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First responders‘ pathway requirements in perilous incidents

Bachelorthesis

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Abstract

INTREPID is a Europe-funded project, providing a platform for first responders that improves 3D exploration and analysis of a disaster scene. One component of the toolkit consists of implementing a path planning module to determine optimal paths for first responders inside buildings during perilous incidents. The central question of this study is what pathway requirements are essential for the path planning module and the first responder inside buildings during incidents.

The goal of the thesis is to set boundary conditions, gathered from incidents inside buildings, to provide a framework for a path planning module.

The following research was pursued with holistic literature research, followed by the six qualitative interviews with different types of first responders involved in the researched incidents. Based on the results of the interviews, firefighters count as the main actors in this work.

Whether first responders use the shortest path to reach a target position or take a detour is determined by the incident-dependent path safety. The study's main findings on whether first responders take the shortest path or search for alternative routes can be categorized into building- and person-related parameters and conditions for each type of incident.

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List of abbreviations

Abbreviation	Explanation
AEGLs	Acute Exposure Guideline Levels (for Airborne Chemicals)
APR	Air-purifying respirator
ASET	Available Safe Egress Time
BLEVE	Boiling liquid expanding vapor explosion
DGUV	Deutsche Gesetzliche Unfallversicherung
EM-DAT	Emergency Events Database
EPA	The United States Environmental Protection Agency
ERPG	Emergency Response Planning Guideline
NFPA	National fire protection association
PPE	Personnel protective equipment
RPP	Radiant Heat Performance
TPP	Thermal Protection Performance
INTREPID	Intelligent Toolkit for Reconnaissance and assessment in Perilous Incidents
USAR	Urban Search and Rescue

1 Introduction

Initiated in 2020, INTREPID (Intelligent Toolkit for Reconnaissance and assessment in Perilous Incidents) is a three-year-long Europe-funded project, providing a platform for first responders that improves 3D exploration and analysis of hazardous areas when arriving at a disaster scene. Amongst others, the data is gained by Smart Cybernetic Assistants (drones) combined with indoor Networking and Positioning methods. (Bochev et al., n.d.)

One significant component of building exploration is the implementation of a path planning module inside the navigation system of INTREPID, allowing first responders to reach their target position effectively. Besides the shortest path to a target position, different hazards could determine the path planning of the operating personnel drastically. Within the framework of this research, the question of what input data and pathway requirements are essential for a path planning module and first responders operating in perilous incidents inside buildings is pursued.

The study aims to find valid parameters and boundary conditions, that determine the accessibility of paths inside buildings during hazardous events, based on the impact of incidents on buildings and people. Parameters are predominantly derived from technical data or facts and function as the main foundation for setting a boundary condition that proposes a path to first responders.

From the literature research, technical information related to path planning requirements is collected and evaluated from public sources. In-depth data is gathered by conducting qualitative interviews with first responders. With these interviews, first-hand experience and insights of operations involving hazardous incidents in buildings are made accessible to the research field of path planning.

The structure of the thesis begins with the literature research in Chapter 2, including a categorization into study relevant types of incidents based on a general overview. For each defined incident, the literature review in section 2.2 is subdivided into causes and frequencies of the hazard and the impact of the incident on the building and people.In chapter 3, the procedure of further research is described, consisting of the conduction of qualitative interviews and the subsequent evaluation of the gathered information, which is introduced in chapter 4. This section is subdivided into building- and person-related path planning parameters for each type of incident and a subsequent summary and weighting of the results.

In section 5 a critical analysis of the results is presented, followed by a discussion of the limitations of the study and recommendations for further research. Finally, a conclusion in chapter 6 provides the reader with the summarized findings and the major results of the thesis.

2 State of the Art

This chapter presents the basis of the thesis in terms of path planning parameters for first responders, operating in hazardous incidents. First, an overview of different types of disasters is provided. Based on these types a classification into relevant incidents is made, forming the basis for the examination of the impact of disasters on buildings and humans wearing protective clothing. These categories were each further divided into the subsections causes and frequency, impact on buildings, and impact on humans with protection. Each of the incidents can occur in different combinations and are partially related to each other. This section attempts to cover general incidents, from which special variants could be derived.

2.1 Category Selection for types of incidents

2.1.1 General overview of disasters

Disasters can be classified into natural and manmade disasters (Wirtz & Below, 2009). In the following, a categorization into further subcategories of natural and manmade disasters is made.

Natural disasters

According to (Wirtz & Below, 2009), natural disasters can be subdivided into six disaster groups: Geophysical, Meteorological, Hydrological, Climatological, Biological, and Extra-Terrestrial. These six categories each have further subcategories, as presented in Table 1. Disaster groups are divided into geophysical, meteorological, hydrological, climatological, biological, extra-terrestrial disasters. Each of these disaster groups is in turn subdivided into respective disaster main types seen in the last column of Table 1. The disaster groups biological and extra-terrestrial are not regarded in the further study, due to the lack of data and secondary importance for the goal of the thesis. (Wirtz & Below, 2009)

Disaster Generic group	Disaster Group	Disaster Main Type
Natural Disaster	Geophysical	Earthquake Volcano Mass movement (dry)
	Meteorological	Storm
	Hydrological	Flood Mass movement (wet)
	Climatological	Extreme temperature Wildfire Drought
	Biological	Epidemic Insect infestation Animal stampede
	Extra-terrestrial	Meteorite / Asteroid

Table 1 Classification of natural disasters. Adapted from: (Wirtz & Below, 2009)

In Figure 1 the distribution of worldwide events by type of disaster between 2000 and 2008 is shown. The difference between the two natural disasters databases EMD-DAT and NatCatSERVICE is explained by dissimilar entry criteria. For example, the event Storm in NatCatSERVICE (39 %) is higher than in EM-DAT (28 %). One reason could be that the storm is registered due to monetary effects and damages in NatCatSERVICE, but not in EM-DAT since in these events no humans were harmed, or a state of emergency was not declared (Wirtz & Below, 2009).

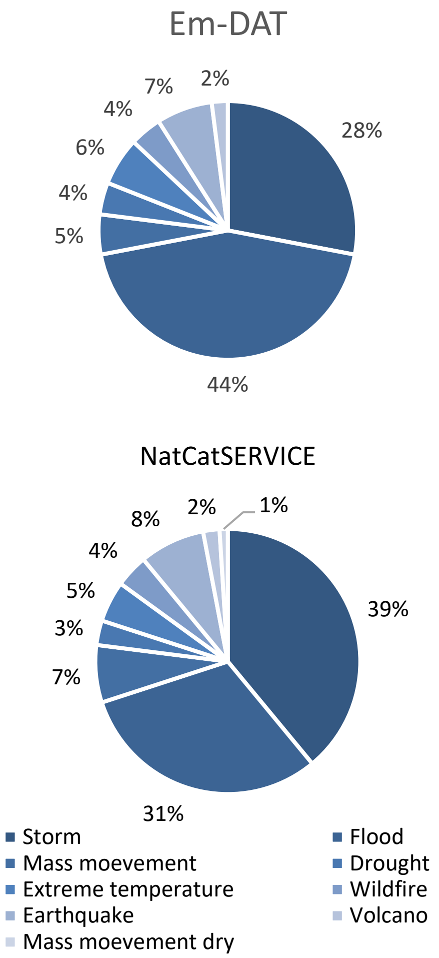


Figure 1 Distribution of events by type of disaster, 2000-2008. Adapted from: (Wirtz & Below, 2009)

Man-made disasters

Man-made disasters result from catastrophic incidents caused by human decision-making. These can be divided into socio-technical and warfare disasters. The socio-technical disasters include technological disasters, transport failures, public place failures, and production failures. (Mohamed Shaluf, 2007)

According to the International Labor Organization (1988), a technological disaster is defined as “an occurrence such as a major emission, fire or explosion resulting from uncontrolled developments in the course of an industrial activity, leading to a serious danger to man, immediate or delayed, inside or outside the establishment, and to the environment, and involving one or more dangerous substances”. (Mohamed Shaluf, 2007).

Emerging hazards from technological disasters that are considered relevant for the following study are fire, explosion, and the release of toxic substances. In this enumeration, fire is the most common danger, especially explosions that have a high number of fatalities and damages. The release of toxic substances potentially has the highest large-scale danger to humans, but this type of disaster is rarely the case. (Mohamed Shaluf, 2007)

2.1.2 Classification choice for types of incidents

The previous classification into natural and man-made disasters presents an overview of the most common types of disasters. It is necessary to list these most common events to understand the possible consequences as each of these disasters have various impacts on buildings and people.

The parameters, which determine the optimal path for first responders, require a building-oriented perspective including the effects on the structure. In hazardous situations, first responders need quick information about the type of incident, which determines their further course of action and necessary equipment. One type of incident can be caused by multiple events. Fire, for example, could be initiated due to a short-circuit or human misbehavior. If a fire does occur in a building, however, the cause is secondary, while the type of incident which influences the path accessibility for first responders is the primary relevant information.

To specify the focus of this thesis, five disaster types were chosen, for which an impact-related analysis is conducted in this thesis. This classification consists of:

- Structure fire
- Building collapse
- Flooding in buildings
- Incidents caused by hazardous materials
- Incidents caused by terrorism

Each of these groups is divided into the subcategories: causes and frequency, impact on buildings and humans. Additionally, general constraints for human bodies, as the fundamental boundary condition for every human, forms an additional category, which always has to be considered.

2.2 General constraints for first responders (and building occupants)

The following section is focused on pathway parameters found in the literature by describing physiological properties for first responders during an operation that could influence a calculated path by a path planning module that incorporates these parameters.

2.2.1 Physiological properties of first responders

Physiological properties of first responders, which are relevant for the thesis, should be correlated to the corresponding boundary conditions of the building during an incident.

Firefighters must perform a variety of tasks during an operation, wearing thermal protective clothing in hazardous areas with high ambient temperatures. Therefore, thermal regulation of the body is necessary. The mean core temperature is 37 ±1°C and tolerates a maximum increase of 5°C and decrease 10°C. (Lesniak et al., 2020)

The following study investigates how the maximum tolerances of firefighters are reached during an operation. The research was divided into two parts; safe working conditions for firefighters in their protective clothing during heat exposure; and secondly to investigate methods to encourage the thermal capacity and performance of the firefighters. For the first phase over 70 test persons were chosen to perform four different levels of work intensity in groups of ten people. The ambient conditions were Temperatures of 25°C, 30°C, and 35°C at a relative humidity of 50%. In Table 2 the mean values for exposure time until the reach of critical conditions for firefighters, such as a dangerously high heart rate or body temperature, are presented. (McLellan & Selkirk, 2006)

Group	25°C	30°C	35°C
Heavy [min]	56.4 (4.4)	47.4 (3.3)	40.7 (2.3)
Moderate [min]	91.9 (8.5)	65.4 (3.7)	54.0 (3.5)
Light [min]	134.0 (9.3)	77.1 (3.1)	67.3 (3.0)
Very Light [min]	196.1 (12.9)	121.2 (8.4)	86.8 (5.1)

Table 2 Mean values (± standard error) for exposure times [min] for the given ambient temperatures. Adapted from: (McLellan & Selkirk, 2006)

2.3 Structure Fire

2.3.1 Structure Fire: Causes and frequency

A specific incident can be caused by multiple events with different frequencies of occurrence. In Figure 2 the overall causes of fire in Germany, including all damages over 500.000€ within a total number of 2702 damages, according to DGUV Information 205-001, is provided. (Kaiser, 2018)

