal staircase to reach the canteen everyday. They are, therefore, familiar with this evacuation route.

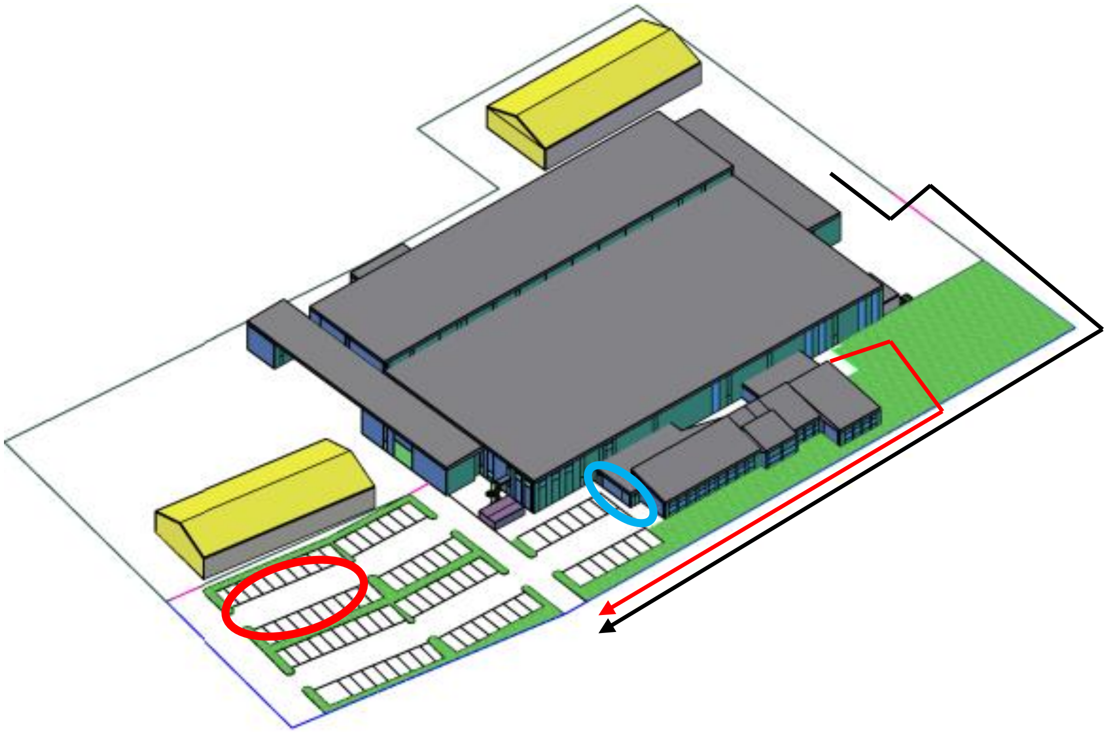


Figure 42: Indication of the assembly point-NE view (author's model)

Employees inside the administration building will use the emergency doors in this part of the building to evacuate. Due to their familiarity with the main entrance and the building layout, these employees will prefer the emergency doors indicated with the blue shape on Figure 42 over the emergency doors found on the opposite side of the building. The evacuation route for these doors is indicated with the red arrow (Figure 42).

At the assembly point, the production manager is responsible for performing the roll call. Due to this person's position within the company, it is assumed that they know the different people that are present inside the building. Additionally, the organization of the employees according to their respective departments will give a clear overview of all employees that are present at the assembly point. The time duration of the performance of the roll call is, therefore, optimized. The roll call will be finalized directly after the last person reaches the assembly point.

5.2.3. Adaptations to the input for different scenarios (scenario 2-10)

The simulation of scenario 2-10 is performed by adapting the input from the base-case (scenario 1, section 5.3.1). The part of the simulation that is adapted for each scenario is indicated in Table 13. More information regarding the specific changes made for each scenario listed below (Table 13) can be found in the appendix (11. Appendix, section 11.4.).

Scenario	Spatial model	Occupancy model & Demographics	Physical model	Interaction model	Cognitive model	Hazardous condition
2					X	
3				X		
4	X			X		
5				X	X	
6						X
7	X					
8	X					
9				X	X	

10				X		X

Table 13: Adaptations to the base-case (author's model)

6. Discussion

6.1. Categorization of the human errors based on the system identification

6.1.1. Procedures regarding fire contingency plans

To investigate the possible causes of human errors, the cycle illustrating the company's procedures regarding the development, distribution and implementation of fire contingency plans was defined. This cycle is inserted in Figure 43. The cycle shows the different stakeholders that are involved with the different components regarding these procedures. Additionally, the cycle also includes the representation of the components that are included in accordance with the described sections of BR and/or ISO (section 3.1.3).

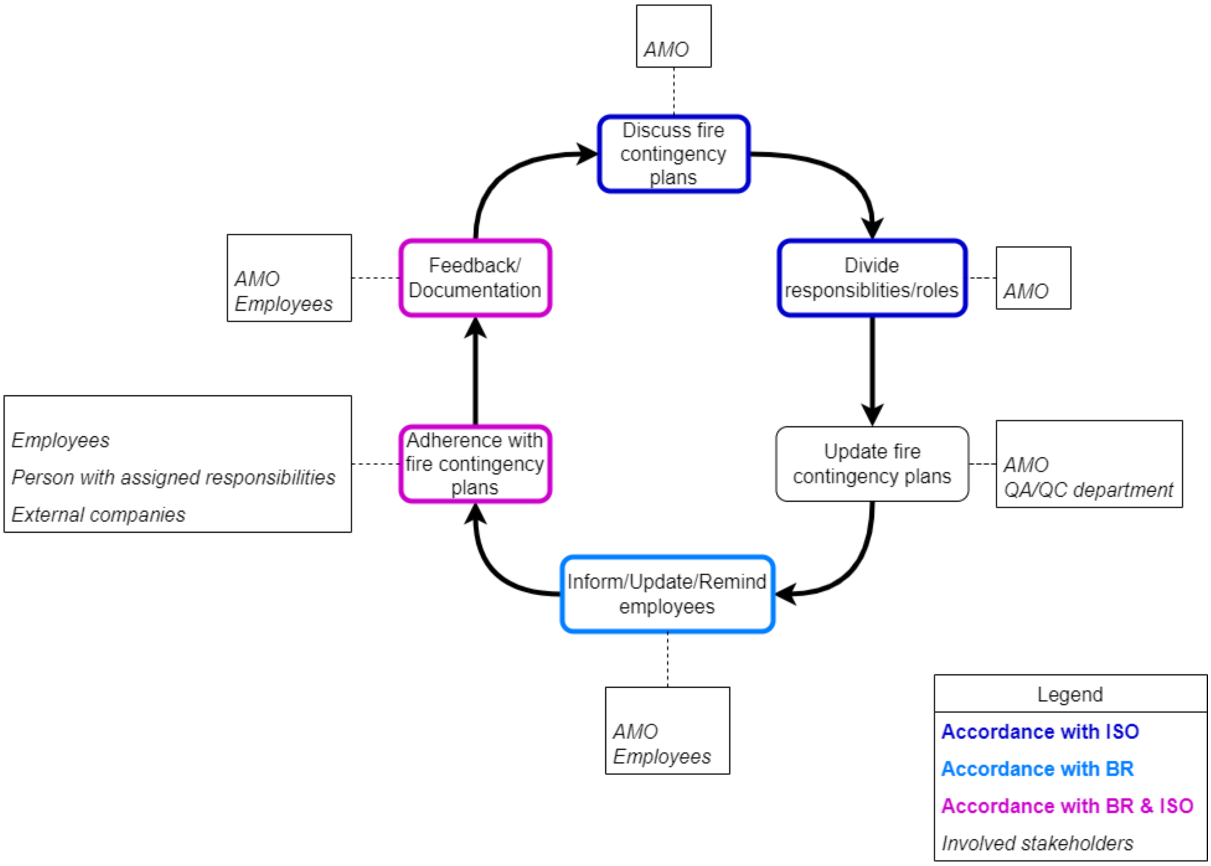


Figure 43: Cycle of fire contingency plans based on company procedures (author's model)

Firstly, the AMO organizes a meeting to discuss the fire contingency plans. Based on this discussion the AMO decides how to divide the roles and responsibilities regarding these plans between all the companies' employees, including both employees that are members of the AMO and employees that are not. Both the discussion of the fire contingency plans, and the division of roles and responsibilities is described in ISO 45001. This description details the foundation of the AMO and its tasks. The finalized decision regarding this division of roles and responsibilities, and regarding the changes that must be implemented within the fire contingency plans are communicated by the AMO with the QA department. This department is tasked with updating these plans and including the correct role and responsibility distribution. The AMO, however, must ensure that this task is completed before sharing and communicating the adapted plans with the employees. All employees inside the company are briefed regarding the safety instructions and the emergency floor plans. Additionally, all employees with assigned roles and/or responsibilities receive a detailed description regarding their part in the safety instructions. In accordance with BR18, this component within the cycle of fire contingency plans must be performed for each newly hired employee and at least once a year for all employees in the company. After informing and updating all employees regarding the relevant fire contingency plans, the adherence with these plans is executed. This adherence is divided in components that are performed before a fire event and components that are performed during a fire event. These components are illustrated in Figure 44. The DKV plan describes requirements regarding the maintenance of fire safety equipment and the inspection of the building's inventory and organization. The maintenance of fire safety equipment is done through the performance of internal services and external inspections at pre-determined intervals. These intervals are described in BR18. The internal services are performed by an assigned person. This person must perform them in accordance with the decided time intervals. They are also required to log all services and provide the necessary documentation regarding the completion of these services. The inspection of the building's inventory and organization, furthermore, includes the performance of an external fire inspection and monthly internal inspections for the compliance with the 5S organization system. The fire inspection is completed by the fire brigade in accordance with the Emergency Preparedness act. The monthly internal inspections are performed by the production manager and the supervisor responsible for the inspected department. The production manager is, therefore, responsible for adhering with the company's procedures. These procedures are included to comply with the requirements set by BR18 regarding the building inventory and organization. Since certain components within the DKV plan are performed by external companies, a person inside the company is responsible for the communication with the fire brigade regarding fire inspections and the hired certified companies regarding the inspection of fire safety equipment. Additionally, this person must log the inspection reports in the designated program. The compliance with the components described in the DKV plan has an impact on the execution of the evacuation process as described in the safety instructions and supported by the emergency floor plans. This evacuation process is performed during fire events or planned fire evacuation exercises. The components within this process are the performance of fire extinguishing actions, the completion of the manual fire alarm, the inclusion of the evacuation team and the wayfinding behaviour experienced while using an evacuation route. These components and the connected components described in the DKV plan are illustrated on Figure 44. Figure 44 also shows the components from the safety instructions and emergency floor plans in connection with their effect on each other. For example, since the fire alarm is performed manually, the time at which different departments are alarmed is affected by the spread of the fire and the followed evacuation route.

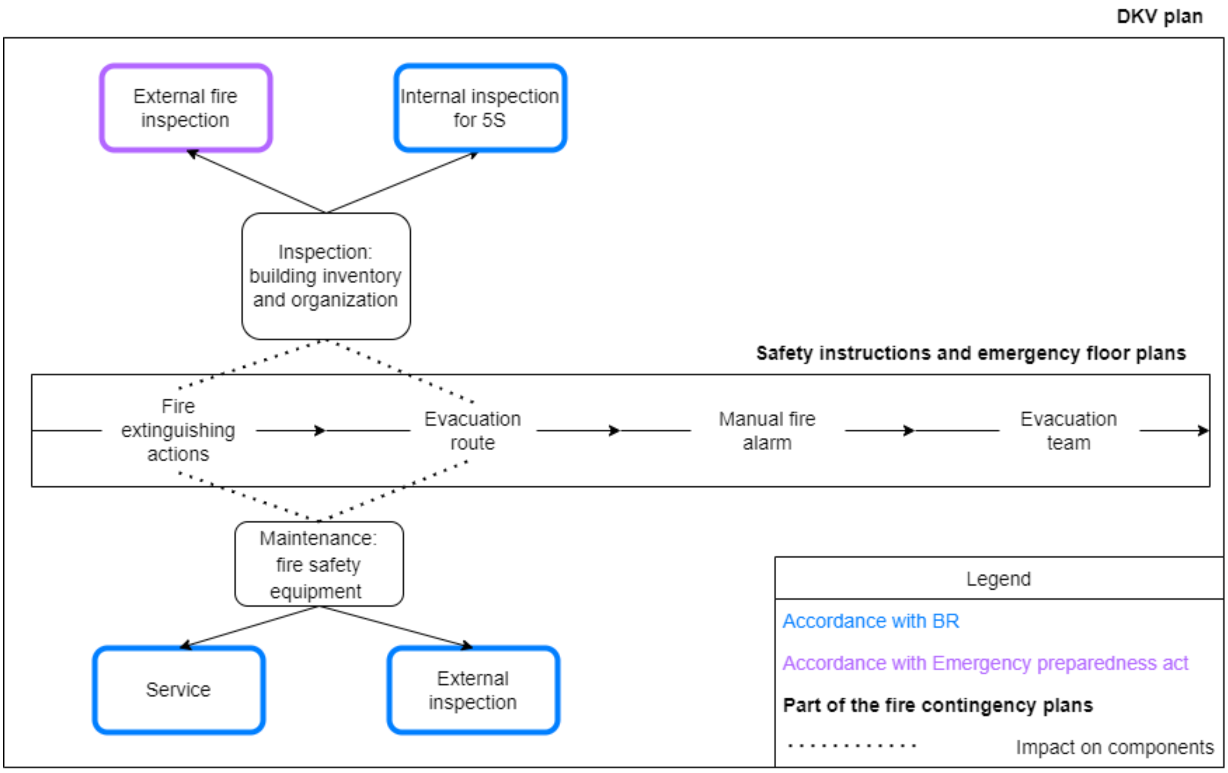


Figure 44: Adherence with fire contingency plans (author's model)

After the compliance with the DKV plan (before the fire event) and the completion of the evacuation process (during the fire event), the actions and events are documented. Additionally, feedback from the employees is provided to their representant within the AMO (section 3.2.1). The necessity of documenting these actions and events is described in both BR18 and ISO 45001. The AMO is responsible for compiling the documentation and for ensuring that the required documentation is available. Based on the provided documentation and feedback, the fire contingency plans are discussed by the AMO and adapted where needed.

6.1.2. Categorization of human errors

The various human errors that can be identified in the investigated scenarios (scenario 2-10, section 5.2) are categorized in accordance with (Glendon, Clarke, & McKenna, 2006). This categorization is performed dependent on the occurrence of the error in relation to the fire event. The perpetrator of the error is, therefore, found within the stakeholder structure described in the stakeholder analysis (section 3.2.1 and 3.2.2).

The human errors that impact the evacuation process in the different scenarios are found in accordance with the above-described procedures regarding fire contingency plans (6.1.1). The different scenarios and the categorized human errors affecting them are indicated in Table 14. The table also indicates the direct level of impact of these human errors.

