Path planning through disaster scenes: qualitative interviews to assess relevant parameters

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Abstract

Death tolls resulting from natural or man-made disaster scenarios are high. Among the different facilities, a large amount of these deaths are connected to disasters in buildings. This paper investigates existing measures for managing disasters in buildings and formalizes key requirements to adopt them for automated path planning.

Path planning is a research field focused on finding optimal paths in varying environments according to specific metrics. As the followed evacuation path has a high impact on the success of managing disasters, it is necessary to optimize the available paths. This can be done by considering numerous different aspects such as the incident type, facility type, and the surroundings. By using path planning in disaster scenes, the effectiveness of first responders on site can be increased. While optimization of the path length can enhance the speed of first responders, the provision of safe paths through disaster scenes offer protection from hazardous situations. Relying on past experiences to plan paths through disaster scenarios is a common approach for first responders. However, the approaches to improve first responder operations while using novel path planning support often lack this experience. One approach to overcome this gap is to use qualitative interviews to gain knowledge on how first responders choose paths in disaster scenes. We conducted six qualitative interviews with three different types of first responders to understand how they determine paths through four chosen building disaster scenarios. Four firefighters, one police officer, and one search and rescue responder were interviewed concerning their behaviour when facing a building collapse, fire, flooding or hazardous material in a building.

The results show a comprehensive list of parameters that can be used as test parameters to plan paths through various disaster scenes. The parameters that represent decisive criteria for determining a path are expected to be a valuable contribution to generating path planning frameworks. They would not only take into account the navigability of spaces due to dimensional constraints but also allow first responders to access hazardous situations and disaster scenes safely.

Keywords: path planning, disaster management, path planning parameters, dynamic environments, path planning optimization

1 Introduction

First responders are among the first to arrive and interact with hazards at disaster scenes. First responders' operations involve finding and saving victims as well as fighting disasters' hot spots. Typically, disaster environments include diverse kinds of facilities, such as infrastructure and residential buildings, where the facilities' size and complexity are continuously increasing due to modernization processes in the construction industry. This change is a challenge for first responders as numerous aspects and dependencies must be accounted for before and during their operations [6, 5].

Researchers, during the past century, have been working on improving complex disaster situations for first responders [23, 8, 12]. Modern mapping technologies in combination with state-of-the-art unmanned vehicles and scanning technologies allow real-time mapping of the scene [4]. The use of artificial intelligence enables the identification of obstacles, victims, and disaster hot spots. With path planning, fast and safe paths to goal positions can be generated for mobile objects, such as first responders and unmanned vehicles [8]. All of these state-of-the-art computational solutions promise considerable improvements in the acceleration of disaster scene understanding and decision-making support for first responders in pressuring situations. The ultimate goal is the enhancement of the speed and safety of disaster operations.

Particularly path planning, of the above mentioned, is a research field which offers different dimensions of complexity as it comprises multiple interconnected parts. In this regard, path planning algorithms themself can be improved so that they provide more reliable or faster results. An extended research in this field focuses on the time dimension and dynamics in the scene to provide real-time assistance in the case of disasters. Especially the variety of obstacles that occur during disaster scenarios challenges path planning researchers when generating a holistic system. The question on how different obstacles can be included in a path planning module does not only involve considering where these obstacles are, and with how much certainty the obstacle boundary can be determined, but also the question on how different obstacles influence the accessibility of the path. For example, obstacles like fire may make paths not accessible. On the other hand, smoke does not necessarily block the path but only increases the difficulty of accessing the path. Trade-offs between different paths to the goal position need to be made when several ways are hampered by different obstacles like smoke, fire, or toxic gases.

Current literature on disaster path planning tends to simplify this problem to an obstacle-avoidance problem, not taking into account the different types of danger of obstacles that can be found in disaster scenes [8, 23]. Paths are planned around obstacles, like fire or smoke. Not only is this list of considered obstacles very simplified, but moreover, no distinction is made between the different hazardousness of obstacles.