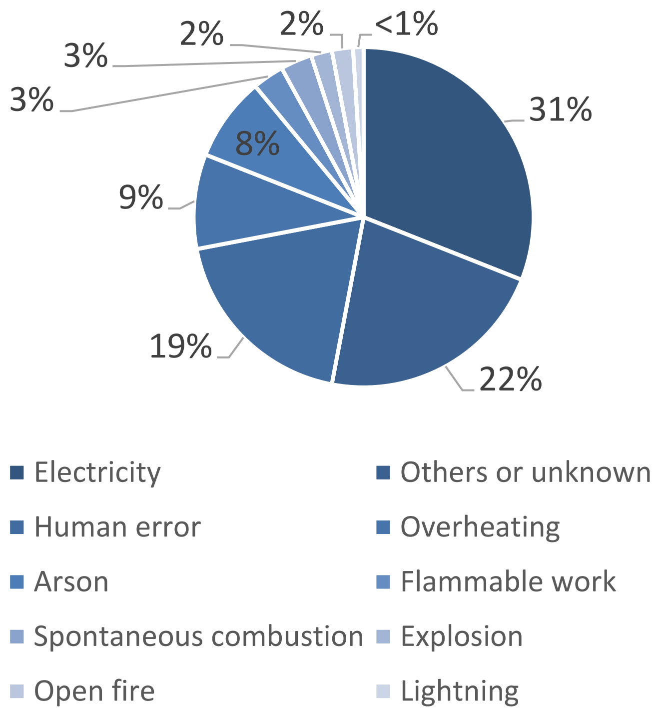


Figure 2 Overall causes of fire in Germany. Adapted from: (Kaiser, 2018)

The data shows that 31% of the fire is caused by electricity. Defective electronic devices, short circuits, or multiple sockets connected in series are possible causes of fire. The third most common trigger of fire with 19% is human misconduct, potentially caused by negligence. (Kaiser, 2018).

2.3.2 Structure Fire: Impact on buildings

The goal of the thesis is to determine pathway requirements for first responders' pathways in buildings during or after an incident. To find the necessary boundary conditions, a building-oriented perspective with fire safety installations and further properties is relevant. Most of the following attributes are based on a fire safety design calculation model, which analyses evacuation life safety in terms of uncertainty and risk. (Magnusson et al., 1996). The following categories of building-related parameters can be formed and are introduced in the following:

- Fire protective non-technological building elements
- Fire alarm system
- Sprinkler and smoke vents

To be within the scope of work, the norms used in this thesis are not representative of all countries in Europe and rather function as demonstrative examples. (Magnusson et al., 1996)

Fire protective non-technological building elements

The fire protective non-technological building elements consist of load-bearing and non-load-bearing construction elements. For the load-bearing elements such as walls, ceilings, pillars, etc. the structural stability during a fire is of high importance. The non-load bearing components are space-enclosing elements to prevent fire and smoke spread. Examples are fire-resistant doors and windows with fire safety classes, which determine the degree of fire resistance. (Willems et al., 2010)

Concrete, for example, is in the class of non-combustible building materials, fit for purpose under generally common fire temperatures around 1000°C. The heat resistance of concrete is demonstrated with the following properties:

- Concrete stays mainly solid during a fire.
- Concrete does not transmit the fire.
- Concrete has no smoke formation during a fire.
- Concrete has no release of toxic gases.

These characteristics ensure that concrete is not a risk factor, rather being a prevention of fire and smoke spread. Depending on the fire resistance classes each building material has an admissible durability time. (Han & Goleman, Daniel; Boyatzis, Richard; Mckee, 2019)

Fire protection closure is according to DIN 4102-5 a self-closing door or building installation that prevents the spread of fire. Those doors or installations can further be divided into fire resistance classes such as concrete components. A smoke protection door is according to DIN 18095, a self-closing door hindering the passage of smoke when correctly installed. (Matschi, n.d.)

For a better understanding, the fire behavior of building elements and materials is described in DIN 4102. The fire resistance duration of the most important building components is summarized in Table 3. In this norm, fire resistance classes of F30 to F180, equal a fire resistance duration of 30 to 180 minutes. (DIN 4102, n.d.)

Building element	DIN 4102	**Fire resistance class** **Equals a fire resistance duration of**				
		≥ 30 min	**≥ 60 min**	**≥ 90 min**	**≥ 120 min**	**≥ 180 min**
Walls, ceilings, pillars	Part 2	F30	F60	F90	F120	F180
Firewall	Part 3	-	-	F90 (F120, F180) + impact stress		
Non-load bearing exterior walls	Part 3	W30	W60	W90	W120	W180
Fire protection closure (doors, gates, damper)	Part 5	T30	T60	T90	T120	T180
Fire protection glazing -transmissible for radiation	Part 13	F30	F60	F90	F120	F180
-not transmissible for radiation	Part 13	G30	G60	G90	G120	G180

Table 3 Summary of fire resistance classes for building elements: Adapted from DIN 4102

The letters in front of the fire duration time have the purpose of classification into different building elements. T30 for example describes the fire resistance duration of doors. (DIN 4102, n.d.)

Fire alarm systems

In the following chapter, a general operating principle of fire alarm systems is presented. It is of secondary importance to know how exactly every type of fire alarm system works. The focus of this chapter is on the purpose of such a system and its effect on the building, in the matter of pathfinding.

The central fire alarm system evaluates the information of the automatic and manual fire detectors, in terms of the location of the fire outbreak. Depending on the settings, the system can transmit the information to acoustic and visual signaling devices or additionally to first responders. With the central fire alarm system, various fire safety installations (for example fire-extinguishing systems, ventilation systems, etc.) can be controlled. (Merschbacher, 2018)

In Germany, a control panel for firefighters must be installed to provide a uniform operation and overview of the building layout. The control panel also provides the operating status of the fire alarm system, for example, the activation of the fire-extinguishing system. Variations of this system with additional information are possible. In addition, key depots with universal bug wrenches for firefighters, enable the access of all rooms with fire detectors and automatic extinguishing systems. The locations of these systems vary, because of different building types and sizes. (Merschbacher, 2018)

Sprinkler and smoke vents

The goal of this section is to explain the effects on the building of the combined and individual use of sprinklers and smoke vents. It is important to know in which way these fire safety installations influence the spread of fire and smoke. With that information, useful conditions for the first responders' paths could be evaluated.

The activation of smoke and heat vents has no negative influence on the performance of sprinklers. Venting releases the products of combustion from the building, within the operating compartment. This improves the general visibility in this area, allowing first responders to find the source of the fire. (Beyler & Cooper, 2001)

According to a study based on numerical analysis (Khoat et al., 2020), "The available safe egress time depends (ASET) on how the smoke spreads from compartment to compartment more than considering the fire itself in many cases". ASET is defined as the maximum time available for people to leave a hazardous area (Tosolini et al., 2012).

2.3.3 Structure fire: Impact on humans wearing protective equipment

In this work, firefighters are considered as the main group of first responders because the covered incidents are their main area of responsibility. The general requirements for protective equipment for firefighters during structure fire are discussed in the following section. Research that focuses on requirements and test methods for protective clothing against thermal radiation, flame and further, is introduced. The study refers to standards for requirements based on NFPA, EN, and polish norms.

According to (Roguski et al., 2016)" The major hazards during fire-fighting are from radiant or convective heat, explosions, falling objects, debris, fine airborne particles, limited oxygen supply, hot liquid, molten substances, noise, toxic chemicals, smoke, and hot gases (Nayak R. et al., 2014).” The main requirements of protective clothing are to protect firefighters from as many health-threatening hazards as possible. (Roguski et al., 2016)

A summary of thermal requirements according to NFPA 1971 “Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting” and EN 469 ”Protective clothing for firefighters – Performance requirements for protective clothing”, is made in Figure 3. (Roguski et al., 2016)

Most testing methods focus on determining the thermal (heat, flame, and conductive heat) resistance of protective clothing for firefighters because these properties are crucial for protecting the health of the wearer. According to NFPA 1971, the Thermal Protection Performance (TPP) is an essential parameter for assessing heat resistance. The difference between TPP and Radiant Heat Performance (RPP) is the distribution of the heat source from radiant heat and heat from burners. The heat source in RPP is from 100% radiant heat. (Roguski et al., 2016)

To be within the scope of work a detailed explanation of each parameter and the respective testing method is not provided.

Category		Standard for requirements		Parameter	Requirements	Standard for test method
Thermal	Radiant Heat	NFPA 1971		TPP (Thermal protection performance)	TPP ≥ 35.0 at: heat flux during test 84 kW/m^2	ISO 17492
				RPP (Radiant heat performance)	intersect time ≥ 25s	ASTM F 2702
				Transmitted and stored energy	time before 2nd degree burns ≥ 130s	ASTM F 2731
				Total Heat Loss	THL ≥ 205 W/m^2	ASTM F1868
		EN 469		$RHTI_{24}$ (heat transfer - radiation)	$RHTI_{24}$ ≥ 18.0 for level 2 at: heat flux during test 40 kW/m^2	EN ISO 6942
				$RHTI_{24}$ - $RHTI_{12}$ (heat transfer - radiation)	$RHTI_{24}$ ≥ 10,0 for level 1 at: heat flux during test 40 kW/m^2	
		НПБ 162-02		-	heat flux on inner surface not more than 2.5 kW/m^2 at: heat flux during test 40 kW/m^2	НПБ 161
	Flame	Flame	NFPA 1971	Flame Resistance	after flame no more than 2 s no melting or dripping	ASTM D 6413
			EN 469	HTI_{24} (heat transfer - flame)	HTI_{24} ≥ 13.0 for level 2 HTI_{24} ≥ 9.0 for level 1	EN ISO 9151
				HTI_{24} - HTI_{12} (heat transfer - flame)	HTI_{24} - HTI_{12} ≥ 4.0 for level 2 HTI_{24} - HTI_{12} ≥ 3.0 for level 1	
			EN 469	Flame spread	index 3 of prEN ISO 14116	EN ISO 15025
			НПБ 162-02	Flame Resistance	after flame no more than 2 s shrinkage ≤ 10%	ISO 6941
	Hot atmosphere	NFPA 1971		Heat resistance	shrinkage ≤ 5% at: temperature 180 ± 5 °C exposure time: 5 min	ISO 17493
		EN 469			shrinkage ≤ 5% at: temperature 180 ± 5 °C exposure time: 5 min	ISO 17493
		НПБ 162-02		-	shrinkage ≤ 5% at: temperature 150°C	НПБ 161
	Contact heat	NFPA 1971		Conductive and Compressive Heat Resistance	time before 2nd degree burns ≥ 25 s	ASTM F1060
		EN 469		-	-	-
		НПБ 162-02		-	shrinkage ≤ 5% at: 400 ± 5 °C exposure time: 5 s	НПБ 161

Figure 3 Summary of requirements for thermal, mechanical, and chemical factors according to the standards from NFPA 1971[3], EN 469[4]. From: (Roguski et al., 2016)

2.4 Building collapse

2.4.1 Building collapse: Causes and frequency

In the following, an overview of possible causes and the frequency of building collapses is presented. As explained in Chapter 2.1.2, an impact-orientated view is essential. Nonetheless, the causes and the general occurrence of a collapse should be mentioned to know if further investigation is necessary.