Scenario	Human error				Direct level of impact	
	Violation	Mistake	Lapse	Slip	DKV plans	Fire contingency plans
2	X	X				X
3	X		X	X	X	X
4	X		X	X	X	X
5	X	X	X			X
6	X		X	X	X	

7	X	X	X	X	X	X
8	X	X	X		X	X
9	X	X				X
10	X		X	X	X	X

Table 14 : Categorization of human errors for each scenario (author's model)

The adherence with safety instructions and emergency floor plans relies on the employee's knowledge of the safety instructions and the emergency floor plans. The last update of these plans and instructions was, however, made in 2018. Additionally, all employees that are not directly involved with the AMO are not reminded of these plans since the time of their initial employment. This failure to update the plans and instructions, and to inform the employees of them is an intended action where the procedures described by the company are not complied with. This human error is, therefore, categorized as a violation. This violation means that during a fire event employees will experience a situation where they make mistakes due to the adherence with bad rules. This human error is caused by the compliance with the actions described in the safety instructions and emergency floor plans that were current at the time of the employee's initial employment in the company. Due to changes made to the fire management system, these actions are not necessarily adaptable to the current situation in the company regarding fire events. Additionally, the failure to inform the employees regarding the safety instructions can lead to memory failures where employees will forget to perform certain actions described in these instructions. These memory failures are categorized as a lapse.

The compliance with maintenance and organizational procedures is reliant on the adherence with these procedures by the responsible employees. The failure to comply with the requirements written in BR18 can be caused by human errors defined as violations, lapses and slips. The violation can be described as the failure to provide a DKV plan in accordance with BR18. The lack of a DKV plan can cause a failure to plan the maintenance and inspection. Additionally, the described procedures regarding the internal servicing of fire safety equipment and the implementation of the 5S organizational system are not completed within the time intervals described in the procedures. For example, the last inspection round regarding the implementation of the 5S system was performed in March 2021. The performance of these inspection rounds is described to be completed monthly within the procedures provided by the company. This failure to comply with the procedures can also be defined as a violation. Finally, the actions required to complete the internal inspection rounds and servicing of the fire safety equipment can be affected by memory and/or attentional failure. Both failures are unintended actions that cause human errors categorized as slips or lapses for the responsible employee. This employee will, therefore, fail to complete certain actions due to inattentiveness to the task at hand or due to a failure to remember the requirements and/or time intervals. A practical example of the defined human errors is a situation where the inspection rounds are not performed. The person responsible for performing the inspection rounds might not follow the required procedures since they do not think that this task should be prioritized above other tasks (violation). This could be caused by a lack of time. This person might, however, have simply forgotten to perform the inspection (lapse) or to document the more recently performed inspections in the shared documentation system (slip).

6.2. Discussion of simulation results

This part of the case-study focuses on the outcome of the performed simulations individually. First, the evacuation process for these different scenarios is discussed based on the occupancy density, the usage and the mean required safe egress time (RSET). Afterwards, the discussion will focus on the hazardous condition and its influence on the evacuation process. There are five different cases for this hazardous condition. These cases are included for the available safe egress time (ASET) calculation of the various scenarios. The different cases indicated for each scenario are shown in Table 15.

		Evacuation process RSET (scenario)									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Hazardous condition (case)	**1**										X
	2	X	X	X	X	X				X	
	3								X		
	4							X			
	5						X				

Table 15: ASET scenarios-hazardous conditions for each scenario (author's model)

Additionally, each case is defined by the different operational conditions that affect the hazardous condition. These operational conditions are indicated in Table 16.

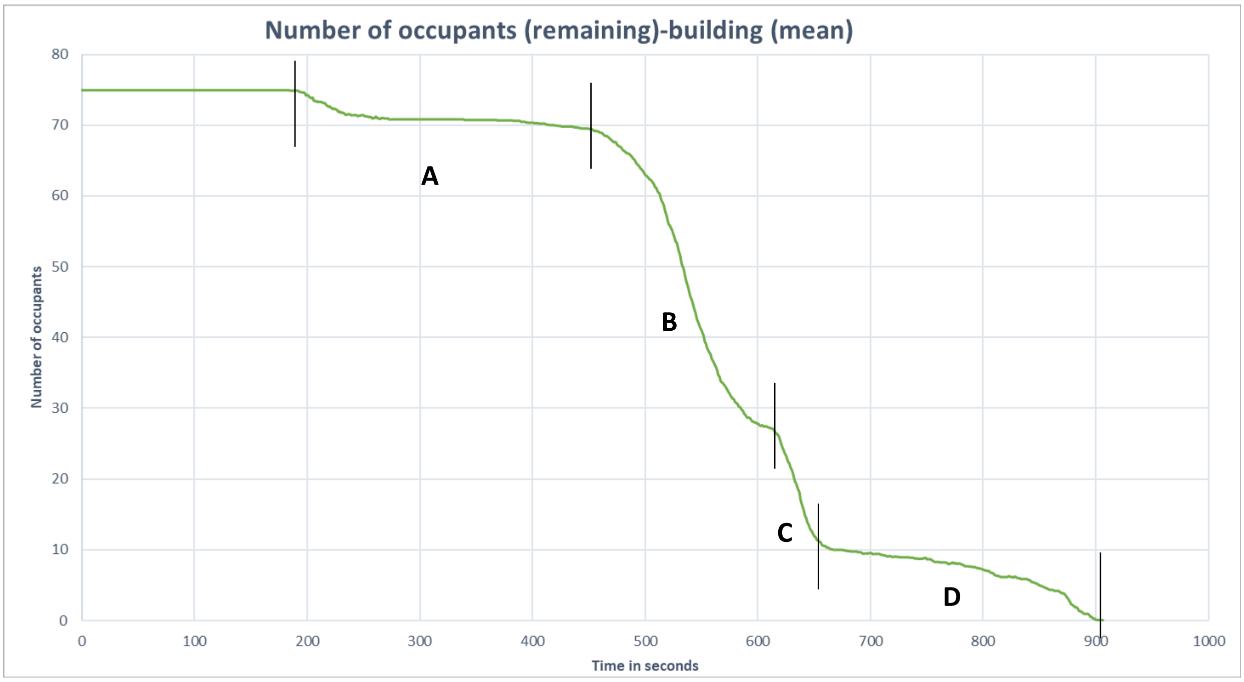
		Fire extinguishing actions	**Closed doors and windows**	**Operational fire doors**	**Successful risk minimization system**
Case	**1**		X	X	X
	2	X	X	X	X
	3	X		X	X
	4	X	X		X
	5	X	X	X	

Table 16: Conditions affecting the hazardous condition (author's model)

6.2.1. Evacuation process (based on RSET)

6.2.1.1. Base case (scenario 1)

The base case (scenario 1) describes a scenario where all employees have sufficient knowledge regarding the safety instructions and the emergency floor plans to successfully complete the evacuation process. This scenario does, therefore, not include the effect of human errors. The scenario does illustrate the safety instructions and floor plans and their effect on the evacuation process. Firstly, the alarming of the employees that are not able to detect the fire event is performed using a manual fire alarm. This fire alarm is performed by an employee that informs all departments individually. Employees in different departments will, therefore, be alarmed at different points in time as illustrated on Figure 45. This diagram shows the mean RSET to illustrate the evacuation process from the building dependent on the employee's position within the building.



Legend

A: employees that notice the fire event (incl. production manager)

B: employees in production (no vision of fire event)

C: employees in administration

D: employees alarmed by evacuation team (excl. production manager)

Figure 45: Mean RSET-scenario 1 (author's model)

The delay in alarming actions (Figure 45) is dependent on the reaction time, the walking speed, and the knowledge regarding the building of the employee that performs the action. This impacts the employees in the administration building the most since the person performing the fire alarm reaches this part of the building last. For example, employees in the prefab and cutting department are alarmed after 236 seconds whereas employees in the administration building are alarmed after 370 seconds. Additionally, some employees will not be alarmed by this manual fire alarm. These employees are occupying rooms that are separated from the main areas. These rooms are indicated with the green shapes on Figure 46. Due to these employees' placement, they are not able to notice the fire event or the manual alarm. They, therefore, rely on the evacuation team to be alarmed of the fire event. This also affects the production manager since their office is placed outside of the main production facility without an internal connecting door. The placement of the production manager's office is indicated with the arrow on Figure 46. Since the evacuation teams are positioned in different departments within the company, their initial delay is dependent on the manual fire alarm. The alarming of the production manager is, however, prioritized since this person is responsible for organizing and leading the process at the evacuation assembly point. Lastly, occupants prefer using doors on the east side of the building as described in section 5.3.1.5. This is indicated with the blue pathways in Figure 46.

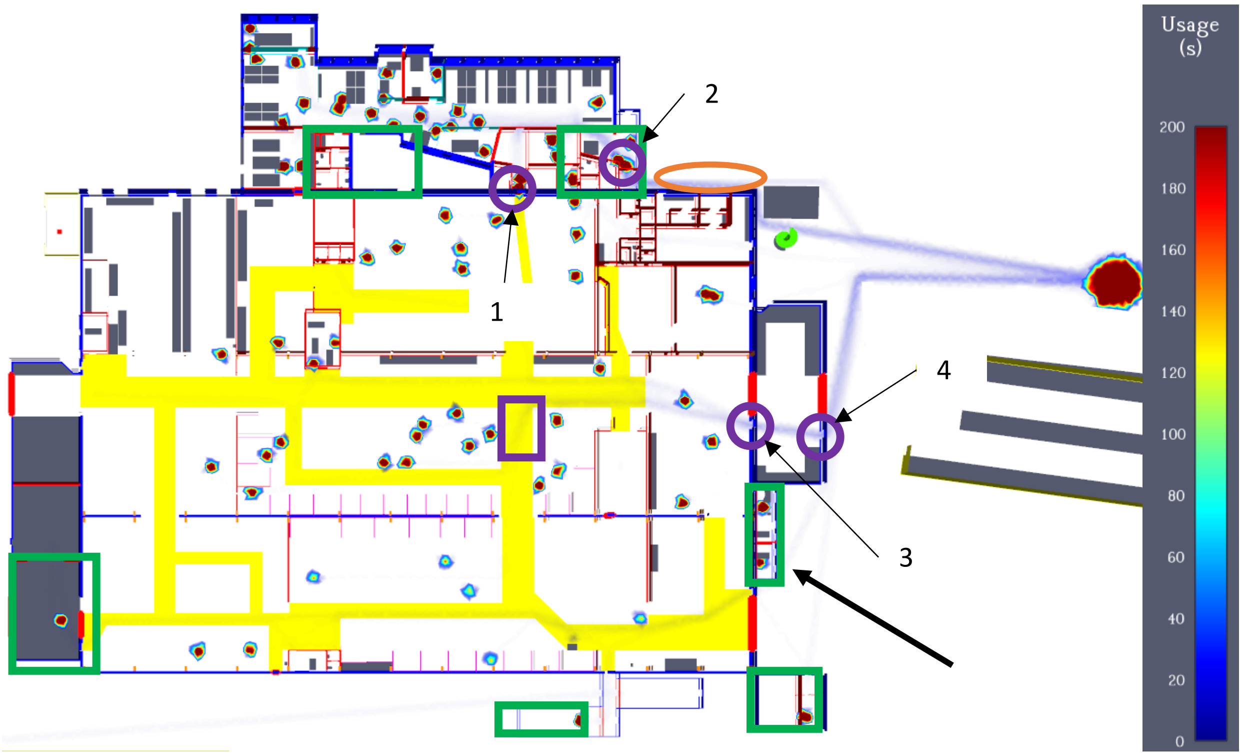


Figure 46: Accumulated occupancy-scenario 1 (author's model, 1-5)

This door preference causes queuing in certain doorways. These doorways are indicated with the purple circles on Figure 46. The queueing behaviour at the doorway leading to the administration building (doorway 1) is caused by the positioning of occupants near the doorway. This positioning slows down the movement of both the person performing the manual alarm and employees from the bellow department. The employees from this department prefer to use the emergency door in the administration building (doorway 2) instead of the door found near the gates in the production facility (doorway 3 and 4). The described queuing behaviour is illustrated using the occupancy density in Figure 47.

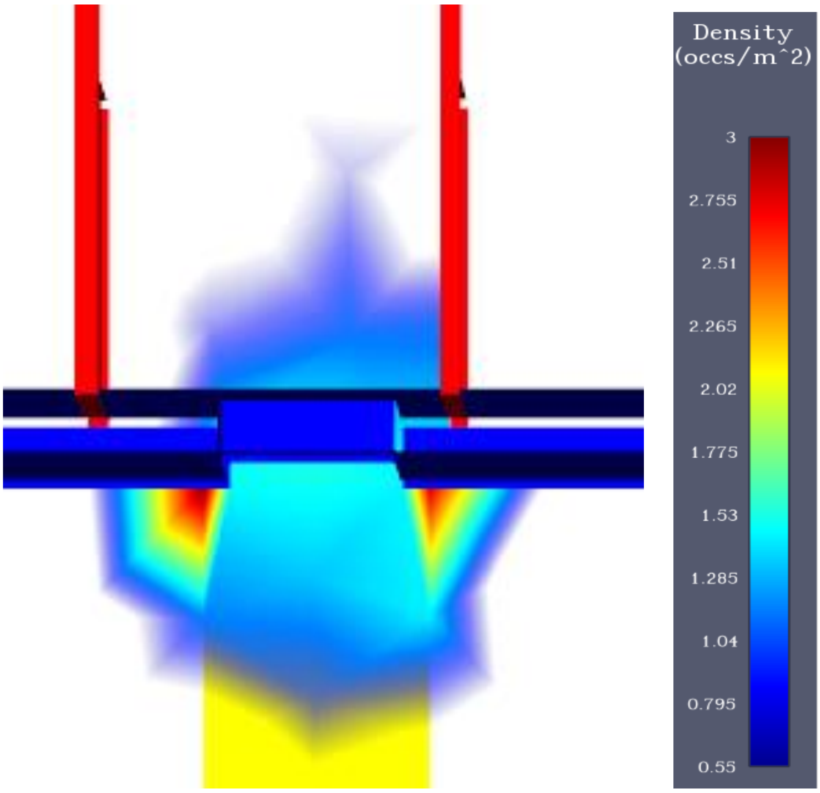


Figure 47: Doorway 1-occupancy density (author's model, 1-5)

The evacuation door in the administration building (doorway 2) also indicates queuing behaviour. The cause of this behaviour is the door preference of the employees in the administration building. These employees prefer to use emergency doors that lead directly to the parking lot and the evacuation assembly point. The queuing behaviour indicated by the occupancy density is shown in Figure 48.