To allow first responders to receive valid paths from a path planning solution, specific situations must be defined as obstacles with weights, describing the severity of the presence of these obstacles in the identified possible paths. Hence, this paper addresses this research gap with a holistic literature review, extended by qualitative interviews to generate a list of parameters that can be used as obstacles and their weighting to represent the relevance of avoiding specific obstacles when determining a path. Four significant disaster situations were chosen, representing the main categories for which parameters should be identified. To generate a holistic list of parameters, six first responders from different departments were interviewed. The interviews were analyzed according to the retrieval of relevant parameters and the significance of each parameter with regard to the other parameters.

2 Literature Review

A vast amount of regulations and training material on how first responders should behave in different incidents exists. The main characteristics are that these regulations are not necessarily consistent in different countries and also cities [26]. Not only does the building material which differs per region influence the tactics, but moreover, different countries and cities by history have different regulations and training manuals [26]. A further characteristic described in the regulations and training material is that there is most of the times not only one clear solution to a problem but multiple. Different factors determine the procedure in an operation. Pulm [20] gives an example for the complexity of a kitchen fire leading to influencing questions like "Are lives in danger? Is the stairwell filled with smoke? What kind of building type is it? Are the windows opened?" Based on the different types of factors, different solutions may be applicable in the same situation.

2.1 Parameters influencing first responders' pathway decisions in different incidents

The most common disaster types in buildings can be broken down into four major areas: building collapse, fire, flooding and hazardous material. An optimal path through the disaster scene to a goal position must be found for each incident type. Pulm [20] states that every such solution must base on qualified parameters which are to be taken into account. According to Pulm [20], these parameters can for instance be found in regulations (laws, ordinances, accident prevention regulations, fire department service regulations, etc.). Further sources are natural scientific laws, the available workforce of first responders, their efficiency, and the available equipment.

Existing literature on the above-described categories is investigated to derive suitable parameters for a path planning approach. Generally, a distinction can already be made between the influence that the incident has on the *building* and the impact that the incident has on the *first responder*. An example is a fire, which limits the available paths due to its interaction with the building: fire may impact the stability of the building and therefore make paths not accessible anymore. When fire interacts with the person, the condition must be fulfilled that the surrounding temperature does not exceed the maximum temperature resistance of the person including its protection clothes.

When it comes to the building collapse incident, especially the inaccessibility of parts of the building, due to decreased stability of the structure, plays a role for first responders choosing their path through the disaster scene [15]. Hereby, it is especially important that different types of buildings collapse differently.

Building related parameters that have to be considered when planning a path due to a fire incident in a building are whether construction elements are load-bearing or non-load-bearing [25], their stability and fire resistance [18], space enclosing elements that prevent fire and smoke from spreading [25] as well as smoke protection doors [17]. Technical building elements which may influence the planned path are, for instance smoke vents [2]. According to [21], "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" [16]. Especially fire fighting equipment influences the heat resistance of first responders in fire incidents.

Flood depth and its intensity are the main parameters that affect a building in a flooding incident. Maiwald and Schwarz [14] introduce five structural damage degrees of facilities depending on flood depth, and intensity. For first responders, especially water temperature is an important parameter influencing their possibility to access a flooded area [24].

Hazardous material refers to either explosive, flammable, or toxic substances. [19] describes the reaction of a building on an exploding material. While the explosive and flammable impacts come down to the same effects as defined by the *fire* and *building collapse* sections, the toxicity of material mainly has an impact on the person itself.

2.2 Current parameters used for path planning

A path planning module perfectly representing the real-world environment would have to consider all the parameters described in Chapter 2.1. However, state-of-the-art path planning solutions do not represent such a holistic solution that includes several different types of disasters. This section analyses to what extent existing literature on path planning in disaster scenarios includes and represents the above-described obstacles and their corresponding parameters. Based on the investigation of how current literature distinguishes between different obstacle types, the research gap addressed with this paper is defined.