Building collapses are a result of limited structural resistance, which could be caused by the exceedance of the load-bearing capacity. Such a structural failure occurs when the building elements are stressed to their limits, causing damages to the structure. Specific causes of a building collapse could be: (Michael & Razak, 2013)

- Structural failure
- Faulty design
- Poor workmanship
- Substandard materials

- Due to surrounding building development
- Illegal conversion
- Inexperienced contractor
- Building usage

Another study (Savoia et al., 2017) collected data from about 2000 industrial reinforced concrete precast buildings after the 2012 Emilia earthquake in the region of Northern Italy. The damages and structural characteristics were collected in a database by the engineers. The main reason for the structural collapses was the non-compliance of seismic design criteria for precast buildings in Italy.

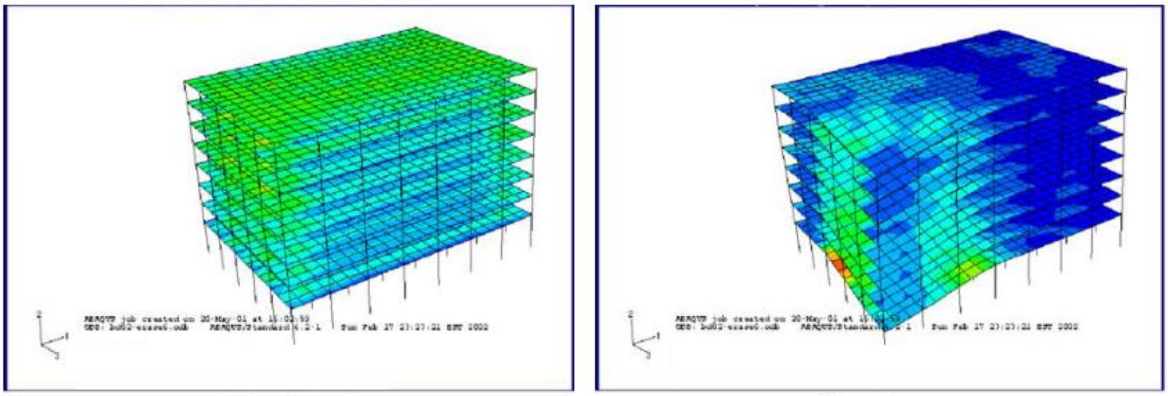
This study underlines that the causes of the collapse are based on the building's design errors and not on the disaster itself. In general, meaningful statistics considering the frequency of building collapse and their causes could not be given, because its occurrence is too rare to justify a solid data collection (Dandoulaki & Andritsos, 2007).

2.4.2 Building collapse: Impact on buildings

A literature review of the consequences of a building collapse is eminent to understand the dangers of operating in these hazardous areas. Certain parameters can indicate a building collapse, which determines if certain areas should be accessed by rescuing personnel. In the following chapter, a method predicting partial building collapse is introduced.

Real-time information concerning the status of the structure is used in the introduced study to indicate future conditions for the pathway evaluation. For example, such a method could be used to determine which structural components have failed and forecast which parts of the building could collapse subsequently.

To visualize this method, an eight-story building model where a column from the corner was removed, is evaluated in Figure 4. This case simulates an instantaneous failure of the column, which is for example caused by blast damage in this area. From a load distribution perspective, the removal of the column instantly shifts the load towards the remaining structural components of the building. Followed by a response of the structure, which could result in further failure of structural components within minutes or perhaps hours. In Figure 4 the stress intensities before and four seconds after the removal of the column are shown, demonstrating a redistribution of the stress intensities. (Miller-Hooks & Krauthammer, 2007)



(a) pre-damage (b) post-damage

Figure 4 Load distribution of an eight-story building. From: (Miller-Hooks & Krauthammer, 2007)

A similar event could also be triggered by other accidents or as the result of a fire. For example, a gas explosion could create blast damage, destroying load-bearing walls. The floor which is located above that walls could also collapse and cause a chain reaction. Additionally, structural fires could cause a redistribution of the loading, ending in the collapse of a building. A detailed description of different types of building collapse caused by structural fire is given in (V. Dunn, Collapse of Burning Buildings, Fire Engineering Books and Videos, New Jersey, 1988). (Miller-Hooks & Krauthammer, 2007)

First responders could be in danger during a rescuing operation after an earthquake, which can cause post-building collapse due to delayed load distribution. To prevent tragic events the publisher of the study (Zhu et al., 2009) presents a method that evaluates a quick and rough estimate of the damaged building. Based on digital visual data, the damages on structural building elements, as columns are identified with the help of visual pattern recognition methods. If for example the dimensions and positions of a crack on a column are overlayed, the case-based situation is classified into a priori states of damaged columns. If this method declares that the damage on the columns is severe, a structural collapse is assumed, and the first responders are animated to evacuate from the building. The adequate boundary conditions for buildings can be derived from the safety evaluations that should only be made by qualified personnel (e.g., structural engineers, building inspector). (Zhu et al., 2009)

A detailed description of visual recognition and safety evaluation of structural elements after earthquakes is presented in Zhu et al., 2009.

2.4.3 Building collapse: Impact on humans wearing protective equipment

The Urban Search and Rescue (USAR) team during a building collapse requires a variety of personnel, including local responders, specialized units of fire departments, and federal USAR teams. Due to the operation of different responders, a great variety of personal protective equipment (PPE) could be used. According to NFPA 1951, the appropriate PPE for USAR teams consists of garments, helmets, gloves, footwear, and eye or face protection. This equipment does not protect against extreme heat and is typically lighter than the one used during operations involving fire. USAR teams are additionally provided a half-mask air-purifying respirator (APR). (Willis et al., 2006)

2.5 Flooding inside buildings

2.5.1 Flooding inside buildings: Causes and frequency

European floods can be caused by numerous meteorological events:

1) Flash floods are caused by rain floods from convective rain, typically with a short duration and high intensity.
2) Frontal systems are a type of rain floods, caused by long-lasting advective precipitation, lasting for several days.
3) Snowmelt-induced floods, by the melting of snow masses, when the temperatures rise.
4) Ice-jam floods, where ice forms are blocking the river flow.
5) Storm surges originate from coastal floods occurring at estuaries and the mouths of rivers. (Brázdil et al., 2006)

Flooding is often correlated with events such as fatalities and damages to buildings. The main types of floods are coastal, river, and flash floods. In Figure 5 an overview of 1564 flood events between 1870 and 2016 is illustrated. These events are accumulated by month and include the type of flood and the number of fatalities caused by these disasters. (Paprotny et al., 2018)

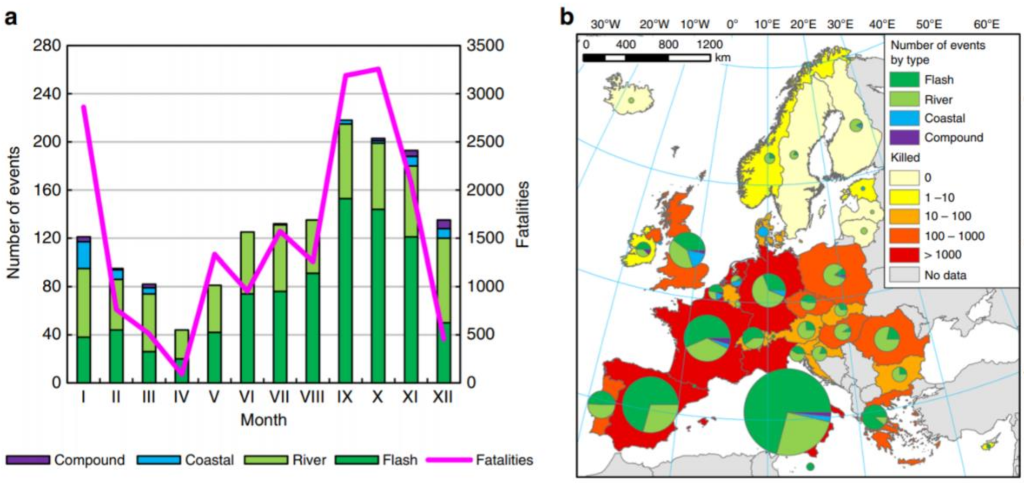


Figure 5 Frequency of flood events. The total number of flood events between the period of 1870 and 2016, a) by month, b) by country. From: (Paprotny et al., 2018)

The most frequent types of floods are flash and river floods. From the map on the right side of Figure 5 the regional differences, concerning the type of floods and the number of fatalities are illustrated.

2.5.2 Flooding inside buildings: Impact on buildings

The following research takes the flow velocity in terms of flood damage models into consideration. For the damage analysis of buildings caused by flood impact, plausible relations between the causes and effects, are required. The following study provides a method to describe the structural damage for various flooding scenarios. Additionally, this method considers the relation between inundation, flow velocity, and structural damage, based on datasets of the flood in 2002 in Saxony, Germany. (Maiwald & Schwarz, 2009)

To be within the scope of work, solely the degree of damage in correlation with the flow velocity is shown. The method describing the structural damage due to the impact of flooding is derived from the concept of “Schwarz and Maiwald” and extended with the parameter of flow velocity. The categorization of structural damage caused by flood impact is divided into five damage classes from D1 to D5, visible in Figure 6. Each of them regarding structural and non-structural damage, additionally providing examples for each case. (Maiwald & Schwarz, 2009)

Di	Structural Damage	Description	Damage (Schematic sketch)
D1	none	• pure moisture penetration damage	
D2	none to slight	• fine cracks • dented doors and windows	
D3	moderate	• larger cracks on load-bearing walls • deformations on ceilings/walls • subsidence	
D4	heavy	• collapse of load-bearing ceilings/walls	
D5	very heavy	• collapse of larger building elements	

Figure 6 Classification of damage grades, examples from the flood in 2002. Adapted from: (Maiwald & Schwarz, 2009)

The above-listed classification of damage grades is correlated to the parameters flood depth, the intensity of the flood, and specific energy height. (Maiwald & Schwarz, 2009)

2.5.3 Flooding of buildings: Impact on humans wearing protective equipment

Technical rescue, amongst others, involves the deployment of search and rescue diving teams. The presented study (White et al., 1998) compares continuously monitored core temperatures of search and rescue divers under warm and cold diving operations. Nine subjects were diving in cold water and eleven divers in warm water. The mean values for anthropometric and temperature data are shown at the bottom for ice and warm-water dives in Table 4. (White et al., 1998)

	Age (Years)	Weight (Kg)	Ambient Temperature (°C)	Time in Suit (Minutes)	Baseline Core Temperature (°C)	Highest Core Temperature (°C)	Change in Core Temperature (°C)
Ice dives							
Subject 1	38	773	34.0	95	37.4	38.4	1.0
Subject 2	34	85.0	34.0	145	37.4	37.8	0.4
Subject 3	35	72.7	35.0	172	36.1	38.0	1.9
Subject 4	29	94.5	35.0	100	37.6	37.9	03
Subject5	43	78.6	35.0	189	37.5	38.5	1.0
Subject 6	34	93.6	37.0	73	37.3	38.6	1.3
Subject 7	25	85.0	37.0	131	37.4	38.9	1.1
Subject8	38	77.3	29.0	120	37.1	38.2	1.1
Subject 9	28	88.6	29.0	50	36.8	37.7	0.9
Mean: subjects 1-9	34	83.6	33.9	119	37.2	38.3	1.0
Warm-water dives							
Subject 10	39	86.4	72.3	66	36.2	39.2	3.0
Subject 11	35	72.7	70.2	90	36.2	37.6	1.0
Subject 12	35	109.0	81.9	90	37.2	38.8	1.6
Subject 13	34	80.0	76.3	104	38.6	38.9	0.3
Subject 14	35	81.8	67.5	41	36.8	37.8	1.0
Subject15	34	80.0	69.0	61	36.5	37.5	2.0
Subject 16	40	88.6	74.5	107	37.0	38.1	1.9
Subject 17	38	77.3	83.1	70	37.6	38.2	0.6
Subject 18	33	86.4	84.9	90	38.0	38.9	0.9
Subject 19	35	72.7	67.0	126	36.7	37.1	0.4
Subject 20	32	86.4	62.0	34	37.5	37.8	03
Mean: subjects 10-20	35	83.8	73.5	80	37.1	38.2	1.2

Table 4 Anthropometric and temperature values for each subject

The equipment used by the diving personnel protects against environmental hazards while ensuring maximum mobility. During all seasons, a dry suit made of vulcanized rubber is used by the rescuing divers. Additionally, a self-contained underwater breathing apparatus (SCUBA) and a communication system are part of the diving gear. Amongst others, the sudden change in core temperature of the rescue divers is one of many hazards during a diving operation. (White et al., 1998)

2.6 Incidents caused by hazardous materials

2.6.1 Incidents caused by hazardous materials: Causes and frequency

According to (Ignou, n.d) “A chemical substance can be hazardous if is explosive, flammable, corrosive, poisonous radioactive or a hazardous micro-organism. In addition, the frequency of occurrence for these types of disasters underlines the importance of this study.