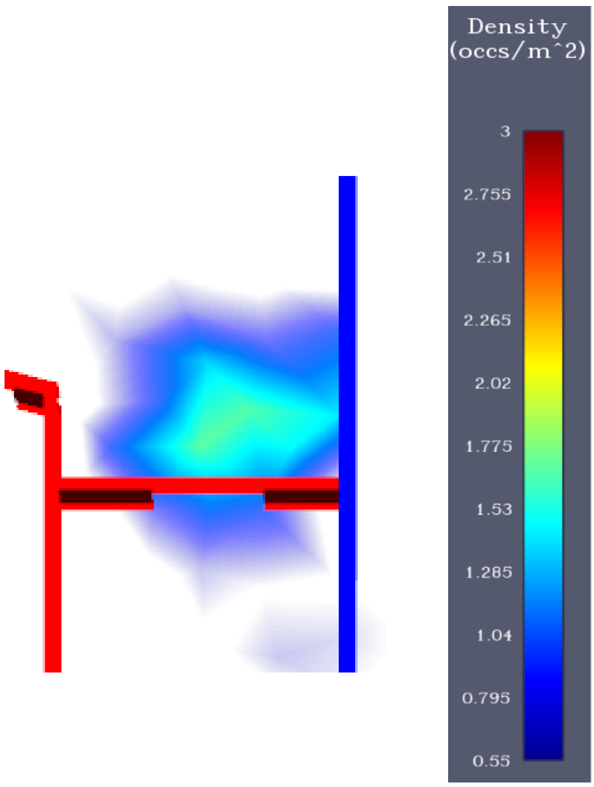


Figure 48: Doorway 2-occupancy density (author's model, 1-5)

Additionally, queuing behaviour is shown at the emergency doors in the production facility as illustrated in Figure 49. These doors are preferred by most employees found in the main area of the production facility. This preference is the main cause of this queuing behaviour.

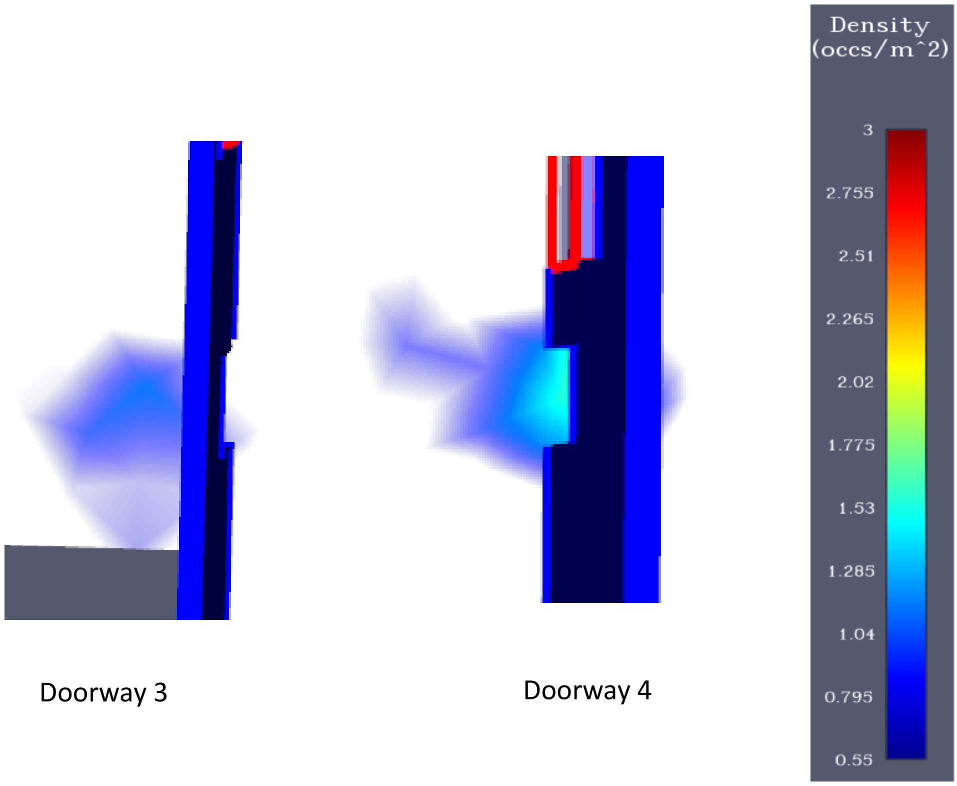


Figure 49: Doorway 3 & 4-occupancy density (author's model, 1-1 & 1-3)

The evacuation paths in the production facility are used by all employees positioned within the nearby areas. As illustrated by the instantaneous usage (Figure 50), several employees are crossing each other or passing next to each other on these evacuation paths. In these cases, employees need the entire width of these paths to avoid queuing. This specific situation is illustrated with the purple rectangle on Figure 46.

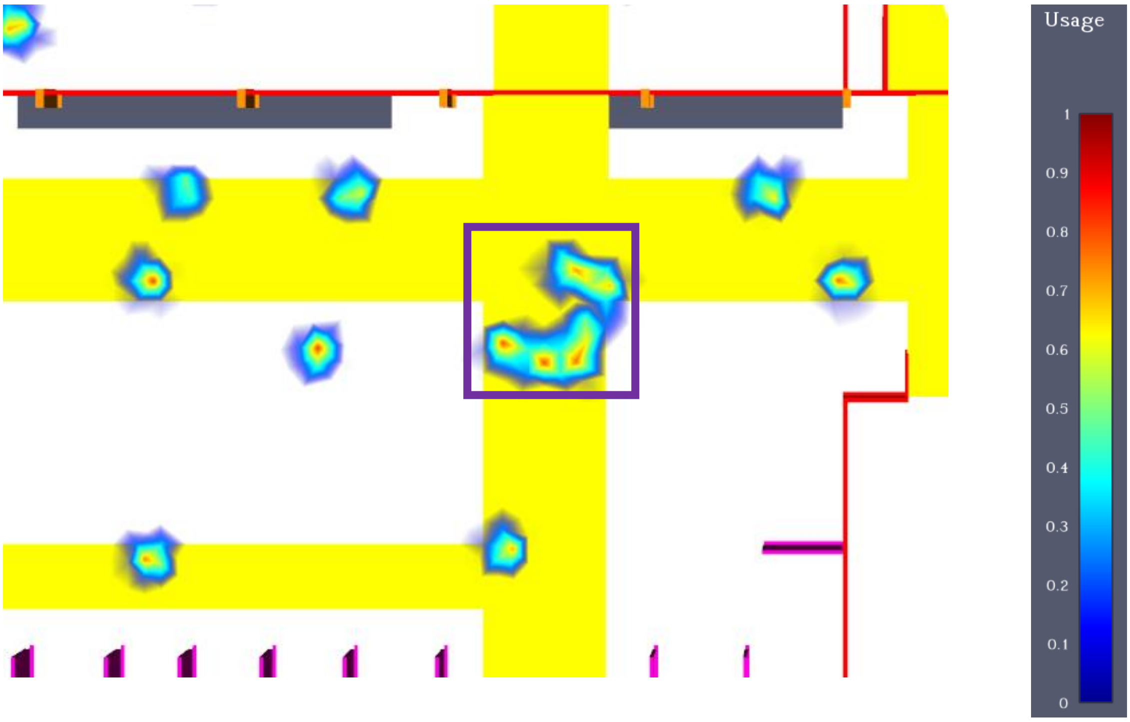


Figure 50: Instantaneous usage-scenario 1 (author's model, 1-9)

Finally, employees leaving the building through the administration use the pathway next to the production facility to reach the evacuation assembly point. This pathway is indicated with the orange shape on Figure 46. Due to the placement of bushes, parking spaces and the bicycle shed adjacent to this pathway, an increased occupancy density is observed. This leads to queuing behaviour for these employees. The increased occupancy density is illustrated on Figure 51.

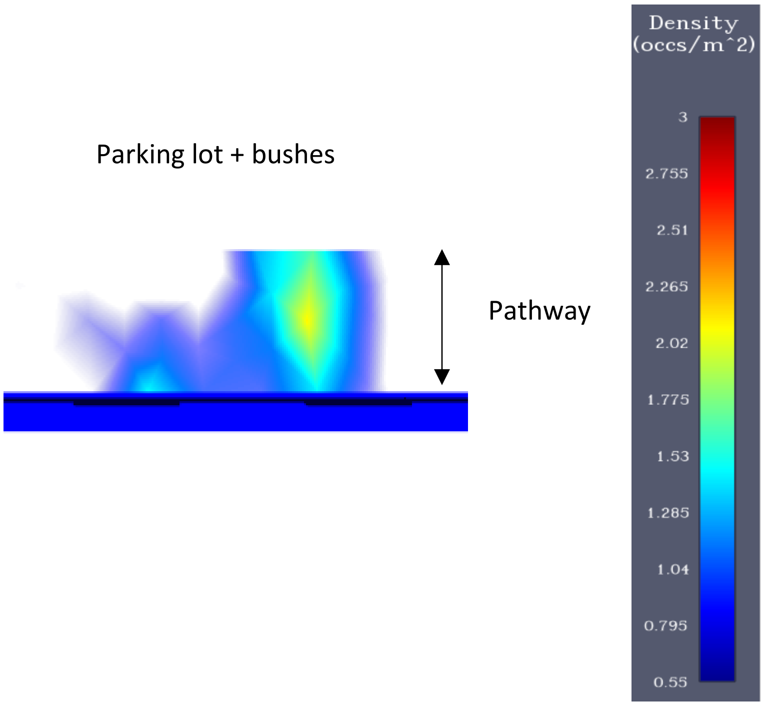


Figure 51: Exterior pathway-occupancy density (author's model, 1-9)

6.2.1.2. *Component: emergency signs (scenario 2)*

The impact of emergency signs on the evacuation process is illustrated by the door preference of the employees in both the administration building and the production facility. Employees in the QA/QC, IT and finance department are simulated to use the doorway indicated with the orange shape on Figure 52. These employees are, therefore, following a different path than in scenario 1 as indicated by the arrow (Figure 52). Additionally, employees in the production facility prefer using the gates instead of the doorways. These gates are operated manually by lifting the gate or by using a button. These gates are indicated with the green shapes on Figure 52.

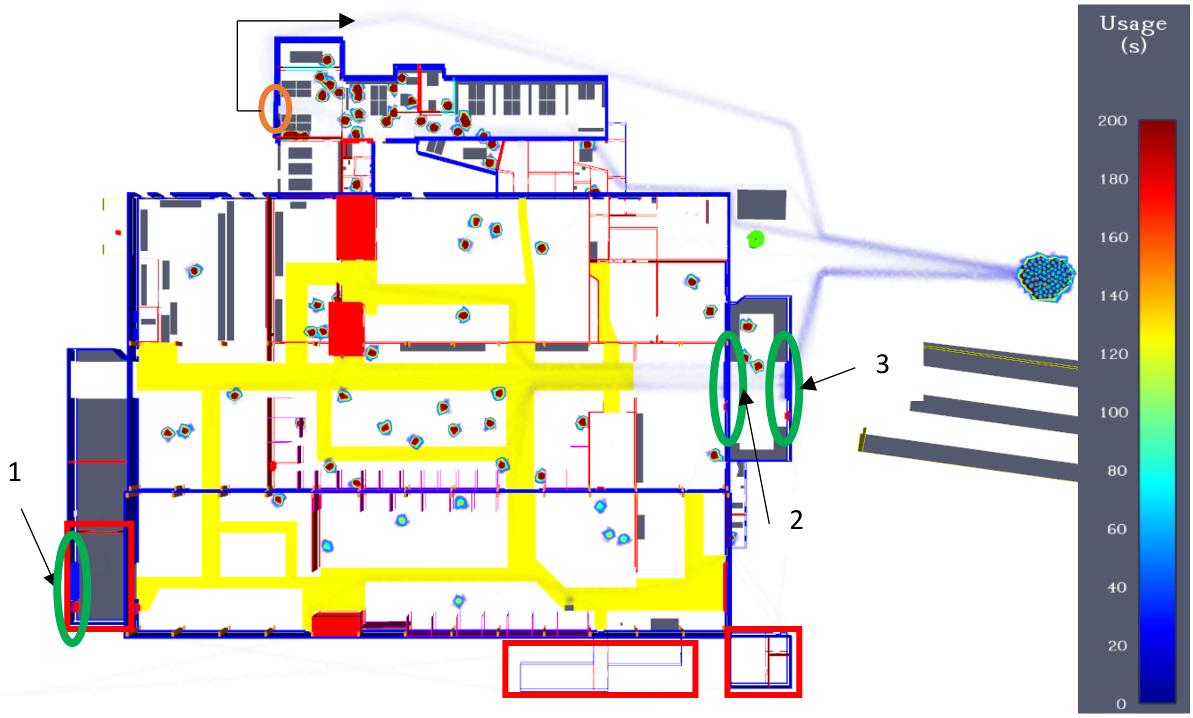


Figure 52: Accumulated usage-scenario 2 (author's model, 2-1)

Due to the door preference of the employees in the mentioned departments of the administration building, queuing behaviour will be experienced at the indicated doorway (orange oval, Figure 52). This behaviour is illustrated by the occupancy density (Figure 53). Since these employees prefer the indicated doorway, the queuing behaviour at the doorway described in scenario 1 (doorway 1, Figure 47) is diminished. This is also illustrated in Figure 53.

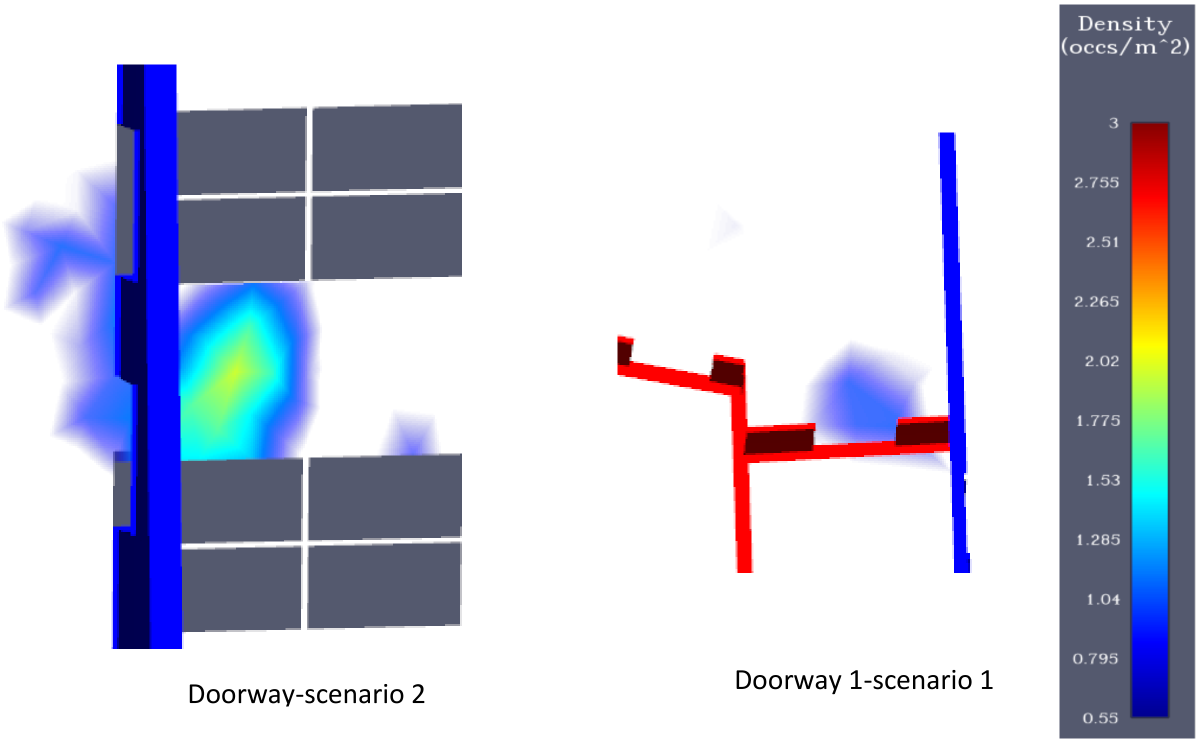


Figure 53: Doorway administration building-occupancy density (author's model, 2-1)

The gates that are used by the employees positioned within the production facility are operated by pressing a button or by hoisting the gate up. The employees, therefore, experience a delay as they must wait for the gate to open. This waiting behaviour is experienced at all the gates indicated in Figure 52. Gates 2 and 3 are used by most of the employees in the production facility. The waiting behaviour at these gates is illustrated using the instantaneous usage (Figure 54).