Similarly to the approach presented in this paper, Chou et al. [8] base their decisions on how to plan paths through a fire incident using a survey which they conducted with the Disaster Rescue Division of the Tamsui and Zhuwei brigades of the Third Emergency and Rescue Corps of the New Taipei City Fire Department. The path-planning model developed by Chou et al. [8], however, only takes into account ignition points of fire and plans paths around them. These ignition points are defined based on information gathered from Bluetooth sensors measuring temperature and smoke.

Wang, Zlatanova, and Oosterom [23] name "fires, plumes, [and] floods" as examples for obstacles. Their research does not contain further investigation on what other hazardous situations could be obstacles. Instead, they focus on how to handle these obstacles. Besides Wang, Zlatanova, and Oosterom [23] and Chou et al. [8], various researchers [22, 7] define plumes or fire as obstacles in disaster areas.

Another type of parameter, also related to flooding, can be found in Liu, Hatayama, and Okada [13]. Instead of treating a flooding situation as an obstacle that is to be avoided, their flood model, takes into account the decrease of walking speed depending on the water depth during a flood.

2.3 Applicability of parameters with building models

To what extent path planning parameters, which influence pathway decisions, can correctly be represented in a model depends on the technical possibilities of the chosen modeling paradigm. A common form to represent buildings in computational environments is using digital building models. Two of the most popular building representations [9, 11] are building information models (BIM) includings its vendor neutral format, industry foundation class (IFC), and geographic information systems (GIS) which can be represented through the city geography markup language (CityGML).

The concept of building information modeling generally consists of creating and using digital representations of buildings and other infrastructure asset, which store more than only the geometrical information. A building information model thus stands for a comprehensive, informative representation of a building consisting of three-dimensional building components and additional non-geometrical information [3]. The data model IFC [10] is the standard format in which building information models are stored to exchange them with other disciplines and manufacturers. IFC consists of a data structure to describe 3D objects in the building construction industry. Besides construction elements like walls, the model also contains non-physical spatial objects like spaces [11]. By storing information like the type of the room, or the material of a wall in the building information model, this kind of model becomes an essential source of information for parameter-centric path planning.

The concept of GIS is closely aligned, however not directly comparable with BIM. While BIM focuses on the digital representation of single buildings or infrastructure asset, GIS represents a larger scale of the environment, including buildings, streets, trees, bridges, and the terrain with a coarser level of detail [11]. Similar to the dataformat IFC for BIM, there exists the dataformat GML for GIS. CityGML, a GML application schema, is the international standard when it comes to the manufacturer-neutral exchange of semantic 3D city and landscape models [11].

The approach presented in this paper aims to extract the generated parameters list from IFC- and CityGML-models. Then the extracted environment information can be used as an input for the different path planning algorithms, which facilitates an automatic and seamless workflow. Additional information about the incident type could be stored in an IFC- and CityGML-model, but may be extracted from other information sources as well.

3 Concept

Literature review revealed that no holistic set of parameters exists, that describes various obstacles in various incidents. Moreover, when various obstacles were considered by researchers, they were all handled similarly; with no special attention to their individual characteristics. However, literature review about first responders' regulations revealed that these obstacles must be considered with a different weighting since they are associated with different harmful effects and require special inclusion in order to be safely avoided. The regulations of first responders are often comprehensive, not normed, and contain information that can not be directly mapped to the topic of path planning. Path planning is rather about how to get somewhere if the goal position and all obstacles on the way are known. The regulations are more likely to describe the procedure of a first responder having to search a path for an uncertain goal position. Moreover, these regulations mostly rely on training material for new first responders and contain very little on-site expert experience of trained first responders.