Given the fact that there are many different types of incidents in various facilities with different causes, the data in the following chart is not considered reliable. Nonetheless, a rough overview of the most common accidents caused by different types of hazardous materials is given in Figure 7. (Wood & Fabbri, 2019)

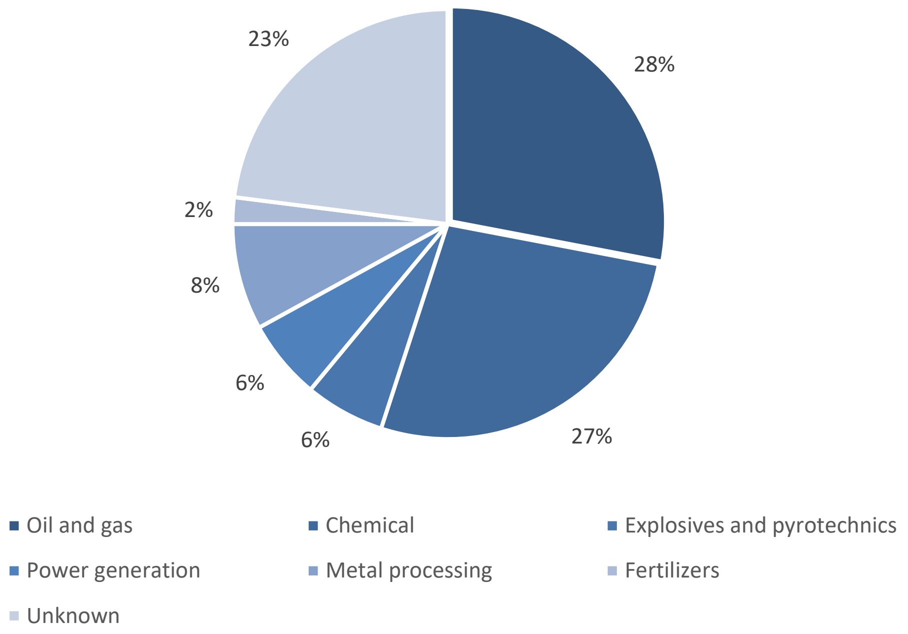


Figure 7 Distribution of accidents caused by types of hazardous materials. Adapted from: (Wood & Fabbri, 2019)

2.6.2 Incidents caused by hazardous materials: Impact on buildings

Chemical disasters cause a variety of severe consequences, including physical damage, fatalities, and environmental damage (Ignou, n.d.). For this section, only the physical damage is relevant, because it relates to damages to buildings. Possible impacts on a structure would be the occurrence of an explosion or/and fire (Ignou, n.d.).

In Chapter 2.3.2 the impact of fire inside a building is in-depth discussed. Therefore, this section is mainly focused on the consequences of explosions from a building-related perspective. In the following study, a definition of explosions and their general influence on structures is described.

An explosion followed by an air blast inside an enclosure increases the internal pressure drastically. The pressurized gas could then be released by the failure of windows, wall sections, or the activation of an explosion vent. For the release of pressure through an explosion vent, the turbulence of the gas increases the acceleration of the fire spread, enhancing the severity of the explosion. The propagation of the explosive reaction can expand from one room to another or along a corridor, increasing the speed of the flame front, due to a rise of turbulences and pressure of the yet unreacted substance. (Pape et al., 2010)

Summarized an explosion within a building can cause structural collapse, damages from debris impact, and the occurrence of fire and smoke (Mahajan & Pasnur, 2009). A detailed description of the above-listed impacts on the building can be found in chapter 2.3.2 (structure fire) and chapter 2.4.2Building collapse: Impact on building(building collapse).

2.6.3 Incidents caused by hazardous materials: Impact on humans wearing protective equipment

Before emphasizing the protective requirements of chemical protective clothing, a short introduction for the categorization of different types of chemicals is presented. The United States Environmental Protection Agency (EPA) proposes Acute Exposure Guideline Levels (AEGLs) for emergency planners and responders worldwide as a guiding framework for the release of chemicals into the air. AEGLs are specific concentrations of chemicals in the air at which a health risk to people can occur. AEGLs are designed for the periods, 10 minutes, 30 minutes, 1 hour, 4 hours, and 8 hours. The categorization into three different levels depends on the level of severity of the toxic impact caused by the exposure. There is a variety of different chemicals and in this work, it is referred to the AEGL Chemical database by EPA. (Environmental Protection Agency, n.d.)

Operations involving hazardous materials require the use of chemical protective clothing to shield and isolate the first responders from potential damage. There are various types of protective clothing for different chemical hazards. Consequently, no combination of protective clothing provides safety against all hazards. In contrast, the protective clothing could even be a risk for the user, causing heat, physiological and physical stress, and restricted vision, mobility, and communication. The wearer risk is in general dependant on the degree of severity caused by the chemical hazard. (OSHA, 1999)

According to EPA, there are four different levels of chemical protection, with Level A and providing the highest form of chemical protection, followed by Level B. Level C and D are not acceptable for chemical emergency response and therefore not further mentioned. (OSHA, 1999)

To be precise, Level A protection provides according to EPA the “highest level of respiratory, skin and eyes protection from solid, liquid and gaseous chemicals.” The external conditions for the use of this level of equipment is a prior identification of the chemical substance in terms of hazard to respiratory systems, skin, and eyes. Additionally, Level A equipment must be worn by the emergency responders during operations in confined or badly ventilated areas. (OSHA, 1999)

Level B protection provides the same form of respiratory protection as Level A, with less skin protection. In addition, liquid splash protection, not including chemical vapors or gases, is provided. This level of protective equipment is also used when the chemical hazard was identified, a high level of skin protection is excluded, and the primary chemical hazards include liquid instead of vapor contact. (OSHA, 1999)

2.7 Incidents caused by terrorism

2.7.1 Incidents caused by terrorism: Causes and frequency

Besides incidents caused by hazardous materials, chemical disasters can also be induced by terroristic activities, due to the use of chemical warfare such as Sarin, Chlorine, Cyanide, etc. (Ignou, n.d.). The Pinkerton Corporation's Global Intelligence Service (PGIS) divides the type of attacks by terrorism into 7 different groups (Arson and mass disruption were later added): (Lafree et al., 2006)

- Bombing
- Facility Attack
- Assassination
- Kidnapping
- Assault
- Hijacking
- Maiming

The GTD recorded the number of fatalities caused by the weapons used in terroristic attacks from 1970 through 2007. The total amount casualties in this period are 82.910. In Figure 8 the distribution of fatalities caused by arms used in terroristic attacks is shown. (Lafree, 2010)

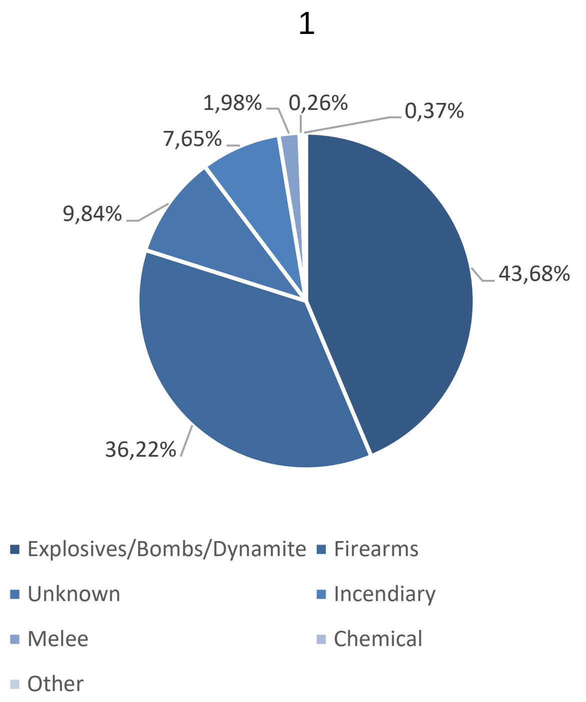


Figure 8 Distribution of weapons used in terrorist attacks, 1970 through 2007. Adapted from: (Lafree, 2010)

According to this data, the use of explosives, bombs, or Dynamite is 43.66% the most common method of terrorist attack (Lafree, 2010). On this basis, the potential impact on structures, first responders, and building occupants is conducted.

2.7.2 Incidents caused by terrorism: Impact on buildings

Derived from Figure 8, events that potentially influence building properties in hazardous ways are predominantly explosives and incendiary involving arson. As already mentioned, from the buildings' perspective the cause of the explosion is peripheral for its impact on the structure. Merely the type and extent of the explosion give information about further consequences, which are discussed in Chapter 2.6.2.

2.7.3 Terrorism: Impact on humans wearing protective equipment

As described in Chapter 2.7.1, terrorism affects people in terms of casualties. Depending on the type of terrorist attack, different first responders are required for a rescue operation, consisting of firefighters, Emergency Medical Technicians (EMT), or law enforcement personnel. However, in this thesis, the regarded hazardous events caused by Terrorism, are those affecting the buildings' safety properties. That includes the occurrence of an explosion or a fire, caused by arson. The effects of structure fire and explosion on humans wearing PPE are described in Chapters 2.3.3 and 2.6.3. During an operation where law enforcement personnel is involved, the situation would be too complex to provide useful information for pathway conditions. To be within the scope of work and to not provide misleading information, further consideration of this field is not provided.

3 Methods

To provide sufficient parameters for a path planning module, a content analysis based on the literature is conducted. The information is gathered by the evaluation of public information, based on technical and empirical data. Additionally, six qualitative interviews of first responders are separately conducted to provide information about incident-related parameters, that objectively influence the decision-making of the first responder. Additionally, information collected from the literature research is complemented with the results of the interviews. In conclusion, this study combines elements of the literature review and field research.

For the literature research, data from various academic papers, texts, works, and, norms, etc. for deriving parameters for path planning, were collected and evaluated. This information was gathered by searching for incident-related topics on Google Scholar. In terms of boundaries for path planning, most of the information gathered from the literature is contextualized and not found directly. To provide a general overview and sense for each topic, a section about the causes and frequencies of each type of incident is presented. These sections could reveal further hazards that need to be taken into consideration. For the main sections for each type of incident, data that reveal properties of structural and technical building elements affected by the hazardous events are researched. Conclusively the impact on humans wearing protective equipment during hazardous incidents is covered, to provide a two-sided perspective.