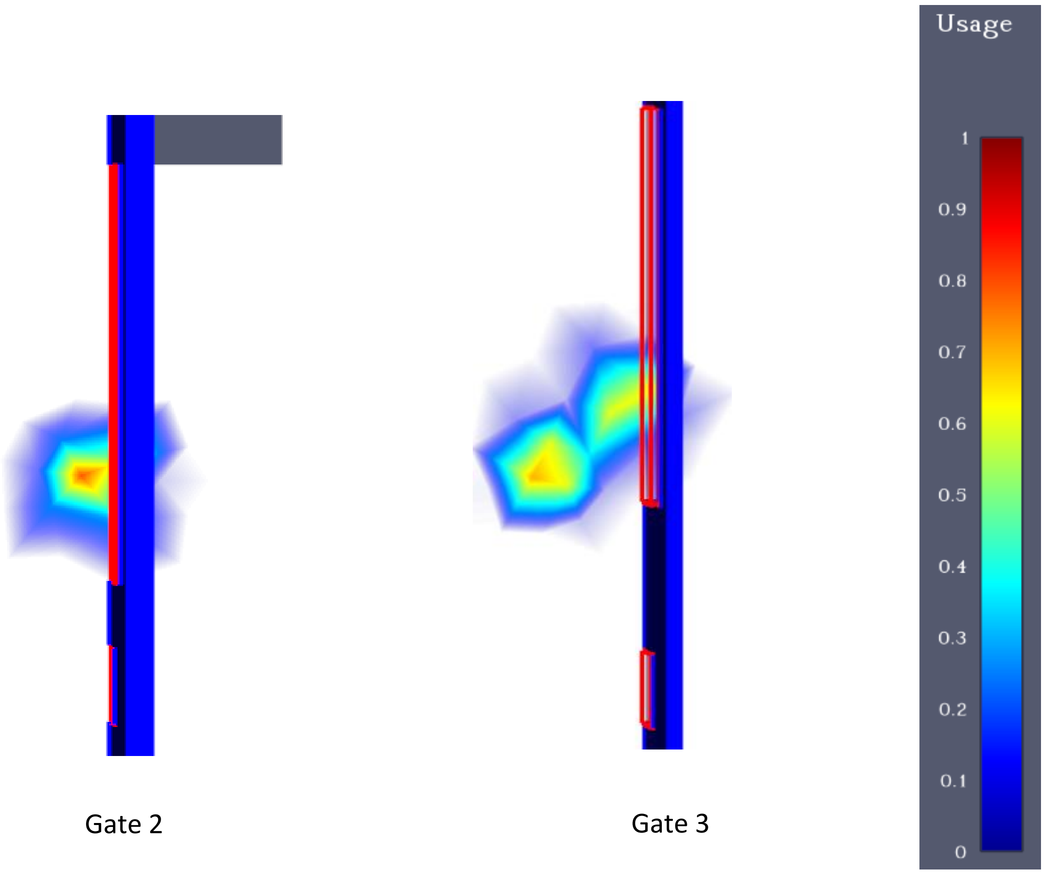


Figure 54: Gate 2 & 3-instantaneous usage (author's model, 2-5)

Additionally, gate 1 is used by the evacuation team and any employees that are positioned in the connected storage room (storage room 4-drawing 3.01, 12. Drawing folder, p. 6). The waiting behaviour at this gate is illustrated in Figure 55.

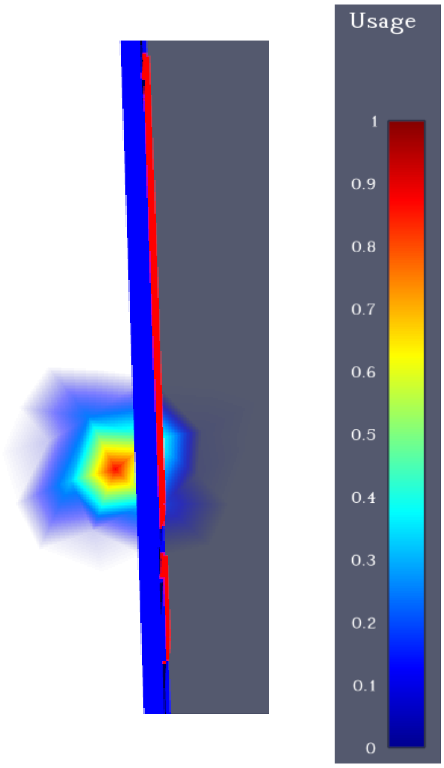
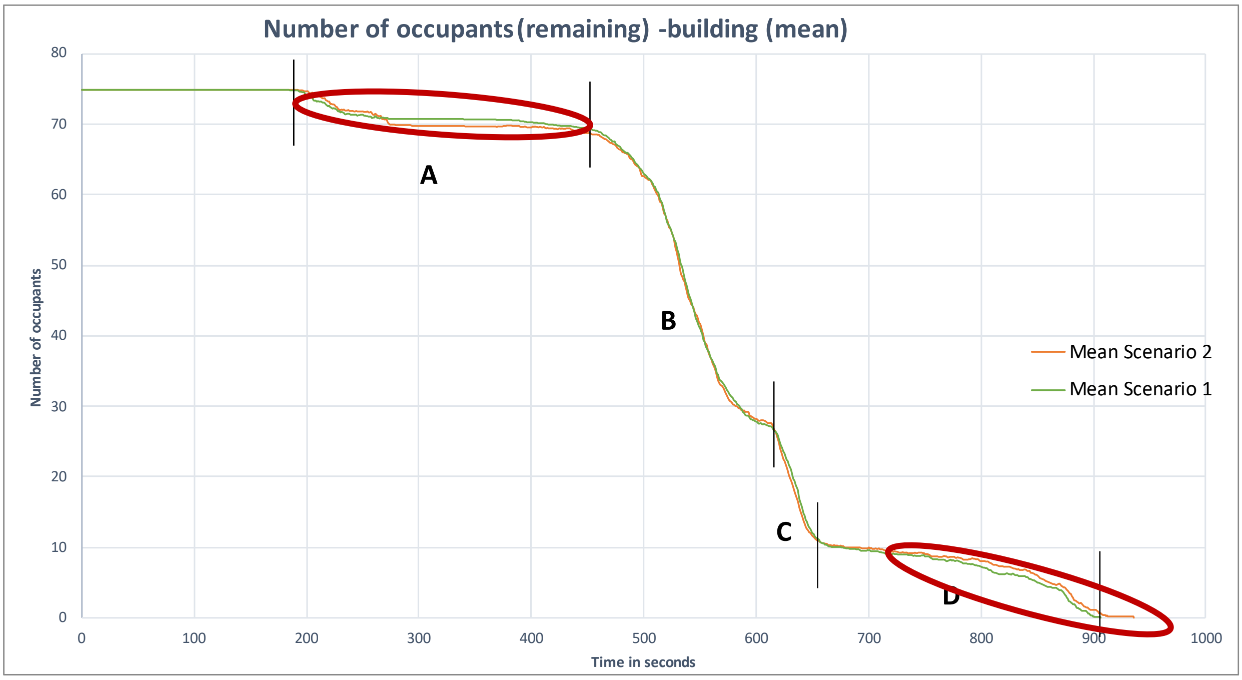


Figure 55: Gate 1-instantaneous usage (author's model, 2-1)

The effect of the waiting behaviour and the adapted preference of gates and doors on the mean RSET is illustrated in Figure 56. The impact of these adaptions is highlighted with the red shapes. The first red shape in area A shows the effect of the gate preference for employees in the production facility. The initial waiting behaviour is indicated with a higher number of occupants that are still in the building compared to scenario 1 at the beginning of area A. The gates are, however, modelled to stay open after their opening mechanism is initially activated. The evacuation process of employees in the production facility that are alarmed by the fire alarm is, therefore, not affected by additional waiting behaviour. Lastly, the red shape in area D illustrates the impact of the waiting behaviour on the employees that are alarmed by the evacuation team. This waiting behaviour impacts the initial delay of employees positioned in the rooms indicated with the red rectangles on Figure 52.



Legend

A: employees that notice the fire event (incl. production manager)

B: employees in production (no vision of fire event)

C: employees in administration

D: employees alarmed by evacuation team (excl. production manager)

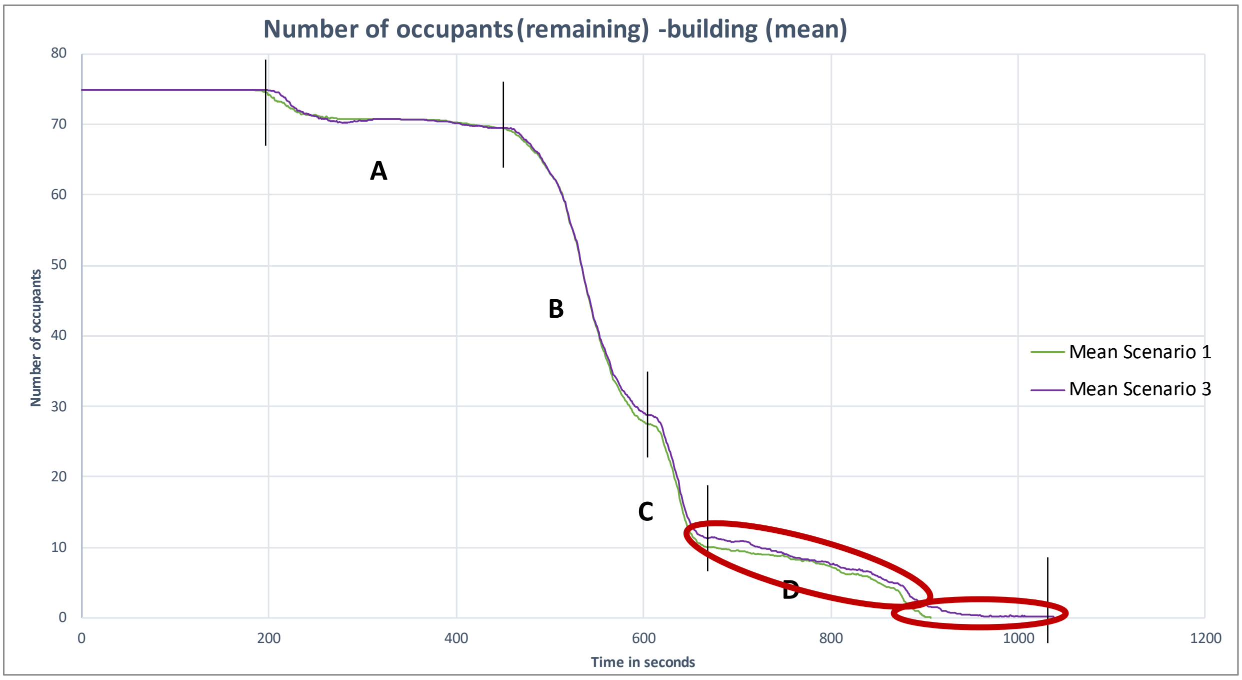
Figure 56: Comparison mean RSET-scenario 1 vs 2 (author's model)

6.2.1.3. Component: emergency doors (scenario 3)

The effect of failing emergency doors on the simulation is created through blocked emergency doors. The doors that were blocked based on the description of this fire evacuation scenario (section 5.2.2.2) affect the route taken by the person from the evacuation team in hall 1. This person is forced to use alternative doors to reach the office from the production manager and storage room 4 (drawing 3.01, 12. Drawing folder, p. 6). The paths to both rooms are indicated with the arrows on Figure 57. Due to these alternative paths the travelling time between the different rooms is longer. This affects the initial delay of all employees in separated areas that must be alarmed by this person. The areas that are affected by this longer travelling time are indicated with the green shapes on Figure 57.

Figure 57: Accumulated usage-scenario 3 (author's model, 3-5)

The impact of the adapted route taken by the person from the evacuation team on the mean RSET is illustrated on Figure 58. The red shapes show that the employees that are alarmed by this evacuation team stay in the building for a longer time compared to the base case scenario.



Legend

A: employees that notice the fire event (incl. production manager)

B: employees in production (no vision of fire event)

C: employees in administration

D: employees alarmed by evacuation team (excl. production manager)

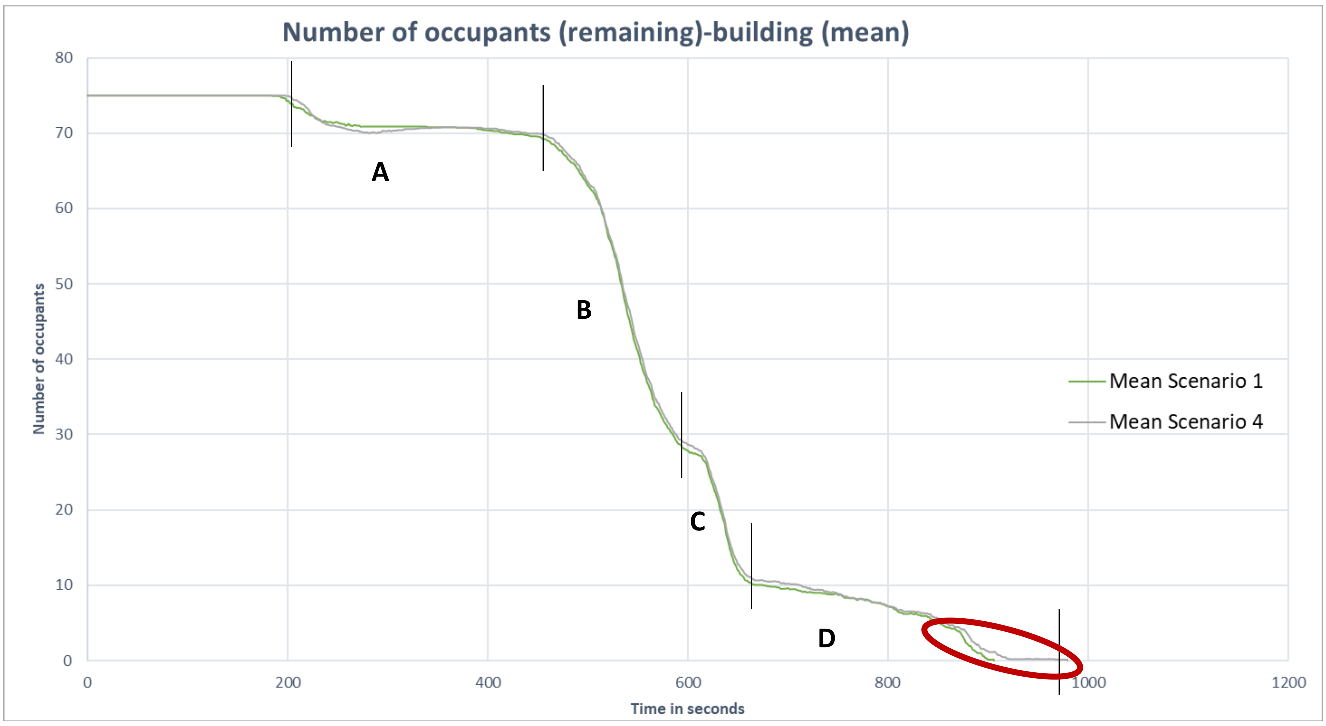
Figure 58: Comparison mean RSET-scenario 1 vs 3 (author's model)

6.2.1.4. *Component: evacuation paths (scenario 4)*

In accordance with the description of scenario 4 (section 5.2.2.3), several obstacles were placed on the evacuation pathways in the production facility. These obstacles are the pink rectangles shown on Figure 59.