Expert interviews have been proven to be a useful tool to collect valuable information and generate data. The concept of this paper does therefore rely on expert interviews. Six expert interviews have been conducted with three different types of first responders to generate a parameter set that describes various obstacles in various incidents and their severity. Police, firefighters, and search and

Parameter	Description	Rating
Path length	The shortest Path is preferred.	1
Explored areas	Paths that are already explored should be preferred over those that are unexplored.	1

Table 1: For all incidents: Categorization of parameters for firefighters.

rescue responders were among the interviewees. The first three interviews revealed that police and rescue responders do not enter the disaster scene in the considered scenarios. As a result, the last three interviews were conducted with firefighters. For each covered incident type, three main topics were addressed. These were:

1. What is the general approach in the operation?
2. How does the first responder plan a path to the target position?
3. What are potential obstacles/hazards that could block the path?

Depending on the interviewees' replies, the conversation was steered individually to a more detailed elaboration of path planning parameters.

The evaluation of the interviews includes the derivation of path planning-related parameters and an assessment regarding their importance concerning the other parameters. Four levels of significance were chosen to weight the determined parameters.

4 Results

One police officer, one search and rescue responder, and four firefighters were interviewed regarding their path planning behavior in buildings in four different incidents: building collapse, fire, flooding, and hazardous material. The first three interviews were conducted with all three different types of first responders to gain a general overview of the distribution of responsibility between them. These interviews revealed that, while police officers and urban search and rescue teams are present at the scene, they would not enter a building. Thus, there do not exist any path planning parameters for those responders. The parameter list that was generated based on the interviews therefore only contains parameters for firefighters.

The generated parameter lists for the incidents building collapse, fire, flooding, and hazardous material are presented in Table 2 - 5. While each of those tables refers to one incident, Table 1 shows parameters that account for all incidents. Each parameter that could be found with the interviews is presented in the left column. Each parameter is given a rating, presented in the right column. This rating describes how this parameter should be handled, thus, whether this parameter describes a circumstance that is preferred in the path planning or a circumstance that should be avoided. Four levels of significance describe the different parameters: 1 = preferred; 2 = can be used; 3 = should be avoided; 4 = must be avoided.

Some parameters have different ratings according to specific circumstances. One example is *explosive material*, the last parameter in Table 3. While both *material in danger of explosion that is in contact with fire*, and *hazardous material which shows a temperature increase*, must be avoided under all circumstances, *material in danger of explosion that is not in contact with fire* can be handled with a lower level of significance. Thus, the significance rating for the latter case is three, contrary to the first two having a rating of four. The descriptions for which ratings are made are given in the middle column of each table.

4.1 General parameters

Two parameters were determined as general parameters. These parameters, presented in Table 1 account for all incidents. Both, a preference for the shortest path, and already explored areas were mentioned by the first responders. Already explored areas should, however, only be preferred, if the task is to reach a specific goal position fast and safe, which is the assumption for this path planning task. If the area should be explored for further victims on the way to a goal position, explored areas may not be preferred.

4.2 Building Collapse

The parameters for firefighters in a building collapse can be broken down into seven main parameters. These parameters, presented in Table 2, describe the main obstacles that need to be considered in a path planning module that plans a path through a collapsing building. 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 is that the respective emergency responder should not enter areas in danger of collapsing. However, if a partly collapsed building is entered, the accessibility of narrow passages in case of a building collapse must be assured. The path with the least resistance of building elements is thus preferred.

Parameter	Description	Rating
Stability of the building elements	Paths where parts are unstable / moving must be avoided.	4
Narrow passages	Paths where the passages are too narrow must be avoided.	4
Resistance of building elements	Paths with the least resistance of building elements is preferred.	1
Use of SCBA	If an SCBA is used due to low oxygen levels, paths where the operation time would exceed the volume of the oxygen tank must be avoided.	4
Falling debris from the ceiling	Paths where debris is falling from the ceiling must be avoided.	4
Damaged gas bottles	Paths with damaged gas bottles must be avoided.	4

Table 2: Building Collapse: Categorization of person related parameters for firefighters equipped with (non-thermal) protective clothing.

The interviewed firefighter assured that the equipment does not negatively influence the accessibility decisively in a confined space. This is because the appropriate equipment in case of a building collapse is typically lighter than firefighting equipment. It does, however, not offer protection against heat. The interviewed firefighters stated that a self-contained breathing apparatus (SCBA) is used in operations where the level of oxygen is too low. If an oxygen tank is needed because of a limited amount of oxygen in the atmosphere, the limited volume of the oxygen tank providing a limited operation time must be taken into account.