How incidents influence the decision-making of first responders, based on incident-related parameters, is hardly gained from common literature research. Therefore, six expert interviews with first responders from five different organizations were conducted. The selection of interviewed emergency responders was based on the coverage of the field of competence for each type of incident. Firefighters are directly involved in all our considered events, therefore four separate interviews with firefighters from three different organizations were made. Additionally, police and search and rescue personnel from two different organizations were interviewed separately. The interviews are conducted via Zoom and the interviewed responders are from Germany, Spain, France, and Sweden.

The interviews are semi-structured and consist of one or two interviewees for each session. The questions are predominantly formulated openly to gather new insights and detailed information for each topic. The first interview is structurally different from the following interviews because it additionally included feedback provided by the interviewee. Based on the feedback and own insights gained from the first interview, an adaptive structure for the remaining interviews was made. The interviews follow a structure that is based on the professional specialization of the respective interviewee. At the beginning of each interview, the importance of the researched hazardous events for the occupancy of the first responder is determined. For each covered incident type, three main questions were asked to provide a broad frame for the procedure of the interview. The main questions consist of:

1. What is the general approach in the operation?
2. How are you planning a path to your target position?
3. What are potential obstacles/hazards that could block your path?

As mentioned before, each question creates room for additional questions and information.

For the data analysis, the interviewees consented to a recorded Zoom-meeting, to evaluate the interview in an altered form without the publication of the recorded data. The recorded audio track is afterward summarized in transcripts and evaluated with coding followed by categorization into qualitative parameters.

The parameters gathered from the transcript are based on concrete information about parameters and contextualized statements according to the goal of the thesis. Information that is not decisive for the research issue, such as building exploration or searching for the location of the target position is excluded from the consideration.

4 Results

4.1 Path planning parameters and conditions

From the information gained by the literature review, a concept that determines valid boundary conditions in path planning for first responders is introduced. The presented chapter is subdivided into the following sections:

1. Building related path planning parameters by type of incident
2. Person related path planning parameter by type of incident

The first section consists of the determination of building-related boundary conditions, during the occurrence of all previously discussed types of incidents, in the same order as in the state of the art. Afterward, person-related parameters that are derived from the impact of incidents on humans are explained for each type of incident in analog sequence.

Before emphasizing parameters individually for each type of incident, potential relations between the researched incidents are visualized in Figure 9.

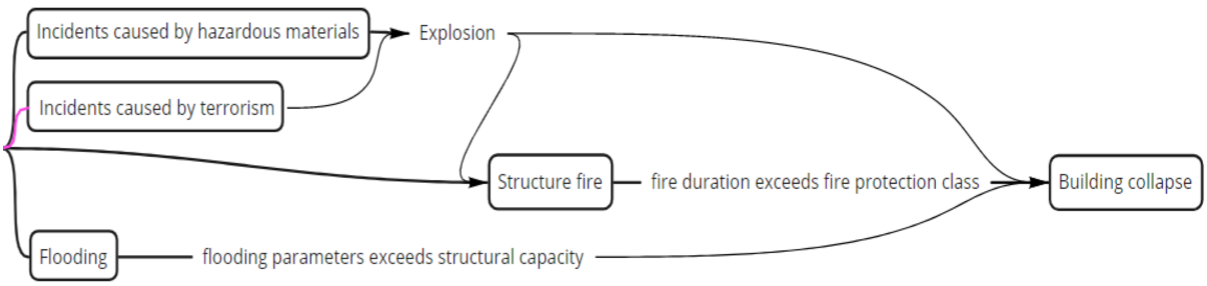


Figure 9 Potential relations between hazardous events (Own presentation)

It is visible that each examined type of incident could potentially lead to a structure fire or a building collapse. These relations illustrate that a combined appliance of incident-related path planning parameters needs to be considered. For example, in terms of incidents caused by hazardous materials, explosions could cause fire and/or building collapse. In terms of path planning the appliance of combined safety parameters and the respective protective parameters of the equipment could be possible but were not discussed for each case, individually.

The main foundation for path planning in this work is the general parameters and conditions for firefighters in Table 10. General boundary conditions for building- and person-related parameters such as priority of target position, path safety, path length, and already accessed areas are arranged in descending order by importance. This hierarchy is necessary for evaluating paths based on the expectations of first responders. The interviewed firefighters mentioned that saving victims has the highest priority in an operation and in some cases, the first responder would consider entering the building and risking their safety. An important consideration is that the hierarchy is flexible and that the path length could influence path safety in special cases. But as already mentioned the path planning module should not make decisions for first responders and rather provide them with multiple ways for solving a problem.

The priority of the target position proposes a path to the location with the highest priority for the operation. The path to the target positions is based on path safety, which determines the safest paths in accordance with building- and person-related parameters and conditions. Within the frame of path safety, the shortest paths are determined to the target position. For already accessed areas by first responders, a more complex consideration is necessary. A recommendation for further research is made in chapter 5.3.

4.1.1 Building related path planning parameters and conditions

Before specifying the pathway requirements from the perspective of the first responder, a building-oriented framework in terms of boundary conditions is necessary. In the following section, the information gained from the literature research and qualitative interviews, arranged by type of incident in the same order as in the state of the art. All building-related path planning parameters and conditions are summarized in Table 11 in the Appendix.

Building related path planning parameters and conditions: Structure fire

Based on the literature review in Chapter 2.3.2 a basis for path-related information in buildings during the occurrence of a structure fire is provided. The fire protective non-technological building elements are all structural components made of concrete (e.g., walls, ceilings, pillars, staircase) and fire protection closure. Fire protection closure is space enclosing and prevents fire and smoke spread inside a building. The building elements made from concrete are mainly solid during a fire, do not transmit fire, have no smoke formation, nor toxic release during a fire. Depending on the fire resistance classes each building material has an admissible durability time. Fire protection closure prevents fire ingress and can further be divided into fire resistance classes like the concrete components.

Based on the fire resistance classes and the types of space-enclosing elements, the fire and smoke spread can be assumed and the best possible path for first responders could be calculated. The fire resistance duration of structural components determines the time in which, for example, firefighters, can operate in specific parts of the building. This information is just given when the approximate moment of the fire outbreak is known. Additionally, the type of closure is essential, because it indicates the movement of the fire and the adaptation of the first responder's operation routes. If for example a fire protection door is installed, the fire and smoke spread is hindered over a period, depending on the fire resistance class. Therefore, a possible path could be taken into consideration that would be excluded if the door was not a fire protection door.

The central fire alarm system evaluates the information of the automatic and manual fire detectors, in terms of the location of the fire outbreak. Smoke vents release the products of combustion from the building, within the operating compartment. This improves the general visibility in this area, allowing first responders to find the source of the fire. Additionally, the smoke spread between building compartments determines the ASET.

From the interviews, additional discussed building-related parameters are gathered. To be within the scope of work, merely new insights regarding building-related path planning parameters are explained. According to the firefighters, activated sprinklers are not decisive in terms of path planning and often not present in residential buildings. However, activated automatic extinguishing systems using gas, should be excluded areas from the firefighters' path.

Building related path planning parameters and conditions: Building collapse

The failure of crucial building elements can cause partial or complete building collapse. Explosions and structural fires can cause building collapse when load-bearing walls or pillars are damaged.

One boundary condition from a building-related perspective is that areas that are in danger of collapsing, should not be entered by the respective emergency responder. The decision, whether an area is likely to collapse should only be made by qualified personnel (e.g., structural engineers, building inspector) (Zhu et al., 2009). Tools discussed in Chapter 2.4.2 support qualified personnel in their decision and describe whether a building is in danger of collapsing. In Chapter 5.2 an explanation of the difficulty in implementing building collapse into path planning is presented.

Building related path planning parameters and conditions: Flooding inside Building

The damage of flooding on buildings is correlated to the flood depth, the intensity of flood, and specific energy height according to the research in Chapter 2.5.2. The damage can also cause a building collapse, in the worst case. Most of the literature covers flooding evacuations on a larger scale, instead of the building itself.

Extracted from the interviews, additional building-related parameters in case of flooding are the opening direction of doors because the water pressure could block the door if it is opened in the same direction as the water masses. Therefore, the assumption that paths should be preferred with a door opening direction against the water masses, is made.

Additionally, not fixated floating objects, such as tables or larger obstacles could block the path if the water flows rapidly. Therefore, a dynamic change of the available paths should be taken into consideration.

Building related path planning parameters and conditions: Incidents caused by hazardous materials

The blast damage from the explosion could cause the failure of windows or wall sections. Explosions can additionally cause building collapse, damage from debris impact, and the occurrence of fire and smoke.

For the already discussed zone pathing an important piece of advice, gained from the interviews, was to not subdivide zones inside the building, but rather mark the whole area as a red zone. The transitional orange zone would for example be an area in front of the building and the safe green zone would cover the remaining hazard-free areas.

Building related path planning parameters and conditions: Incidents caused by terrorism

Terrorist attacks that impact the building structure are explosions and fire. As already discussed in Chapter 2.7.2, the main impacts and building-related path planning parameters can be derived from the incidents involving structure fire, building collapse, and/or hazardous materials. Additional building-related parameters were neither gained from the literature review nor the qualitative interviews.

4.1.2 Person related path planning parameters (firefighter + equipment)

More specific consideration is made in the following section, where person-related parameters, consisting of the incident- and equipment-related properties, are discussed for the regarded types of incidents, involving firefighting personnel. The incident-related parameters are gathered from the literature review and qualitative interviews and serve in accordance with equipment-related parameters. Whereas in Chapter 4.1.1 the impact of the incident on the building is regarded, this section focuses on parameters gained from the effect of the incident on humans wearing protective clothing. Lists including person-related path planning parameters are summarized in the Appendix separately for each type of incident. The respective reference for the list is provided at the beginning of each of the following sections.

General person related path planning parameters and conditions

One general physiological factor determining the safety of emergency responders is body temperature. With the continuous measurement of the core temperature, boundary values that tolerate a maximum increase of 5°C and decrease 10°C, could be applied. If this condition is not fulfilled an abortion of the operation for the emergency responder is proposed. These values refer to general operations conducted by firefighting personnel and can be applied to each type of incident.

Person related path planning parameters and conditions: Structure fire

Person-related parameters and conditions for structure fire are also summarized in Table 12. In the case of firefighting equipment, detailed information on requirements for thermal protective clothing is gathered. First, an enumeration of all potential hazards during firefighting is presented:

- Radiant heat
- Convective heat
- Explosions
- Falling objects

- Debris
- Noise
- Toxic chemicals
- Smoke
- Hot gases

The requirements of protective clothing according to the hazards are determined by NFPA 1971 and EN 469. In Figure 3 a summary of requirements for thermal, mechanical, and chemical factors according to the above-mentioned norms is shown. The most important factor in this section is thermal resistance, which consists of heat, flame, and conductive heat.

According to the interviews, the maximum heat resistance with thermal protective clothing determines the value of the maximum tolerable ambient temperature inside an area. The values for the heat resistance of thermal protective clothing are provided in the respective norms in Figure 3. The PPE has limited protection against direct flame impact and this hazard should therefore be excluded from the path.