Figure 59: Accumulated usage-scenario 4 (author's model, 4-1)

The obstacle indicated with the red oval blocks both the emergency door and the gate in that part of the production facility. This blockage impacts the route from the person that is tasked with alarming the production manager. The alternative path that this person takes is indicated with the arrow (Figure 59). This alternative route impacts the initial delay of employees in separated areas along this person's route. The red shape on Figure 60 illustrates the effect of this different initial delay caused by the alternative route of the person from the evacuation team on the RSET in comparison with the base case (scenario 1).



Legend

A: employees that notice the fire event (incl. production manager)

B: employees in production (no vision of fire event)

C: employees in administration

D: employees alarmed by evacuation team (excl. production manager)

Figure 60: Comparison mean RSET-scenario 1 vs 4 (author's model)

Additionally, obstacles placed alongside connecting pathways between departments impact the movement of employees passing by them. This is illustrated using the instantaneous usage of the area around the obstacle indicated with the green shape (Figure 59). This usage shows the movement of the employees throughout the evacuation process. Figure 61 shows that employees pass each other in the narrower pathway alongside the obstacle. This causes them to inevitably move closer to this obstacle. As shown on the pictures in section 5.2.2.3, the obstacle that was placed in this position during a visit to the production facility could be used for the storage of parts. Since the company uses sharp sheet metal for the formation of certain parts, this material could be placed on top of this obstacle. When employees pass close by this sharp sheet metal, they could get harmed. Between 01-2019 and 06-2019, three individual accidents caused by the sharp edges of sheet metal were recorded.

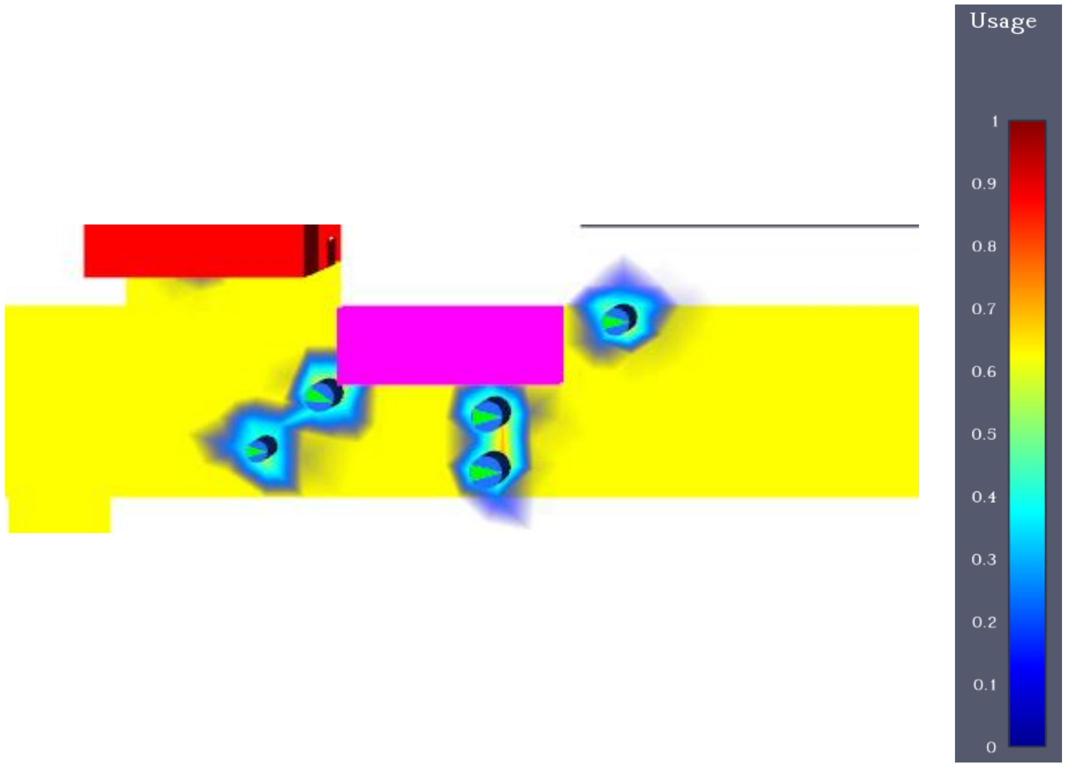


Figure 61: Obstacle-instantaneous usage (author's model, 4-6)

6.2.1.5. Component: evacuation team (scenario 5)

The evacuation team aids with the evacuation process. The effect of the evacuation teams on the evacuation process is illustrated by the time it takes employees in separated areas to escape the building. These employees rely on the alarming actions performed by the members of the evacuation team. When these members do not perform these actions, they will leave the building to gather at the evacuation assembly point without passing by the separated areas. Since the production manager is also reliant on the alarming actions from the evacuation team, this person will not be able to perform the roll call at the assembly point. This roll call is necessary to identify the missing employees. It must, therefore, be performed by a member of the AMO. However, if the roll call is not performed all members of the evacuation team must enter the building again to investigate all separated areas. The different areas that are searched by the members of the evacuation team are illustrated with the green shapes and the arrows on Figure 62.

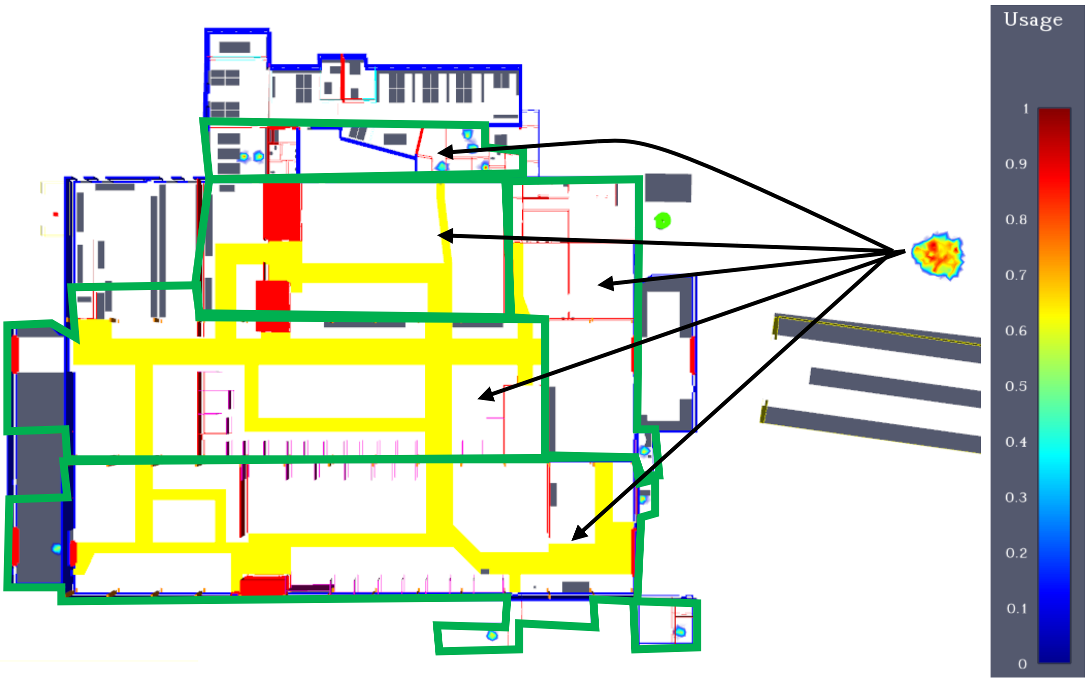
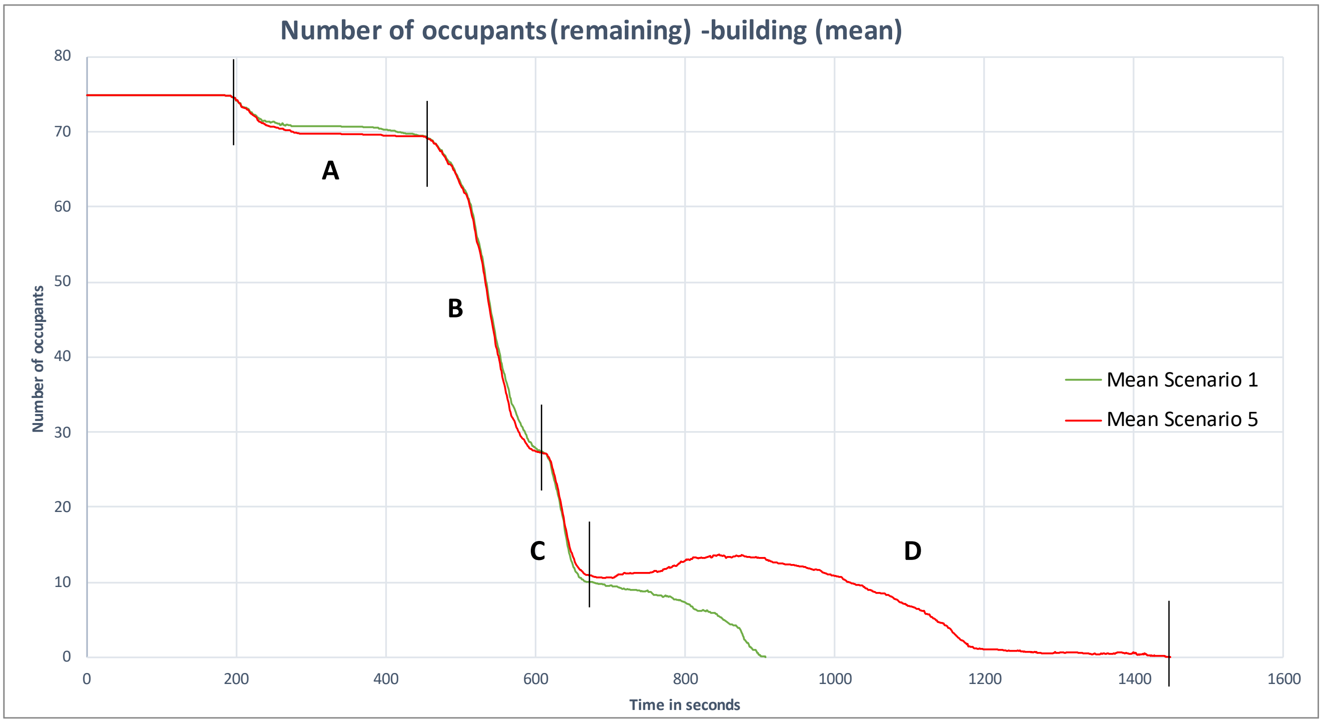


Figure 62: Instantaneous usage-scenario 5 (author's model, 5-5)

The impact of the failure to alarm the employees in the separated areas is illustrated on Figure 63. Area D shows the difference in the mean RSET between the base case where the evacuation teams are functioning as needed and this scenario where these teams fail to provide the required alarming actions.



Legend

A: employees that notice the fire event

B: employees in production (no vision of fire event)

C: employees in administration

D: employees alarmed by evacuation team (incl. production manager)

Figure 63: Comparison mean RSET-scenario 1 vs 5 (author's model)

6.2.1.6. Component: risk minimization system (scenario 6)

The risk minimization system is part of the 5S system that the company uses for the organization of the workspaces and storage spaces within the building. Failure to comply with this organization system can, therefore, cause an increased risk of fire events and the escalation of them. This escalation can affect the ASET but the evacuation process itself is not affected. This process is, therefore, completed as described for the base case scenario (section 6.2.1.1).

6.2.1.7. Component: fire doors and gates (scenario 7)

The fire doors and gates are part of the active fire protection within the building. These components are operated to minimize the impact of the fire event on different parts of the building. The operation of the fire gates during a fire event should be incorporated within the fire contingency plans since they are manually activated. Additionally, employees should be made aware that fire doors cannot be propped open. This component does not implement any additional delays to reaction times compared to the base case scenario. The evacuation process is, therefore, as described for the base case scenario (section 6.2.1.1).

6.2.1.8. Component: doors, gates, and windows (scenario 8)

The malfunctioning of two gates connecting the different parts of the production facility with each other affects the evacuation time of the occupants. The malfunctioning gates are indicated with the black shapes on Figure 64. Additionally, the route taken by the person performing the manual fire alarm after these gates is indicated with the arrow. Since the preferred gate is close, this person will use the gate indicated with the red shape to reach the starting point of the indicated route.