Paths with falling debris from the ceiling must be avoided under all circumstances. Not only the safety of the operating first responder plays a role here. Gas bottles stored in the building may get damaged by falling debris. Paths with damaged gas bottles on the path must be avoided under all circumstances.

4.3 Fire

13 parameters could be determined that should be considered when conducting a path planning task in a disaster scenario that involves fire. These 13 parameters can be divided into 20 cases that need to be handled differently in disaster situations.

The first parameter that could be assessed with the interviews regarding fire is the regularly installed escape route in modern buildings. This escape route is a preferred route for firefighters. In Germany, path planning for firefighters is furthermore dependent on the accessibility of a so-called first and second operation route. The first operation route is predominantly over staircases, which presence is mandatory in the building layout. If the first operation route is not accessible, a turntable ladder on a firefighting vehicle provides a second operation route for entering the building or rescuing victims. The priority of saving lives is the highest in the operation. However, if victims are above the hazard, the interviewed firefighters stated that they would consider extinguishing the fire blocking the path to the victim first.

According to the firefighters, activated sprinklers are not decisive in terms of path planning and often not present in residential buildings. Smoke-reducing installations increase visibility and thus influence the operation positively. However, activated automatic extinguishing systems using gas should be excluded from the firefighters' path since the supplied gas is a threat for first responders.

The maximum heat resistance with thermal protective clothing determines the maximum tolerable ambient temperature inside an area. The values for the heat resistance of thermal protective clothing are provided in respective norms (i.e., [1]). The personal protective equipment (PPE) has limited protection against direct flame impact, and this hazard should therefore be excluded from the path. The same accounts for areas that are in danger of rollover. Areas 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.

Fire influences the stability of a building. Different material has different fire resistance. A route is not accessible when the stability of the route is in danger. The stability of the route is in danger if the fire duration exceeds or is close to exceeding the fire resistance duration of the building material. Unsecured shafts or openings could further harm firefighters by falling in and endangering their lives and the operation and are therefore to be avoided by the path planning.

The amount of smoke in an area influences the visibility and by that determines whether a path is usable. If a way is smoke-free, good visibility is granted, and the path is accessible. In some cases smoke is only located above a certain height under the ceiling. Then, the area underneath the smoke may be smoke-free and passable.

4.4 Flooding

When planning a path through an incident involving flooding six parameters define the accessibility of different paths in the incident for first responders. The parameters, listed in Table 4, can be split up into 14 different path planning conditions.

Starting with the influence that the water masses have on the building, four major parameters describe how safe it is to enter a flooded path in the building: the predictability of the water level dynamics, the water level dynamics itself, the remaining time until a room is fully flooded and the current water height. Since the firefighters, as stated by the interviewees, do wear diving suits in such

Parameter	Description	Rating
Escape routes	Signposted escape routes should be preferred.	1
Stairways	Paths along stairways are preferred.	1
Windows	Paths through windows with a ladder can be used.	2
Victim	If the goal is to reach a victim and the victim is above a fire, a path where the fire can be extinguished is be preferred.	1
Fire safety installations	Paths with smoke-reducing installations (ventilation) are preferred.	1
	Paths with activated fire extinguishing system (CO2) should be avoided.	3
Ambient temperature	Paths where the temperature of the environment exceeds the temperature limitations of the protection equipment must be avoided.	4
Direct flame impact	Paths that cross fire must be avoided.	4
Danger of rollover	Areas in danger of rollover must be avoided since direct flame impact may be caused by the rollover.	4
Fire resistance of material	Paths in danger of collapsing due to the fire duration exceeding the fire resistance duration must be avoided.	4
	Paths that are in danger of collapsing due to unstable material should be avoided.	3
	Paths with stable material can be used.	2
Unsecured shafts and openings	Paths with unsecured shafts and openings that first responders could fall into should be avoided.	3
Smoke / Visibility	Paths with no smoke are preferred.	1
	Paths with a moderate amount of smoke can be used.	2
	Paths where the smoke is only located from a specific height on can be used.	2
	Paths with a high amount of smoke / low visibility should be avoided.	3
Steam development potential	Areas with no steam development potential are preferred.	1
Explosive material	Paths with material in danger of explosion that is not in contact with fire should be avoided.	3
	Paths with material in danger of explosion that is in contact with fire must be avoided.	4
	Paths with material that show temperature increase must be avoided.	4