In Germany, path planning for firefighters is dependent on the accessibility of the first and second escape routes. The first escape routes are predominantly staircases, which presence is mandatory in the building layout. If the first escape route is not accessible, a turntable ladder on a firefighting vehicle could provide a second escape route for entering the building or rescuing victims. The usability of the escape routes is amongst others determined by the compliance of the following safety parameters:

- Danger of collapse
- Visibility
- Amount of smoke

The first escape route is not accessible when the staircase is in danger of collapsing. Furthermore, the amount of smoke that (in)directly influences the visibility inside the escape route, determines if the path is used. For example, if the staircase is smoke-free good visibility is granted, the path is accessible. The amount of smoke could also indirectly influence the visibility if the smoke wall is directly under the ceiling, but the area above the floor is smoke-free and passable. In a complex building, more than one first escape route could be present and therefore the one with the least hazard (best visibility, least danger of collapsing, etc.) is preferred. If the first escape route is not passable, the second escape route creates alternative paths by providing access to the building with a turntable ladder.

Besides the two discussed escape routes the accessibility of the remaining building sections is covered with the following additional safety parameters:

- Maximum ambient temperature
- Danger of rollover
- Unsecured shafts/openings
- Hazardous materials in contact with fire

The maximum ambient temperature needs to be lower than the maximum heat resistance of firefighters (approximately 260 degrees Celsius) with protective equipment. If that is not the case the firefighters need to cool down the area until the ambient temperature is below the maximum. Areas that are in danger of a rollover involve direct flame contact with the firefighters, offering limited protection despite PPE and should therefore be excluded from the path. Unsecured shafts or openings could harm firefighters by falling in and endangering their lives and the operation. If hazardous materials are in contact with fire the affected area should be excluded from the path.

When the target position of the operation includes evacuating victims from the building, additional criteria need to be applied, considering path planning. The safety parameters include:

- Location of the victim (above or beyond the fire)
- State of victim
- Maximum ambient temperature for a victim

As mentioned before, the priority of saving lives is the highest in the operation. But if victims are above the hazard, the firefighters would consider extinguishing the fire that is blocking the path to the victim. Additionally, the state of the victim influences their evacuation route. If the victim is unconscious the first escape route is preferred, because the victim needs to be carried outside. Firefighters carry an additional SCBA, therefore smoke would not be a direct hazard for the victim if equipped. Nonetheless, smoke should be avoided when evacuating building occupants, due to a high-stress intensity. If the victim is conscious, evacuation by the second escape route is an option. In that case, the victim needs to be secured during an operation and will be guided to a safe position (e.g., balcony, roof, hazardous free room). The evacuation by the second escape route is also determined by the accessibility of the first escape route for the victim. For example, if the maximum ambient temperature for the victim is exceeded (approximately 60 to 70 degrees Celsius), the evacuation route is not accessible for people without adequate protection.

Person related path planning parameters and conditions: Building collapse

All relevant data in this section is additionally gathered in Table 13. In case of building collapse, the appropriate equipment offers no protection against extreme heat and is typically lighter than firefighting equipment.

The interviewed firefighters proposed that an SCBA is used in operations, where the level of oxygen is too low. An example of that case would be a building collapse with a limited amount of oxygen in the atmosphere. In each case the volume of the oxygen inside the tanks provides a limited operation time, that needs to be considered. The accessibility of narrow passages in case of a building collapse has no standard framework for body sizes to fit through. The interviewed firefighter assured that the equipment does not influence the accessibility decisively in a confined space.

In terms of a building collapse, different safety criteria for paths need to be applied. These consists of:

- Stability of building elements (Movement of critical building elements)
- Falling debris from the ceiling
- Damaged gas bottles
- The concentration of oxygen in the atmosphere

The safety of the operating personnel depends on the stability of building elements, which is evaluated by specialists regarding the slightest movement of critical building parts. If that safety is not provided the firefighters would not enter the building or affected areas. Additionally, paths that include areas with falling debris from the ceiling should not be passed. Amongst others, the falling debris could damage gas bottles, making them a safety issue for the operating teams. In this case, the firefighter would try to cover or remove the hazard from the room that needs to be entered. Usually, the concentration of oxygen inside a collapsed building does not require the use of an SCBA, but if the rare case occurs this additional protection needs to be equipped.

Person related path planning parameters and conditions: Flooding inside buildings

The results of this section are summarized in Table 14. For incidents involving flooding, search and rescue dive teams are equipped with diving suits, offering protection against environmental hazards. A drastic change in core temperature of rescue divers is amongst others one major hazard in a diving operation.

The interviewed firefighters from Sweden are equipped with a diving suit inside their vehicle, not including a SCUBA. Additionally, a limited operation time is provided by operating with a diving suit. In case of flooding inside a building, the safety criteria are based on interactive parameters, being:

- Water level height
- Dynamic water level
- Static water level
- Water flow velocity

The water level height determines if the firefighters would enter the building with a divining suit sans SCUBA. Therefore, the water level height is dependent on the capability of the firefighter to walk or swim inside the building. If diving is required, specialists with fully equipped diving gear conduct the operation. Additionally, a dynamic water level changes the water level height depending on time. The interviewed firefighters do not enter the building if the water level is dynamic. For a static water level with tolerable water level height, an operation by the firefighters can be conducted. Additionally, water flow velocity that negatively influences the movement of firefighters is a safety hazard and is avoided by the firefighters.

In this work, the more relevant aspect is how to plan the path, if the building is entered by the firefighter. Therefore, the flooding-related parameters could be applied to different building sections. Inside a complex building, the water level height could for example differ from other sections. Based on the condition, if the firefighters should operate without a SCUBA, building compartments could be ex- or included from the paths. In keeping with the flow velocity and dynamic or static water level, the same approach could be applied to path planning. To be more specific paths should not lead through areas with a flow velocity, which is negatively influencing the movement of the first responder and areas with dynamic water levels. Each of the above-mentioned parameters, are limiting conditions and if one is not fulfilled the area should be excluded from the path.

Person related path planning parameters and conditions: Incidents caused by hazardous materials

The following parameters and conditions for incidents caused by hazardous materials are visible in Table 15. According to EPA Level, A protection provides the “highest level of respiratory, skin and eyes protection from solid, liquid and gaseous chemicals.”. The external conditions for the use of this level of equipment is a prior identification of the chemical substance in terms of hazard to respiratory systems, skin, and eyes. Additionally, Level A protection is worn during operations involving confined or badly ventilated areas. Level B protection provides the same form of respiratory protection as Level A, but with less skin protection. This level of protective equipment is also used when the chemical hazard was identified, a high level of skin protection is excluded, and the primary chemical hazards include liquid instead of vapor contact.

Concerning the chemical protective clothing, limitations were provided by the interviewed firefighter from France. These include the combined occurrence of incidents and the limited protection against multiple hazards. If for example, an incident caused by hazardous materials involves building collapse (explosion), the chemical PPE would not be adequate for the operation, due to reduced mobility and lack of tear resistance. Similarly, the use of chemical protective clothing on scenes with hazardous materials and structure fire offers limited protection against both hazards combined. For these scenarios, the interviewed firefighter does consider not entering the building and wait for specialists to arrive.

In this section, a general approach for incidents caused by hazardous materials (chemical disasters), called zone pathing, is introduced. It consists of red, orange, and green zones, which are areas that have a certain degree of hazardousness, based on the limit reference for the type and concentration of chemicals. Summarized, all gathered parameters in terms of incidents caused by hazardous materials are:

- Limit reference for type and concentration of chemicals
- Red zone (Hot zone)
- Orange zone (Warm zone)
- Green zone (Cold zone)
- Radioactive zone
- Explosiveness of chemical
- (Ventilation)

The limit reference for type and concentration of chemicals in France are gathered from databases called Emergency Response Planning Guideline (ERPG) and Acute Exposure Guideline Levels for Airborne Chemicals (AEGL). The values from the databases determine the color or the hazardousness of the respective zone. The red zone is the most dangerous area and usually inside the whole building when an incident caused by hazardous materials occurred. The orange zone functions as a transition zone between the red and green zone for decontamination. The red and orange area should only be entered with adequate protective clothing against the present materials. The presence inside the green zone, in turn, does not require any specific protection and serves as a safe zone for victims and the remaining emergency responders. In Figure 10 a general overview of subdividing an area into different zones is visualized.

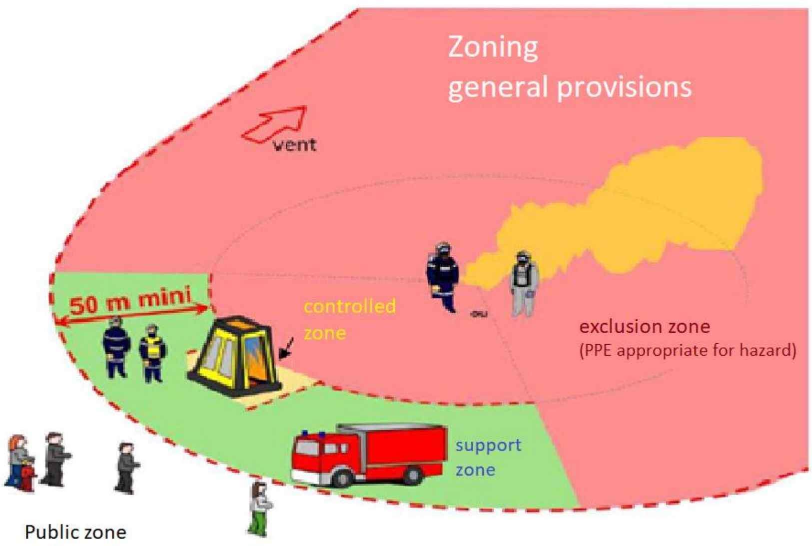


Figure 10 Example for zone pathing. Adapted from: (Nrbce, 2012)

An exception is a radioactive zone, where even special protective equipment offers limited protection inside these areas. If no victims are involved in these hazardous areas, the firefighters would consider not entering the building and wait for specialists.

Before entering the building, the explosiveness of chemicals is evaluated with a databased called BLEVE (boiling liquid expanding vapor explosion). The firefighters have a tool to measure the explosiveness of gases inside the building, solely entering the scene if the explosive level measurement is zero. How certain gases or chemicals spread inside a building is amongst others dependent on the ventilation. The interviewed firefighters proposed that a reliable simulation for chemicals spreading inside a building would have too many factors to be evaluated.

Person related path planning parameters and conditions: Incidents caused by terrorism

Finally, an overview of the following data is provided in Table 16. In case of terrorism, the usual equipment with additional ballistic vests or helmets is worn, according to the interviewed firefighter. The added weight can reduce the operating time of the firefighters.

The gathered path planning parameters for terrorism consist of the following:

- Authorized zones
- (Potential location of the terrorist)
- The appliance of additional safety parameters

For the authorized zones, the police and special forces decide accessible areas inside the building. Inside these authorized zones the fastest path should be proposed for the firefighters. If the firefighters are one scene before the police, they will consider entering the building keeping in mind where the potential hazard could be located. The appliance of additional safety parameters should be conducted if the consequences of terrorism are structure fire, building collapse, or incidents caused by hazardous materials.

4.2 Summary and weighting of the results

4.2.1 Summary of results

In terms of the general boundary parameters for path planning, all the interviewed emergency responders agreed that path safety and path length are the mainframes for their decision-making. Additionally, the priority of the target position or the location where the path should lead needs to be considered. For example, the priority of saving a victim is the highest in the operation and simultaneously the location where the path leads to. The path length is based on dimensions of building areas, corridors, staircases, and further. For path safety, incident-related events determine if certain areas of the building should be accessed.