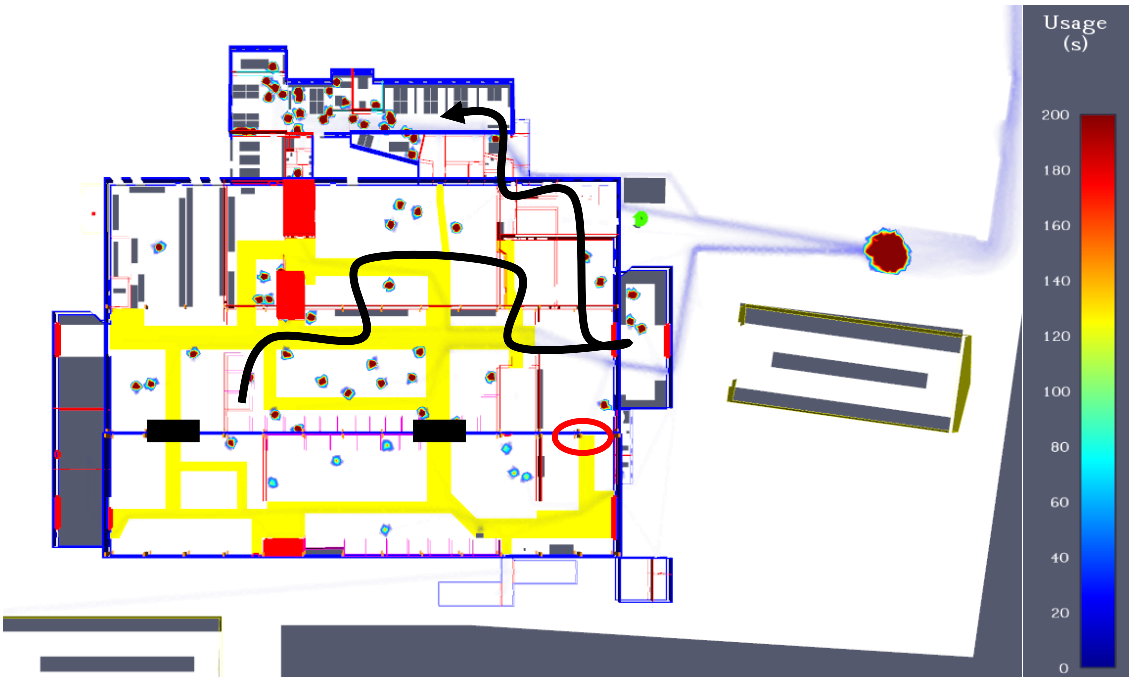
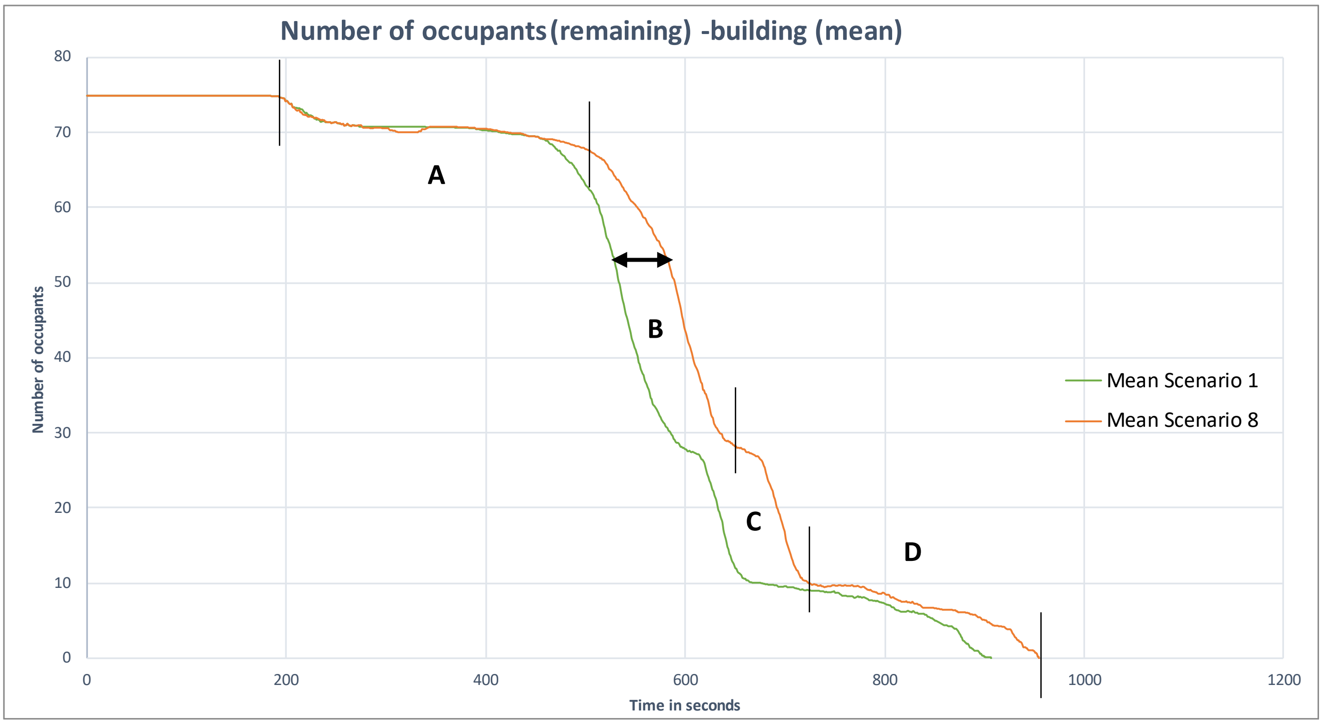


Figure 64: Accumulated usage-scenario 8 (author's model, 8-1)

Since all employees alongside this route experience a longer initial delay, the evacuation time is affected. The impact of the malfunctioning gates on the mean RSET in comparison with the base case is illustrated with the arrow on Figure 65. Additionally, this comparison shows that the employees that notice the fire event themselves are also affected by these malfunctioning gates. This is indicated in area A. In this area the mean RSET for scenario 8 is larger than for the base case.



Legend

A: employees that notice the fire event (incl. production manager)

B: employees in production (no vision of fire event)

C: employees in administration

D: employees alarmed by evacuation team (excl. production manager)

Figure 65: Comparison mean RSET-scenario 1 vs 8 (author's model)

6.2.1.9. Component: manual fire alarm (scenario 9)

The alarming actions are performed using a manual fire alarm. The failure of the fire alarm is simulated through the route of the person that performs the alarm and the delayed reaction time of the employees that are subjected to this action. Firstly, the person performing the manual fire alarm does not alarm the employees in the administration building. This person will, therefore, reach the evacuation assembly point after alarming all employees in the main areas of the production facility. After all employees present within this part of the building including employees positioned in separated areas reach this assembly point, the production manager identifies the missing employees. These missing employees are identified as the employees positioned in the administration building. The production manager, therefore, reacts by performing the alarming action himself. The adapted route of the person performing the initial fire alarm is indicated with the black arrows on Figure 66. Additionally, the manual fire alarm performed by the production manager after the performance of the roll call is illustrated with the red arrow (Figure 66).

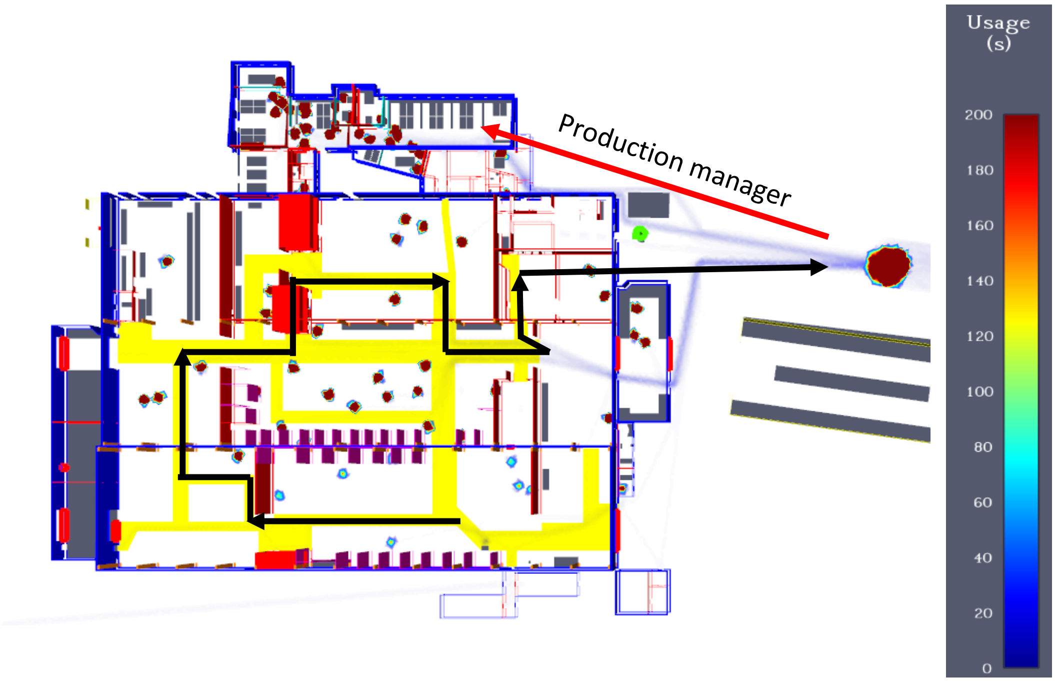
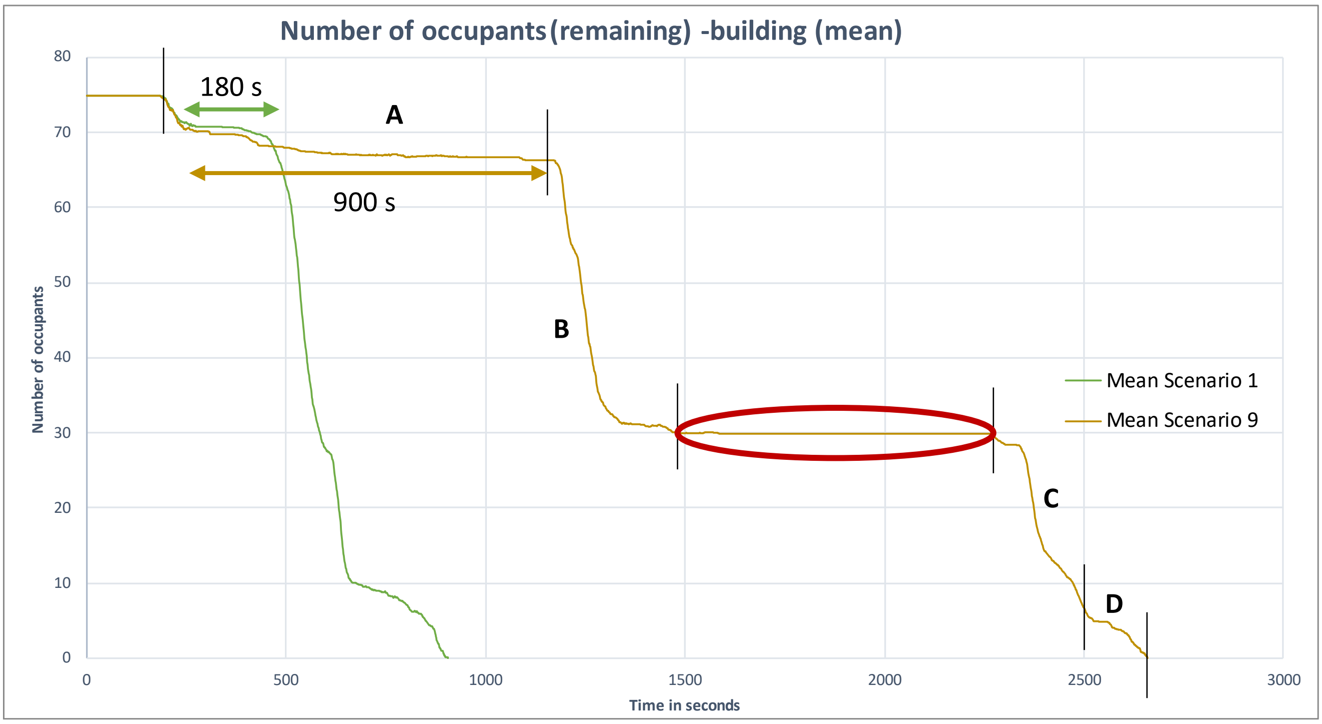


Figure 66: Accumulated usage-scenario 9 (author's model, 9-1)

The increased reaction time for both the employees positioned in the administration building and the production facility is illustrated through the comparison of the mean RSET for this scenario with the base case. This comparison is illustrated with the arrows in Figure 67. The green arrow shows the reaction time of 180 seconds for the base case and the orange arrow shows the reaction time of 900 seconds experienced in scenario 9 (section 5.3.1.5, 5.2.3). Additionally, the red shape (Figure 67) indicates the initial delay that is experienced by the employees positioned in the administration building. As described previously, this delay is caused by the lack of a manual fire alarm for this part of the building. This delay includes the time it takes for all employees from the production facility to reach the assembly point, the duration of the roll call and the duration of the alarming actions performed by the production manager.



Legend

A: employees that notice the fire event (incl. production manager)

B: employees in production (no vision of fire event)

C: employees in administration

D: employees alarmed by evacuation team (excl. production manager)

Figure 67: Comparison mean RSET-scenario 1 vs 9 (author's model)

6.2.1.10. Component: fire extinguishing actions (scenario 10)

The impact of human errors occurring during fire extinguishing actions causes a longer duration of these actions. This is simulated by the person performing the fire extinguishing actions. This person stays near the fire event for a longer duration. This is illustrated by the accumulated usage of this area as indicated in Figure 68.

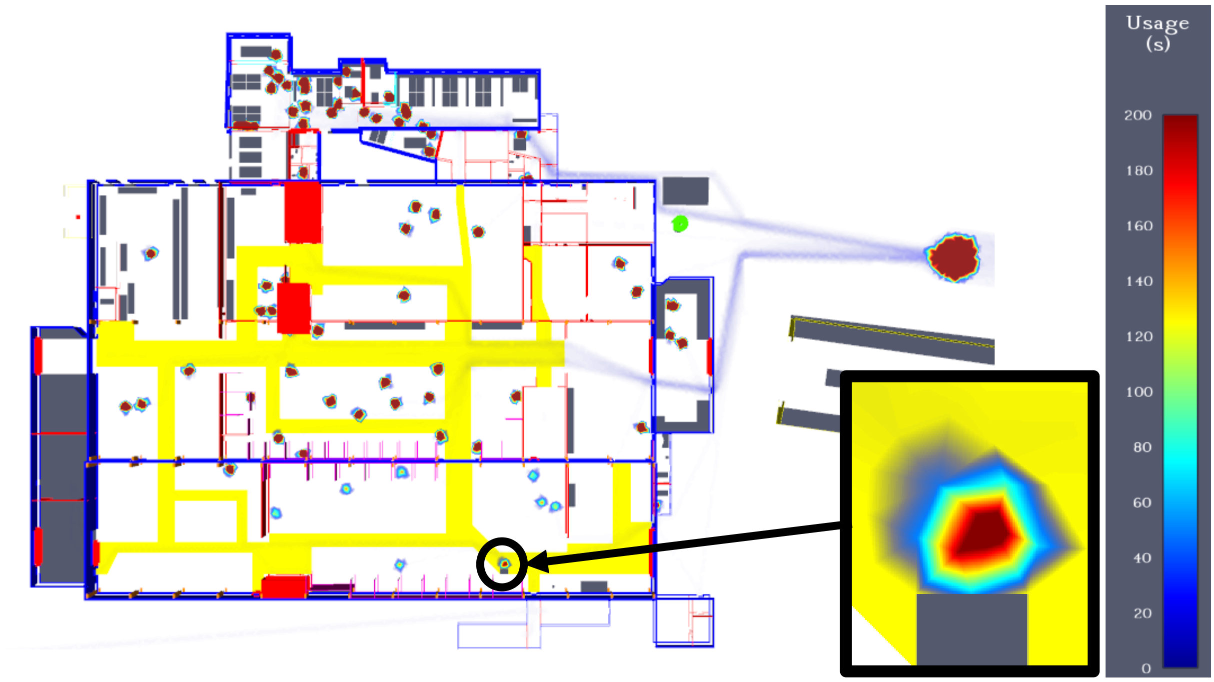
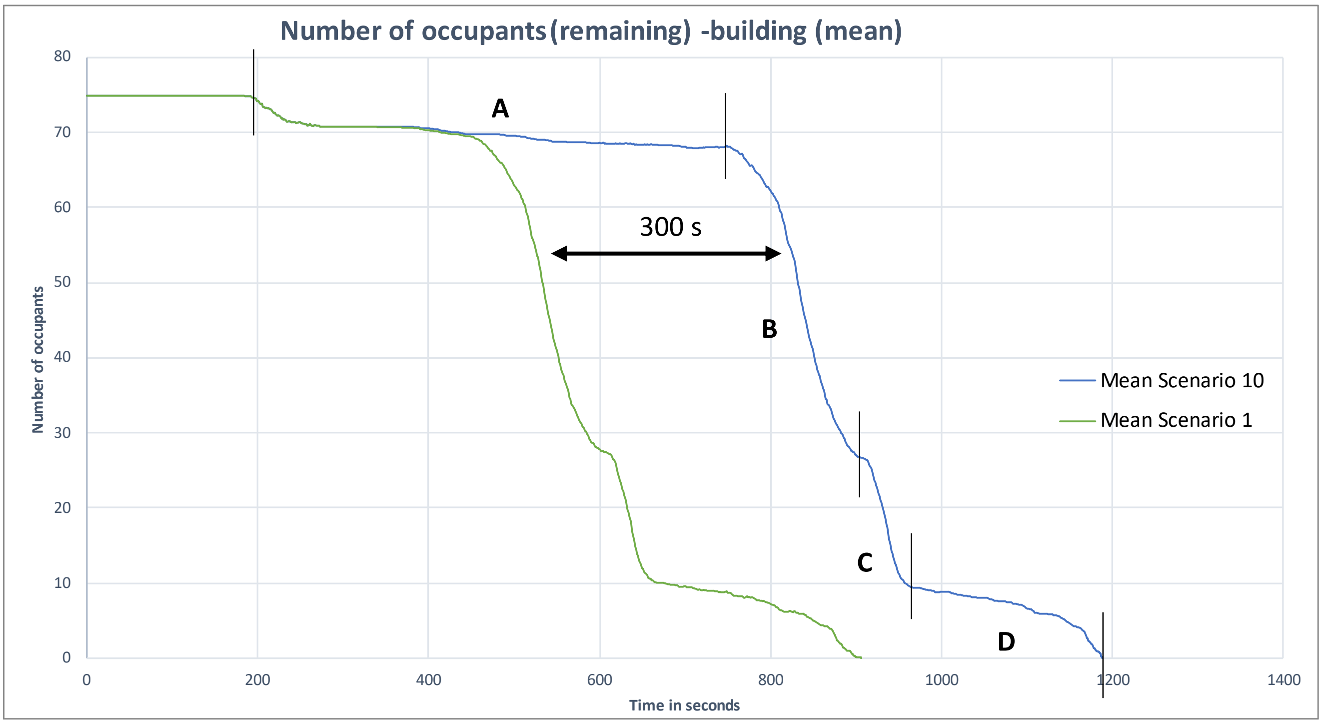