Table 3: Fire: Categorization of parameters for firefighters equipped with thermal protective clothing and self-contained breathing apparatus (SCBA).

Parameter	Description	Rating
Predictability of the water level dynamics	Flooded paths with little dynamic or static water level where the water rise is unpredictable must be avoided.	4
	Flooded paths with little dynamic or static water level where the water rise is predictable can be used.	2
Water level dynamics	Flooded paths with a dynamic water level must be avoided.	4
Remaining time	Flooded paths where the remaining time until a room is flooded can be evaluated and where this remaining time is long can be used.	2
	Flooded paths where the remaining time until a room is flooded can be evaluated and where this remaining time is short must be avoided.	4
Water height	Flooded paths where the water level is at its max. must be avoided.	4
	Flooded paths where the water level is high should be avoided.	3
	Flooded paths where the water level is low can be used.	3
Flow velocity	Paths where the flow velocity exceeds a critical flow velocity must be avoided.	4
	Paths, where the flow velocity is close to a critical flow velocity, should be avoided.	3
Door opening direction	Paths that open doors against the direction of water masses should be avoided.	3
	Paths that open doors with the direction of water masses can be used.	2
Floating obstacles	Paths where no loose objects are expected in the building are preferred.	1

Table 4: Flooding: Categorization of person related parameters for firefighters equipped with a diving suit (without self-contained underwater breathing apparatus (SCUBA)).

Parameter	Description	Rating
Zone pathing	Paths through all three zones, the red, green, and yellow zone can be used with the chemical protective clothing.	2
Radioactive zone	Radioactive zones must be avoided.	4
Explosiveness of chemicals	Paths with an explosiveness level of zero can be used.	2
	Paths with an explosiveness level non-zero must be avoided.	4

Table 5: Hazardous Material: Categorization of person-related parameters for firefighters equipped with chemical protective clothing.

incidents but are not equipped with self-contained underwater breathing apparatus (SCUBA) it is essential that the fire fighters do not run into the risk that their path is fully flooded.

The flow velocity describes an additional parameter. If first responders could safely enter the flooded area without breathing apparatus, but the flow velocity was too high, this would endanger their safety.

Flooded areas may exhibit different water levels in different rooms if doors between rooms are closed. In such cases, the room's door opening direction plays a crucial role for first responders to follow their paths. The door opening direction on a planned path should go with water masses.

Additionally, not fixated floating objects, such as tables or larger obstacles, could block the path. By considering the types of the different rooms when planning a path, a path can be planned through areas where not many floating objects are to be expected.

4.5 Hazardous Material

Whether an area contaminated with hazardous material can be entered or not depends on the toxicity or explosion potential of a chemical. One approach to consider different levels of toxicity is to divide the area into a green, yellow and red zone. Firefighters, in such an incident, do wear chemical protection equipment. With this, they do have the possibility to enter all areas independent of the zone pathing. An exception is a radioactive zone. Even special protective equipment offers limited protection inside radioactive zones. If there is a radioactive zone, the firefighters would consider not entering the building and wait for specialists.

Something that firefighters are not protected against is explosive hazards. When explosive hazards are involved in an incident, the explosiveness level must be determined with common catalogues. If the explosiveness level on a path is zero, this path can be used. If the explosiveness level is non-zero, the path can not be used.