4.2.2 Weighting of person related parameters

Finally, person-related parameters are contextualized with boundary conditions for path planning. The PPE enables first responders to enter hazardous sections of a building if the protective equipment requirements are fulfilled. Based on the interviews and the gathered parameters a distinction between types of hazardous areas is made. The first type of hazardous area is tolerable with PPE (Warning level 1), entering the second type of area should be avoided (Warning level 2) and the third section should completely be excluded from the path (Warning level 3). Separate considerations for firefighters with a different type of PPE are made in the following. It is important to mention that this categorization is situational and a deviation of parameters within warning levels is possible.

For firefighters, different sets of equipment in accordance with the respective type of incident are regarded. Subsequently, the gathered person-related parameters are arranged by the type of hazardous area (Warning level). This categorization provides an overview of the relation between equipment-related properties and the impact of the incident on people.

Warning levels for firefighters with thermal protective clothing and SCBA in case of structure fire are presented in Table 5. A categorization of person-related parameters in case of building collapse for firefighters equipped with (non-thermal) protective clothing is made in Table 6. In Table 7 a categorization based on firefighters equipped with diving suits (without SCUBA) during flooding events, is presented. Warning levels for firefighters equipped with chemical protective clothing during incidents involving hazardous materials are shown in Table 8. In the case of terrorism no additional information, concerning a categorization into warning levels, is provided.

Structure fire: person-related parameter	Warning level
Maximum ambient temperature for firefighters + equipment	3
Danger of rollover	3
Unsecured shafts/ openings	3
In danger of collapsing	3
Moderate amount of smoke	1
High amount of smoke	2
Moderate visibility	1
Bad visibility	2
Stocks of chemicals (heated up)	3
Hazardous materials in contact with fire	3

Table 5 Categorization of incident related parameters for firefighters equipped with thermal protective clothing and SCBA (Own presentation)

Building collapse: person-related parameter	Warning level
Low concentration of oxygen in the atmosphere (just for SCBA)	3
Falling debris from the ceiling	3
Stability of building elements	3
Damaged gas bottles	2

Table 6 Categorization of incident related parameters for firefighters equipped with (non-thermal) protective clothing (Own presentation)

Flooding inside buildings: person-related parameter	Warning level
Static water level	1
Dynamic water level	3
Water level height: if walking or swimming is possible	1
Water level height: until the ceiling	3
No flow velocity	1
Moderate Flow velocity	2
Dangerously high Flow velocity	3

Table 7 Categorization of incident related parameters for firefighters equipped with a diving suit (without SCUBA) (Own presentation)

Incidents caused by hazardous materials: Person related parameter	Warning level
Green zone	1
Orange zone	1
Red zone	1
Radioactive zone	3
Explosiveness of chemicals	3

Table 8 Categorization of incident related parameters for firefighters equipped with chemical protective clothing (Own presentation)

5 Discussion

A basic path planning concept for evaluating expedient routes for firefighters is provided in this study. The main framework consists of the path length and path safety including parameters and boundary conditions based on the impact of hazardous events on the building and persons inside the operating area. The importance of this study lies in optimizing fire brigade interventions to save human lives and materialistic resources. Some parameters and boundary conditions are not always clearly quantifiable and therefore discussed in the following section.

5.1 Analysis of major findings

The fact that saving victims have the highest priority in the operation, overshadows certain path safety parameters, due to a higher risk acceptance of the firefighters. That means some firefighters would always consider entering the building although their lives could be endangered. In this case, the path planning could contradict certain safety parameters of this work.

The path length requires a differentiated consideration because the shortest path is not always the quickest path to a target position. For example, the path length of a corridor should not be compared to the length of a staircase, due to altitude which is in most cases the slower path for the same length.

5.1.1 Analysis of building-related path planning parameters

Analysis of building-related path planning parameters and conditions: Structure fire

In this work solely the fire protection properties of the building material concrete were considered in detail. Nonetheless, the fire protection classes can be applied to the majority of load-bearing building materials according to Table 3.

The components of the fire alarm system, such as control panels, key depots, sprinkler, and smoke vents are difficult to quantify with the given literature, in terms of boundary conditions from a building-oriented perspective. Therefore, fire alarm system component consideration should be possible to be requested from first responders, to allow individual decisions.

Analysis of building-related path planning parameters and conditions: Building collapse

One major issue with areas that are in danger of collapsing is the quantification into reliable building sections. These assumptions should only be made by qualified personnel and should therefore not be conducted in this study. Conclusively, reliable path planning for in danger of collapsing areas should not be made without the assistance of specialists.

Analysis of building-related path planning parameters and conditions: Flooding inside a building

From the literature review, no building-related parameters for flooding inside buildings were gained, because most of the literature covers flooding evacuations on a larger scale, instead of the building itself. Additionally, the dynamic parameter that not fixated objects could block paths inside a flooded building is relatively vague and requires further consideration.

Analysis of building-related path planning parameters and conditions: Incidents caused by hazardous materials

The assumption that in zone pathing the whole area of the building should be considered as a red zone merely provides information about the use of equipment in this study. Technically this building-related condition is an indirect determination of person-related parameters, involving equipment properties.

Analysis of building-related path planning parameters and conditions: Incidents caused by terrorism

No additional building-related path planning parameters and conditions were gained from the literature research or qualitative interviews in this study. Therefore, it is referred to the analysis of the results gathered from incidents involving structure fire, building collapse, and incidents caused by hazardous materials based on the information provided in Figure 9.

5.1.2 Analysis of person-related path planning parameters

Analysis of person-related path planning parameters and conditions: Structure fire

Conditions for path planning based on the visibility or the amount of smoke inside a building, require a deeper analysis. As already discussed, the visibility for the firefighters is amongst others based on the amount, distribution, and density of the smoke. How these properties exactly correspond with each other is beyond the scope of the study. However, a more simple approach would be to neglect the amount of smoke from the consideration and focus on the limiting factor visibility. Therefore, paths with the best visibility in affected building sections should be preferred.

Hazards occurring in the remaining building section can probably be applied to the first escape route but were not in detail discussed. In the interviews, it was assumed that the fire outbreak is inside the remaining building sections instead of the first escape route (staircase).

The maximum heat resistance of firefighters and victims are approximate values and can differ from person to person and/or equipment properties. Nonetheless, the maximum ambient temperature resistance values were mentioned to provide a rough estimate.

Analysis of person-related path planning parameters and conditions: Building collapse

The interviewed firefighter mentioned that damaged gas bottles should be covered or removed from the room you need to pass. Therefore, this parameter would not directly be an inclusion or exclusion condition in terms of path planning.

Analysis of person-related path planning parameters and conditions: Flooding inside a building

The assumption that building areas could be affected differently for each flooding parameter's dynamic/static water level, water level height, and flow velocity is not proven in detail in this work. Additionally, the relations between these parameters inside buildings are beyond the scope of this work.

Analysis of person-related path planning parameters and conditions: Buildings caused by hazardous materials

In terms of zone pathing, areas based on the limit reference for type and concentration of chemicals, subdividing different zones inside the building should be avoided. Therefore, red, orange, and green zones are predominantly influencing the used equipment during an operation. As already discussed, the whole building is usually marked as a red zone, which makes a differentiation solely based on that parameter not reliable. If the whole area is considered a risk zone the shortest path inside the building is determined.

The occurrence of multiple different incidents is a complicated consideration according to the interviewees. In terms of path planning the appliance of combined safety parameters and the respective protective parameters of the equipment could be possible but were not discussed for each case individually.

Analysis of person-related path planning parameters and conditions: Buildings caused by terrorism

The amount of data in terms of terrorism is relatively low because the interviewed first responders are primarily not responsible for incidents caused by terrorism. Path planning is dependent on special forces that determine the path for the remaining first responders during an operation.

5.2 Limitations of the research

During the research, a variety of limitations occurred in terms of the quantification of certain path planning parameters and boundary conditions. One major issue for gathering path planning parameters is the lack of information in the assessment basis of the building, especially in terms of collapse. Whereas in the case of a structure fire, the building is designed based on fire protective properties, that create the basis for building-related parameters. Additionally, the layout of the building after a collapse completely changes or dissolves, which makes path planning even more difficult.

Another limitation is the zero-tolerance policy of the protection from hazards caused by building collapse. Every impact could be life-threatening and no protective requirements of the PPE are present, therefore path planning conditions are hardly gained from the PPE.

In terms of flooding inside a building most literature focuses on a larger viewing frame, for example, the whole area of flooding apart from the building is regarded. It is beyond the scope of this study to examine a large area involving various buildings and streets for path planning.

Further limitations evolved during the interviews because most of the first responders mentioned that their decision-making is often based on experience and intuition instead of specific parameters. Therefore, the implementation of path planning should focus on providing multiple alternatives, rather than making the decisions for the first responder.

The reader should bear in mind that the study is based on data collected from European interviewees. It is important to consider that each country has its approach and equipment when conducting an operation. These properties could strongly influence the respective parameters for path planning.

5.3 Recommendation for further studies

Some of the limitations of the study can serve as a foundation for further research in this field. One major question is how specific parameters gathered in this study are gained on scene. For instance, a key factor in terms of path planning is visibility, which is influenced by smoke. How exactly the visibility is implemented in the path planning or how exactly the smoke determines the visibility could be an own field of research. Similar would count for evaluating in danger of collapsing buildings with the movement of critical building elements. This evaluation is conducted by qualified personnel and a tool that directly evaluates this information could be helpful in time-limited operations. A first visual approach of determining the stability of building elements was already made in a study by Zhu et al., 2009.

Most of the literature in terms of flooding refers to a larger scale beside the building, which indicates a separate consideration for path planning. For operations involving police, the area of responsibility is predominantly the surrounding of the building. This research is restricted to the building itself because the amount of information would be beyond the scope of work. A separate study that is based on first responders and buildings that occur beyond the building, could help to complete the whole extent of path planning.

6 Conclusion

Referring to the question of what parameters and boundary conditions are relevant for path planning, a building- and person-oriented perspective for each type of incident was chosen. The types of incidents: (1) Structure fire; (2) Building collapse; (3) Flooding inside buildings; (4) Incidents caused by hazardous materials; (5) Incidents caused by terrorism; were considered separately in this work for a better understanding. The potential relations between the discussed incidents are formulated in Figure 9.

The first responders' police and USAR teams were excluded from the path planning consideration because they would rarely enter the building directly during the occurrence of the discussed incidents. Therefore, the main parties in this work were firefighters when referring to first responders. Path planning is also dependant on the type of equipment worn during hazardous operations. How exactly the properties of the PPE influence the person-related parameters for path planning is discussed in Chapter 4.2.2.

The main findings of this work are general path planning parameters and conditions that are valid for all discussed types of incidents, summarized in Table 9.