Figure 68: Accumulated usage-scenario 10 (author's model, 10-1)

Due to the longer duration of the fire extinguishing actions, all departments that are reliant on the manual fire alarm experience a longer initial delay. This is illustrated by the comparison between the mean RSET from this scenario with the base case (Figure 69). The arrow indicates the 300 second delay caused by the adapted duration of the fire extinguishing actions (as described in section 5.2.3).



Legend

A: employees that notice the fire event (incl. production manager)

B: employees in production (no vision of fire event)

C: employees in administration

D: employees alarmed by evacuation team (excl. production manager)

Figure 69: Comparison mean RSET-scenario 1 vs 10 (author's model)

6.2.2. Hazardous condition (basis for ASET)

6.2.2.1. Smoke formation

The formation of smoke caused by the fire itself is similar for all five cases, as indicated on Figure 70 and Figure 71. Additionally, the visibility based on the soot density is approximately 25 m for all cases. The smoke disperses within the part of the production facility where the fire event occurs. This part of the production facility has a total height of 8,6 m. Additionally, the occupancy density within this production facility is approximately 0,01 persons per m^2. Due to the considerable heigh and size of this part of the production facility, this dispersion does therefore implicate that the movement speed of the affected occupants is not increased.

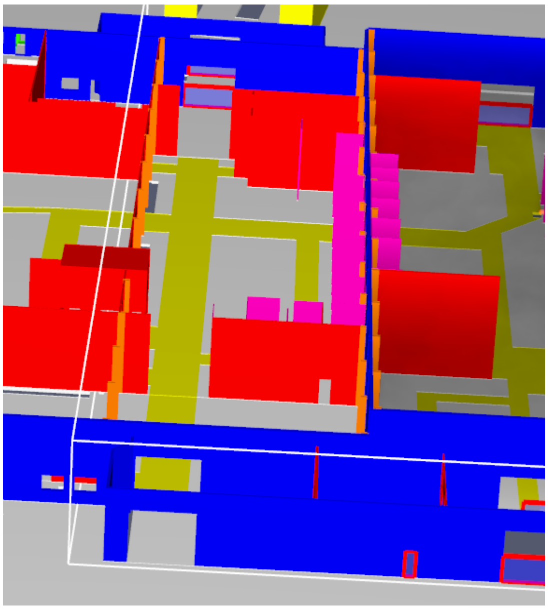


Figure 70: Smoke formation scenario 7-case 5 (author's model, 7-1)

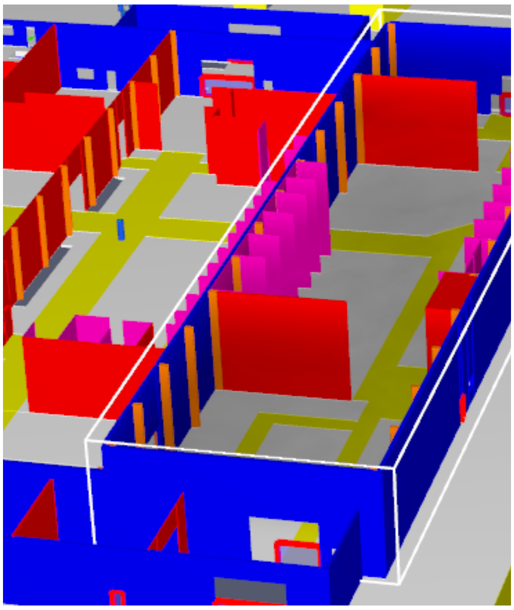


Figure 71: Smoke formation scenario 6-case 4 (author's model, 6-1)

6.2.2.2. Temperature increase

The conditions affecting the temperature increase due to the fire event are indicated as the completion of fire extinguishing actions, the placement of hazardous material near the source of the fire and the operational status of the windows and doors in the production facility. The successful operation of fire doors does not affect the fire event itself due to the placement of this event in comparison with the placement of the fire doors. They are placed on opposite sides of the production facility with approximately 75 m from one end to the other. Both a failure to complete fire extinguishing actions (case 1) and the placement of hazardous material near the source of the fire (case 5) increase the temperature surrounding the fire event. The comparison between these cases and the base case scenario (case 2) is indicated with the black shapes in Figure 72.

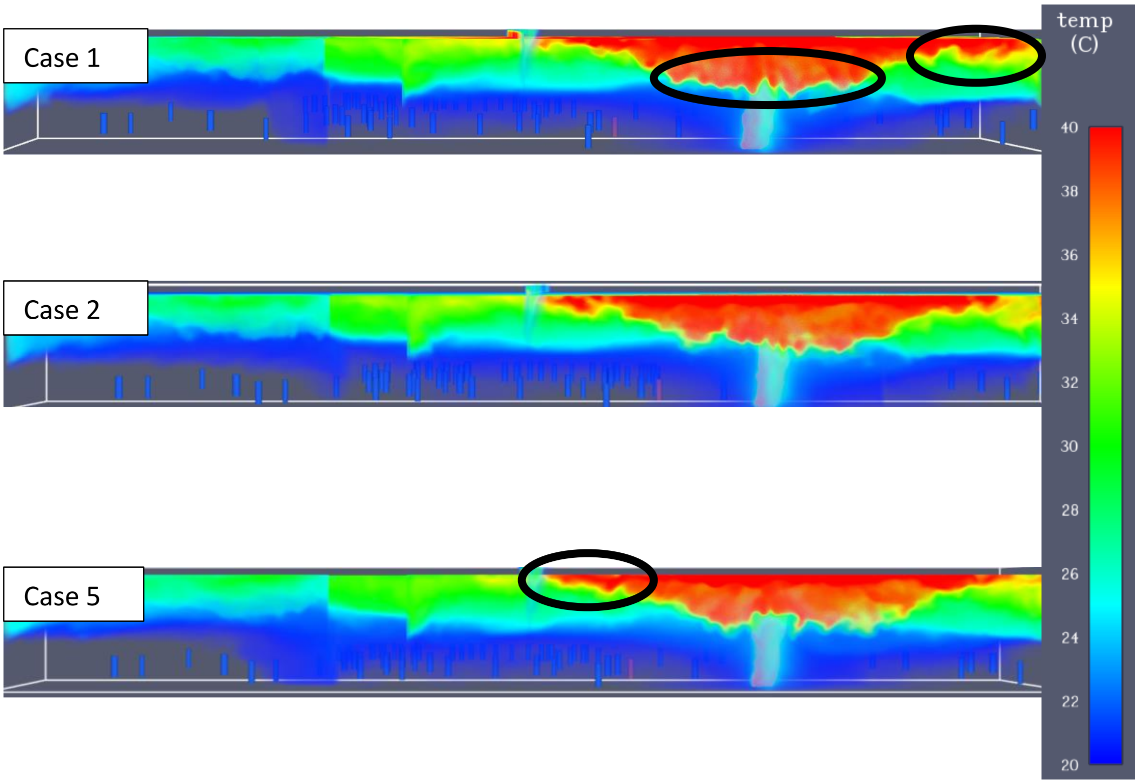


Figure 72: Comparison temperature increase for case 2, 3 and 5 (author's model)

However, due to the height of the building itself the temperature increase does not affect the occupants. This is illustrated in Figure 72 where the temperature at the level of the occupants is indicated to be between 20 °C and 22 °C.

Additionally, the failure to close the gates within the production facility (case 4) causes the fire event to affect the other part of the production facility. This effect is indicated with the black shape on Figure 73.

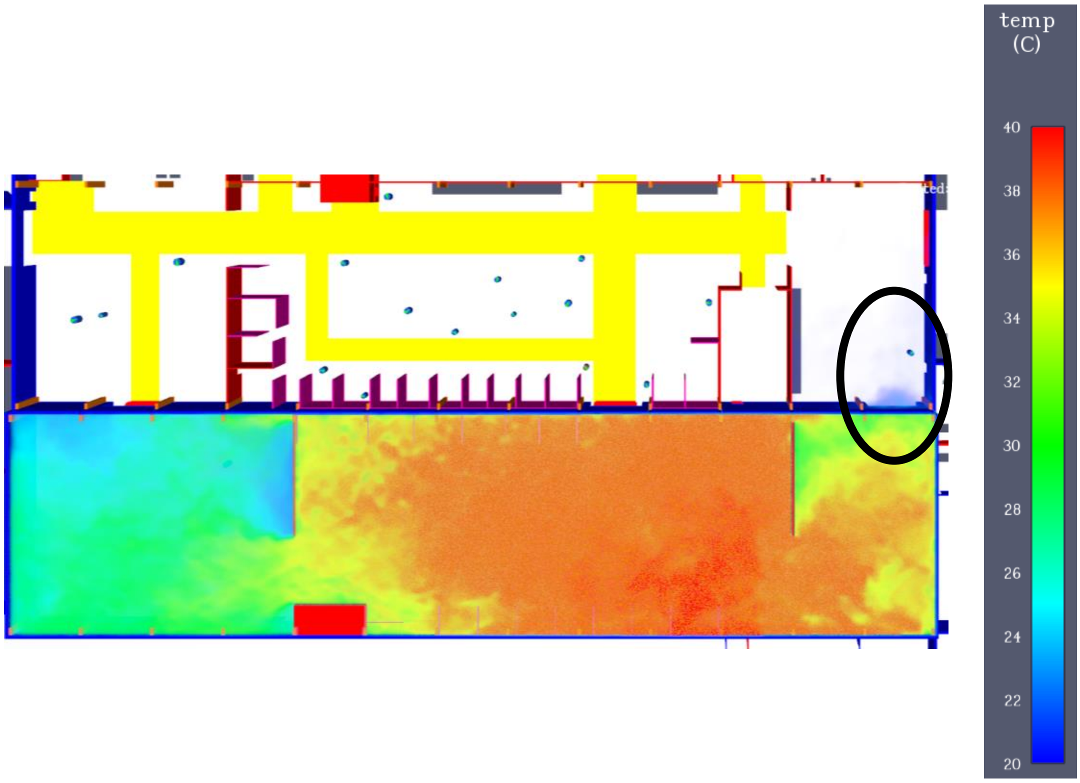


Figure 73: Temperature increase case 2 (author's model)

6.2.2.3. Yield of toxic gases

The fire event causes the yield of toxic gases such as carbon monoxide (CO) and carbon dioxide (CO_2). Carbon dioxide at concentrations above 3 % increases the breathing rate of the affected employees (INSTA, 2013, p. 35). Additionally, carbon monoxide reacts with the haemoglobin in the blood of affected employees to form carboxyhaemoglobin (COH). Concentrations of carboxyhaemoglobin above 15 % are stated to cause confusion and unconsciousness in the affected employees (INSTA, 2013, p. 33). The table below (Table 17) shows the CO and CO_2 yield for each case and the indication of the previously described level that affects the employees within the production facility. These results show that the yield of toxic gases does not affect the employees in the production facility.

		CO yield (mol/mol)	CO yield (ppm)	COH yield (%)	CO_2 yield (mol/mol)	CO2 yield (ppm)	CO2 yield (%)
Case	1	0,00004	40	0,279192627	0,0125	12500	1,25
	2	0,000052	52	0,415096631	0,0175	17500	1,75
	3	0,0000425	42,5	0,29729029	0,0125	12500	1,25
	4	0,0000425	42,5	0,29729029	0,0125	12500	1,25
	5	0,00007	70	0,498530075	0,0125	12500	1,25

Table 17: CO and CO2 yield for case 1-5 at occupant height of 2 m (author's model)

6.3. Analysis of simulation results

6.3.1. Safety condition

The safety condition based on the comparison of the RSET and ASET curves is stated to be the margin condition where the difference between both curves is 0. This is indicated with the RSET and ASET curve comparison shown on Figure 74. This safety condition is observed due to the missing effect of smoke, temperature, and toxic gases on the employees within the entire building.

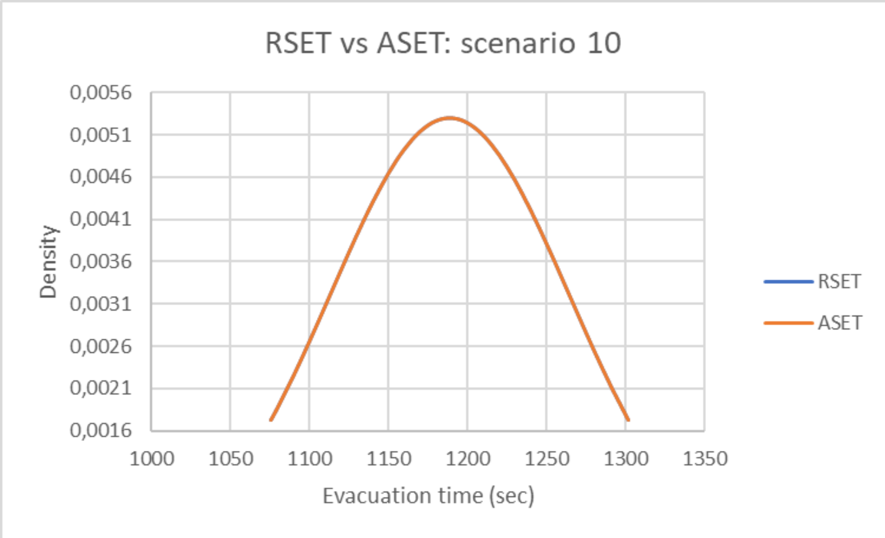


Figure 74: RSET vs ASET curves-scenario 10 (author's model)

Additionally, the execution of the manual fire alarm causes uncertainty within the calculation and the comparison of the RSET and the ASET curves. This uncertainty is illustrated on Figure 75 and Figure 76. Figure 75 shows a scenario with a larger ASET than RSET. This is caused by a higher mean evacuation time and a smaller standard deviation for the calculation of the ASET values. This scenario could, therefore, be assumed to be safe. Figure 76, however, shows a scenario with a larger RSET than ASET caused by a lower mean evacuation time and a larger standard deviation for the calculation of the ASET values. This scenario would, consequently, be described as unsafe.