Type of Building	Path planning parameter	Conditions	Explanatory note
General			
	Priority of target position	• propose paths to the location with the highest priority for the operation	• priority of saving victims is the highest in the operation
	Path safety	• propose the safest paths based on the building-related safety parameters for each type of responder and building	• path safety has the second-highest priority in terms of path planning • (Note: in some cases, the shortest path could be the safest path)
	Path length	• propose the shortest paths in the framework of path safety	• the shortest paths are determined based on the dimensions of the building

Table 9 General path planning parameters and conditions for firefighter (Own presentation)

The priority of the target position functions as the major input parameter for the path planning because it sets the first destination of the path. The path to this target position is then determined with the coordination of path safety and path length. This triplet of parameters in this study is the main foundation for path planning because all further parameters can be implemented into the path safety with the case-specific appliance of the building- and person-related parameters. All gathered path planning parameters can be found in the Appendix of this work:

- General parameters and conditions (Table 10)
- Building-related parameters and conditions. All incidents (Table 11)
- Person-related parameters and conditions: Structure fire (Table 12)
- Person-related parameters and conditions: Building collapse (Table 13)
- Person-related parameters and conditions: Flooding inside buildings (Table 14)
- Person-related parameters and conditions: Incidents caused by hazardous materials (Table 15)
- Person-related parameters and conditions: Incidents caused by terrorism (Table 16)

In general, this study provides a foundation for a path planning module used by first responders. The researched topic is relatively complex, and many aspects need to be considered when implementing the parameters and conditions. The presented findings are a combination of qualitative and quantitative results and the amount of further potential information is unknown. In the future, further research in terms of the evaluation of building collapse and flooding inside buildings could be helpful for this study. Conclusively, new insights in this field could help first responders in perilous buildings, conducting their operations quicker and safer with a higher success of saving lives.

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Appendixes A

Type of Building	Path planning parameter	Conditions	Explanation
Genera	Availability of paths due to the use of equipment	• different/combined appliance of equipment related parameters for each type of first responder	• in Sweden for example the fire protective equipment also protects against chemical hazards • one set of equipment can be used for combined building types
	Priority of target position	• propose paths to the location with the highest priority for the operation	• priority of saving victims is the highest in the operation
	Path safety	• propose the safest paths based on the building-related safety parameters for each type of responder and building	• path safety has the second-highest priority in terms of path planning • (Note: in some cases, the shortest path could be the safest path)
	Path length	• propose the shortest paths in the framework of path safety	• the shortest paths are determined based on the dimensions of the building

Table 10 General parameters and boundary conditions for firefighters

Type of Building	Path planning parameter	Conditions	Explanation
Structure fire	Activated Sprinkler	• not decisive for path planning	• often not present in residential buildings
	Automatic fire extinguishing systems with gas (CO_2)	• exclude paths within areas with activated extinguishing systems	
	Accessibility of areas with special tools	• consider paths through closed doors, window, or metal curtains	• hydraulic cutting or spreading tool provides access to closed areas
	Fire resistance duration	• if the duration of fire exceeds fire safety duration -> building is in danger of collapse • exclude paths within areas in danger of collapsing	• avoid sending in personnel when the building is in danger of • relatively uncommon, due to sufficient fire resistance duration
	Height of building	• determines if a safety elevator is inside (in Sweden) • consider paths developed by elevator	• safety elevators in Sweden provide a safe and quick path to their target position • A special key used by the firefighters provides access to the elevator during a fire
Building collapse	Accessibility of areas with special tools	• consider paths through areas with collapse concrete elements • propose paths with the least resistance or amount of building elements	• difficult to enter even with cutting or drilling equipment
Flooding	Door opening direction	• prefer paths with doors that open against the direction of the water masses	• a door is difficult to open, because of the pressure caused by the water, when opened in the same direction
	Not fixated objects could block the path	• exclude paths within areas where large objects could block the way, due to water flow	• floating materials such as tables or larger objects could block the

			path if the water flows rapidly
Incidents caused by hazardous materials	Zone pathing inside a building	• avoid subdividing zones inside a building	• zone pathing should be as simple as possible and is not recommended by firefighters
	Type of building	• determines if hazardous materials could be on site	• provides information about the presence of hazardous materials inside the building

Table 11 Building related parameters and boundary conditions by type of incident (Own presentation)

Type of Building	Path planning parameter	Conditions	Explanation
Structure fire	Maximum heat resistance of s	• propose paths through areas with ambient temperatures below Maximum heat resistance of PPE	
	Direct flame impact	• exclude paths within areas in danger of direct fire impact (rollover)	
	Maximum heat radiation tolerance	• exclude paths within areas that exceed the maximum heat radiation tolerance	
	Maximum ambient temperature for equipped firefighters	• propose paths through areas below the maximum ambient temperature for equipped firefighters	• the maximum ambient temperature needs to be lower than the maximum heat resistance of firefighter (depends on properties of PPE)
	Danger of rollover	• exclude paths within areas in danger of a rollover	• limited protection of the firefighter with PPE against direct flame contact
	Unsecured shafts/ openings	• exclude paths within areas with unsecured shafts/openings	• firefighters could fall into, endangering their lives and the operation
	Accessibility of first escape route	• exclude paths within areas when in danger of collapsing • propose paths when at least a moderate visibility is present • prefer paths with safer criteria if more escape routes are available	• the first escape route in Germany is in most cases staircase, which is mandatory in the layout of the building
	Accessibility of second escape route	• propose paths within the second escape route, if the first escape route is not accessible	• the second escape route in Germany is in most cases provided by a turntable ladder that

			creates an entrance to the building
	Visibility (Smoke)	• propose paths through areas with at least moderate visibility (if possible) • consider smoke reducing installations within the path	• a smoke wall could also be directly under the ceiling, granting visibility above the floor • visibility depends on many factors including the amount of smoke inside the building
	Heated up Stocks of chemicals	• exclude areas from paths next to heated up chemical hazards	• chemical stocks could cause a potential risk if heated up
	Hazardous materials in contact with fire?	• exclude areas from the path with Hazardous materials that are in contact with fire	
Structure fire: Victim rescue	Location of the victim (above or beyond the fire)	• above fire: propose paths where the fire could be extinguished. beyond: propose safest and quickest paths	if the victims are above the fire, firefighters would consider extinguishing it on the path to the victim
	Maximum ambient temperature for victims	• propose paths through areas below the maximum ambient temperature for victims	• maximum heat a victim can tolerate is about 60 or 70 degrees (no specific value)
	Smoke for victims	• propose paths through areas with at least moderate visibility (if possible)	• smoke is very stressful (not harming) for the victim even with SCBA
	State of a victim (unconscious) -> Evacuation of by the first escape route	• propose path from which the firefighters entered the building (when safety criteria for victims are fulfilled [])	• firefighters have an SCBA for a potential victim • Smoke would not be a hazard for the victim if an SCBA is applied

	State of the victim (conscious) -> Evacuation by the second escape route	• propose paths to safe positions for the victim	• secure the victim inside a hazard-free area (balcony, roof) until the turntable ladder is available
	Safe position for the victim	• propose paths to areas within the safety criteria for victims [])	• the victim will be guided to a safe position (balcony, roof, hazardous free room)

Table 12 Person related path planning parameter and conditions (firefighter + equipment): Structure fire

Type of Building	Path planning parameter	Conditions	Explanation
Building collapse	Use of SCBA	• if the level of oxygen is too low the parameters of an SCBA should be applied	• operation time is dependent on the volume of the oxygen tank
	Volume of oxygen inside SCBA	• determines operation time	• the volume of one gas bottle provides around 30 minutes of operation time
	Accessibility of narrow passages	• propose a path through areas where the body of the firefighter can fit through	• no standard framework for body sizes to fit through confined space • equipment does not influence the accessibility decisively in a confined space
	Falling debris from the ceiling	• exclude paths within areas with falling debris	• limited protection against falling debris
	Damaged gas bottles	• consider damaged gas bottles on the path	• cover or remove these hazards from the room you need to pass
	Concentration of oxygen in the atmosphere	• determines if an SCBA needs to be used for the firefighter and victim • different equipment parameters need to be applied	• usually, the concentration of oxygen in the operating area does not require an SCBA
	Stability of building elements	• consider not proposing a path if the stability of building elements is excluded	• stability of building should solely be evaluated by specialized personnel
	Movement of critical building elements	• parameter for evaluating the stability of the building	• slightest movement of critical building elements is measured with lasers

Table 13 Person related path planning parameter and conditions (firefighter + equipment): Building collapse

Type of Building	Path planning parameter	Conditions	Explanation
Flooding inside building	Use of SCUBA	• exclude paths within areas where the use of a SCUBA is necessary	• if the water level allows firefighters to swim or walk with a diving suit they would enter the building
	Diving suit operating time	• determines the maximum length of the operation	• the water temperature is not decisive for path planning, just the operation time • maximum operation time is between 30 and 45 minutes
	Dynamic water level	• exclude paths within areas with dynamic water level	• firefighters will probably not enter the building if the water level is dynamic
	Static water level	• propose paths within areas with static water level • (if all remaining flooding conditions are fulfilled)	
	Water level height	• propose paths within areas with water levels below x • (if all remaining flooding conditions are fulfilled)	• x is dependent on the capability of the firefighter to walk or swim inside an area • If the use of the diving gear is necessary, the firefighter won't enter the building
	Flow velocity	• exclude paths within areas with a dangerously high flow velocity	• usually, firefighters won't enter the building if the water flow is hindering their movement
	Operation time based on the water level	• evaluation of the operation time with the rise of water level until ceiling height is reached	• If the rise of the water is known or predictable, the remaining time until areas

			are completely flooded can be evaluated

Table 14 Person related path planning parameter and conditions (firefighter + equipment): Flooding inside buildings

Type of Building	Path planning parameter	Conditions	Explanation
Incidents caused by hazardous materials	Limit reference for type and concentration of chemicals	• determines type and accessibility of the below-listed zones	• References are provided by the following database: • ERPG (Emergency Response Planning Guideline) • AEGL (Acute Exposure Guideline Levels for Airborne Chemicals)
	Zone pathing	• propose paths dependent on the type of zone	• Subdividing areas around the building into red, orange, and green zones • Avoid subdividing areas inside the building • Zone pathing should be as simple as possible
	Red zone (Hot zones)	• solely propose paths for personnel with protective equipment	• usually, a hazardous area inside the building
	Orange zone (Warm zone)	• solely propose paths for personnel with protective equipment	• serves as a transitional area between hot and cold zone and is used for decontamination
	Green zone (Cold zone)	• propose paths for personnel without protective equipment	• serves for all types of responder and victims without protective equipment
	Radioactive zone	• exclude paths within areas of radioactive zones	• even limited protection with special protective equipment
	Explosiveness of chemical	• propose paths if the explosive level measurement is	• Determination of explosiveness of the chemical with BLEVE

		zero inside buildings (level of explosive concentration for gas pipes)	(boiling, liquid expanding vapor explosion) database
Hazardous materials and structure fire	Protection	• entering the building should be avoided (besides rescuing victims)	• entering the building should be avoided (besides rescuing victims) • no protection against chemical release and structure fire
Hazardous materials and building collapse	Protection	• entering the building should be avoided (besides rescuing victims)	• no protection against chemical release and building collapse • chemical protective suits are too fragile for entering a collapsed building

Table 15 Person related path planning parameter and conditions (firefighter + equipment): Incidents caused by hazardous materials

Type of Building	Path planning parameter	Conditions	Explanation
Incidents caused by terrorism	Operating time	• determines the maximum length of the operation	• use of additional helmets and ballistic vests -> quicker exhaustion
	Authorized zones	• propose the shortest path within authorized zones	• police and special forces decide accessible areas for firefighters • the decision of special forces is based on the presence of terrorists or bombs
	Appliance of additional safety parameters	• in terms of path planning, all above-listed safety parameters could additionally be applied	• consequences of terrorism could a structure fire, building collapse and is also related to hazardous materials

Table 16 Person related path planning parameter and conditions (firefighter + equipment): Incidents caused by terrorism

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