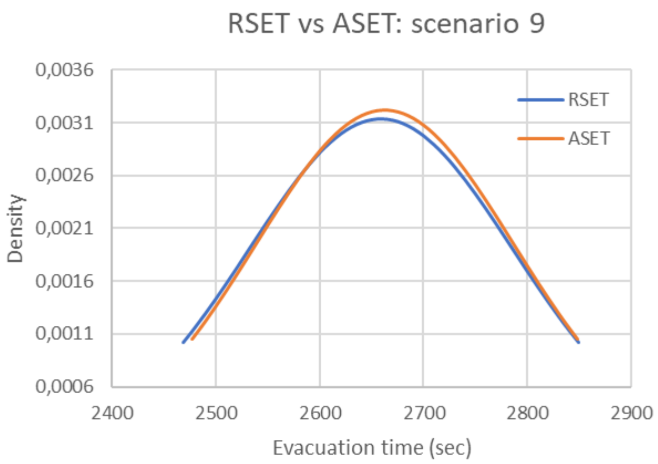


Figure 75: RSET vs ASET curves-scenario 9 (author's model)

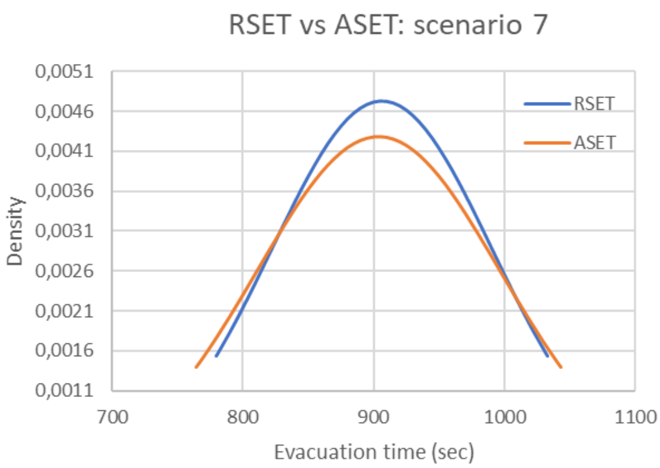


Figure 76: RSET vs ASET curves-scenario 7 (author's model)

The comparison of the mean and standard deviation values for the various scenarios that show a difference between the RSET and the ASET values is illustrated in Table 18. This comparison shows a maximum difference of 1,9 % between the mean values and a maximum difference of 16 % between the standard deviations for the calculated values of RSET and ASET. The results for the ASET calculation are, therefore, uncertain. This is caused by the method for modelling the manual fire alarm where each department is given a different initial delay based on the approximate time at which the person performing this alarm reaches that specific department.

Scenario	**RSET (s)**		**ASET (s)**		**Difference (%)**	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
1	906,4	42,23	912,3	49,0	0,65	16,03

2	935,6	65,14	937,9	63,2	0,25	2,98
4	979,67	96,75	960,5	101,8	1,96	5,22
5	1447,93	84,28	1450,5	86,5	0,18	2,63
6	906,4	42,23	902,9	46,6	0,39	10,35
7	906,4	42,23	903,8	46,5	0,29	10,11
9	2658,73	63,53	2662,3	61,9	0,13	2,57

Table 18: Differences ASET and RSET for mean and standard deviation (author's model)

6.3.2. Comparison and ranking of scenarios

The previously discussed scenarios are investigated using the method described in the discussion of the fire scenarios (section 5.2.1). This method requires both the probability that a part of the evacuation process fails due to human errors and the consequence of the fire event. The various probabilities are described in section 5.2.2. The consequence is, however, defined by the evacuation time for each scenario in comparison with the base case. This comparison is performed by determining both the RSET and ASET curves of each scenario and performing both a chi square goodness of fit and a z test. These tests investigate the relation between both the sample mean and standard deviation between the considered scenario and the base case. The equations used for the completion of both tests can be found in the appendix (11. Appendix, section 11.5.6.1.). The different RSET and ASET curves, the comparison between them and the results from both tests can also be found in the appendix (11. Appendix, section 11.5.3.-11.5.6.). Based on these results, the scenarios (excluding the base case) were ranked from one to nine with one being the scenario considered to be most like the base case and nine being the scenario that differs most from this base case. The product of this ranking and the previously mentioned probabilities determines the adapted ranking of all scenarios in comparison with the base case. This adapted ranking based on the calculated expected value can be found in Table 19. The adapted ranking was found to be the same for both the RSET and the ASET curves due to the safety condition described in section 6.3.1.

Ranking	RSET, ASET (component)	
1	Fire doors and gates (scenario 7)	
2	Risk minimization system (scenario 6)	maintenance plan + emergency floor plans
3	Evacuation doors (scenario 3)	
4	Emergency signs (scenario 2)	
5	Evacuation paths (scenario 4)	
6	Doors, gates, and windows (scenario 8)	maintenance plan + emergency floor plans + safety instructions
7	Fire extinguishing actions (scenario 10)	
8	Evacuation team (scenario 5)	
9	Manual fire alarm (scenario 9)	

Table 19: Adapted ranking of investigated human errors (author's model)

The adapted ranking of scenarios (Table 18) illustrates that the impeded operational state and the non-compliance with procedures affect the evacuation process (section 4.1.3). Based on this adapted ranking (Table 19), it can be stated that the scenarios that are most affected by human errors generally rely on a collaboration between various components within the fire contingency plan cycle such as adherence with the fire contingency plans and informing/updating employees regarding these plans. This fire contingency cycle was described previously in section 6.1.1. Additionally, human errors found in different parts of this cycle affect multiple scenarios, as indicated with the arrows (Table 19). Finally, the affect of obstructions placed on the evacuation paths is not as pronounced due to the low occupational load of 0,01 persons per m^2 (section 4.1.2).

6.3.3. Sensitivity analysis

To investigate the effect of uncertainty on the initial ranking of the scenarios and the determined probabilities, a sensitivity analysis was performed. This sensitivity analysis was performed on scenarios 6, 7, 8 and 10. These scenarios were chosen due to the small difference between the calculated values for the chi square goodness of fit and the z test, and the uncertainty within the probabilities mentioned in section 5.2.2. The performed sensitivity analysis for both the RSET and the ASET curves can be found in the appendix (11. Appendix, section 11.5.7.). Based on this analysis it can be stated that the resulting adapted ranking is robust for the uncertainties regarding the failure of components in scenarios 6, 7 and 8 (section 5.2.2.6, 5.2.2.7, 5.2.2.9).

For the ranking of RSET curves, both scenario 7 and scenario 10 are the most sensitive for changes within the initial ranking of the various scenarios. A difference of 0,75 and 0,15 in the ranking of the respective scenarios will change their adapted ranking. The adapted ranks for both scenarios are indicated with grey in Table 20. For the RSET curves, scenarios 6 and 7 have similar curves (11. Appendix, section 11.5.4.) since the evacuation process during these scenarios is only affected by the smoke formation caused by the fire event. The RSET curves for scenarios 5 and 10 are, however, not similar (11. Appendix, section 11.5.4.). The sensitivity of the adapted ranks of these scenarios is caused by the uncertainty within the RSET curve for scenario 5. The standard deviation for this curve is 84,28 seconds whereas the standard deviation for scenario 10 is 37,63 seconds.

Ranking	RSET (component)
1	Risk minimization system (scenario 6)
2	*Fire doors and gates (scenario 7)*
3	Evacuation doors (scenario 3)
4	Emergency signs (scenario 2)
5	Evacuation paths (scenario 4)
6	Doors, gates, and windows (scenario 8)
7	Evacuation team (scenario 5)
8	*Fire extinguishing actions (scenario 10)*
9	Manual fire alarm (scenario 9)

Table 20: Adapted ranking for sensitivity analysis RSET (author's model)

The analysis shows that the ranking of ASET curves is most sensitive for both changes within the initial probability and the initial scenario ranking. For scenario 6, a difference of 0,13 % with the initial probability and a difference of 0,5 within the initial ranking will change this scenarios position within the adapted ranking as illustrated with the grey area in Table 21. Additionally, scenario 10 is affected by changes to the initial ranking as described for the sensitivity analysis of the RSET curves. This scenario’s adapted ranking is also indicated with the grey area in Table 21. The sensitivity of scenario 6 for the initial ranking of the scenarios is caused by the uncertainty within the ASET curve for scenario 3. The standard deviation for this curve is 78,4 seconds whereas the standard deviation for scenario 6 is 46,6 seconds. Additionally, the sensitivity of scenario 6 for the probability is caused by the method for the performance of the monthly inspection rounds within the production facility. This method includes an arbitrary scoring of the various assessment points without the inclusion of a description for the different components of this scoring system.

Ranking	ASET (component)
1	Fire doors and gates (scenario 7)
2	Evacuation doors (scenario 3)
3	*Risk minimization system (scenario 6)*
4	Emergency signs (scenario 2)
5	Evacuation paths (scenario 4)
6	Doors, gates, and windows (scenario 8)
7	Evacuation team (scenario 5)
8	*Fire extinguishing actions (scenario 10)*
9	Manual fire alarm (scenario 9)

Table 21: Adapted ranking for sensitivity analysis ASET (author's model)

7. Conclusion and further work

7.1. Recommendations

Based on the adapted ranking of the various scenarios and the description of the simulated evacuation process, it can be stated that the human errors connected with each of these scenarios are a combination of various errors that affect the completion of this process. These errors are experienced during the preparatory phase of the fire contingency plans and the consequent adherence phase. Generally, these errors seem to be caused by the violation of the company's written procedures and the relevant regulatory framework. Based on this assessment, it is recommended to ensure that the occurrence of this type of human error is eliminated. Since this error seems to be caused by an issue with the division of responsibilities between the participants within the AMO that fulfill managerial positions and the follow-up of these responsibilities by all members of this organization, the appointment of a person responsible for this follow-up of the fire contingency cycle and the completion of the necessary documentation would help mitigate these errors. Since the moderator of the AMO meetings is already present during the discussion of the fire contingency plans, it is proposed that this person is chosen for the fulfilment of this task. Additionally, it is proposed that the AMO discusses the preparation of a DKV plan for the maintenance of fire safety equipment and the inspection of the building's operational conditions (e.g., emergency paths, emergency doors).

Generally, the revealed violations are found to induce a failure to provide employees with the correct information and a failure to keep this information relevant and up to date. They, therefore, affect the abilities of the employees to adhere with the maintenance instructions and to react accordingly in case a fire event occurs. For example, there are smoke hatches and a button operated mechanism available in the production facility, these hatches are furthermore indicated on the emergency floor plans. The safety instructions do, however, not have any mention of these smoke hatches and actions related to them. It is, therefore, recommended that the AMO focuses on both written and oral communication with the employees regarding the emergency floor plans, and the maintenance and safety instructions. Additionally, the persons responsible for this communication must be aware of the importance of the terminology used during this communication. It is proposed that the communication of the instructions is provided both orally and written so the receiver can refer to the written document in case any issues arise with understanding its content.

The sensitivity analysis showed that the uncertainty regarding the evacuation time and the completion of the inspection rounds within the production facility has the possibility to affect the adapted ranking of the various scenarios considerably. The uncertainty regarding the evacuation time is found to be mainly caused by the manual fire alarm. This alarm leads to a different initial delay for employees positioned within various departments. This initial delay is dependent on the movement speed of the person that performs this alarm. The movement speed of this person can be affected by the smoke formation because of which the initial delay in these departments could be increased. Additionally, the delay caused by the manual fire alarm affects the completion of the warning actions performed by the evacuation team. Employees that rely on these actions will, therefore, experience an initial delay that is dependent on both the movement speed of the person performing the fire alarm, and the reaction time and movement speed of the evacuation team. The inclusion of a button operated fire alarm is, therefore, recommended. It is proposed that this alarm is placed strategically within the production facility with the inclusion of the changing rooms and the canteen for the production employees. Additionally, to decrease the total evacuation time the connection between the fire alarm in the administration building and the production facility is recommended. The uncertainty regarding the completion of the inspection rounds in the production facility could be decreased by providing and adhering with a clearly described assessment scale. Additionally, the inclusion of a description of the situation regarding each assessment point is recommended for the reporting of these inspection rounds.

Lastly, based on the occurrence of violations with the company's procedures it can be stated that the adherence with standards and regulations such as BR and ISO in written procedures does not necessarily imply the practical adherence with these procedures. Based on this case-study, it can, therefore, be assumed that requirements based on the organization and assessment of provided documentation have little to no impact on the occurrence of human errors. Especially since this assessment focuses on the written procedures provided by the company. The company is, therefore, responsible for ensuring the compliance with these procedures. As described previously, it is recommended that a person is appointed with this responsibility. To facilitate the documentation of the various parts of the fire contingency plans such as maintenance and safety instructions and provide a clear overview of them, it is proposed that the company implements a system where all these parts can be documented, mapped, and compiled.

7.2. Limitations

Due to the previously described violations, the assessment of the employees' adherence with the contingency plans could not be completed. Additionally, there was a gap in the documentation because of which the results from the evacuation exercises could not be retrieved. No conclusions could, therefore, be drawn regarding the employees' actual behaviour during a simulated fire event. Their behaviour is consequently only based on the description of the safety instructions and the emergency floor plans. This also affects the completion of the roll call and the behaviour at the evacuation assembly point. The operation of smoke hatches and the performance of first aid were, therefore, excluded from the simulation as they were not mentioned in the safety instructions. Additionally, the simulated evacuation process is limited by the available documentation of the fire contingency plans e.g., the reports from the inspection rounds were not available online and were only present on the production manager's computer after request. Due to these limitations, the presence of guests within the building was excluded.

Finally, the simulation of the fire event itself in Pyrosim was limited by the CPU capabilities of the available systems. The fire event was, therefore, modelled at a smaller scale determined by the different sections in the production facility and the time it took employees in these sections to exit the building.

7.3. Further work

Based on the previously described recommendations and limitations, it is stated that further work should consider the combination of the different human errors and its effect on the evacuation process and time. Additionally, further investigation of the human errors and human behaviour should be considered after the implementation of the recommendations included within this case-study. This investigation should focus on the affect of social influence and the employees' actual behaviour during a fire evacuation or a fire evacuation exercise. It is, therefore, proposed that a fire evacuation exercise is planned and completed after the incorporation of the recommended solutions. This can help determine the complexities of the human behaviour in the investigated company based on the prepared fire contingency plans. This investigation should also include the presence of guests and the impact of their behaviour on the evacuation process and time.

8. List of figures

9. List of tables

10. References

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