5 Implementation

The parameters that were derived from the interviews were presented in Chapter 4. The next step concerning path planning is to set the generated results into a context. This chapter, therefore, bridges the gap between Chapter 4 and the introduction of the usage of BIM and CityGML for path planning in Chapter 2.3.

An example prototype on how the generated parameters can be used in combination with path planning is presented in Figure 1. In this figure, the path planning module is presented in combination with additional processes which often complement a path planning process. Colored boxes indicate the complementing processes. The ultimate goal of the path planning module is to calculate a path for a given mobile object in a real-world disaster scenario. For this, path planning needs to receive information about the real-world situation. The information about the real world situation can be split up into three categories: *Building-related information*, *incident-related information* and *mobile object-related information*.

The *building-related information* contains information directly about the affected building. This information is fed to a building model. The building model can be given and constantly updated when anything building-related during the disaster changes. The alternative is that the building model is fully created based on the real-world scenario. The updating or generation of the model can be conducted with the help of exploration drones scanning the disaster area. These scans, usually stored as point clouds, can be transformed into building models. Using an existing BIM model has several advantages compared to creating a whole new model during the disaster. Benefits are for instance information like room types and material types of the building elements. This information is not directly accessible with scans but usually available with the original BIM version. The types of rooms and types of materials are crucial information regarding the use of the parameters that were presented in Chapter 4. Important updates to the model are major changes to its structure such as holes in walls that can be gained from these scans.

Besides the building-related information, another essential information source for the path planning module is the *incident-related information*. The locations of fire or also the temperature distribution in the building are examples of such kind of information. Similar to the information about the building, this information can be collected via scans or sensors.

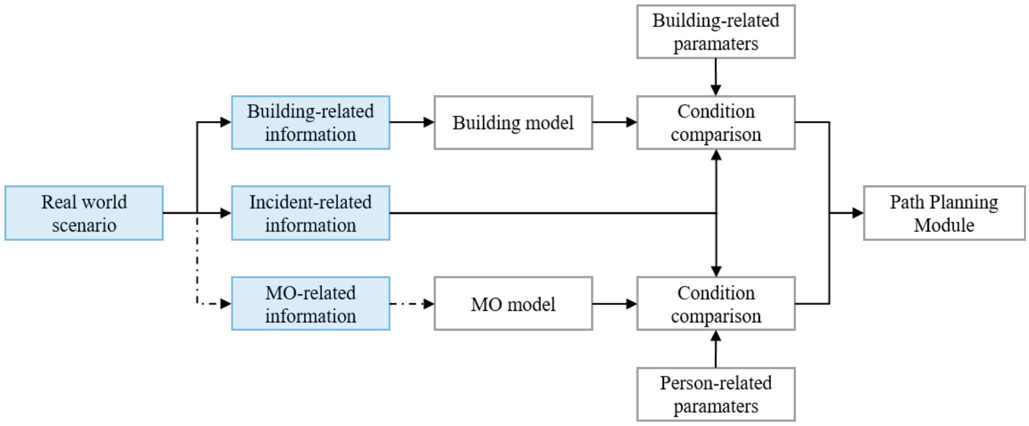

Figure 1: Prototype of a path planning module that uses the, in this paper, determined parameters. MO = Mobile object.

The *mobile object-related* information is, contrary to the other two information sources, connected via a dashed line. This is because this information can be extracted from the real-world scenario, but is however expected to be usually chosen beforehand. A mobile object model, which the information is fed to, would contain information like the type of mobile object, its size, and, for the case that it is a first responder, attributes like protection clothes and equipment.

Besides the building model, the mobile object model, and the incident-related information, the *condition comparison* presented in Figure 1 uses the parameters that were introduced in Chapter 4 as reference parameters to generate data for the path planning module. This data is the source of information needed to provide a holistic path planning in disaster scenarios that is not only restricted to simplified obstacle representations. The parameter lists are split up into mobile object and building-related parameters. The division depends on whether the parameter interacts with the building or mobile object model.

The process shall be explained with an example. A fire incident may be a real-world disaster scenario. The parameter that shall be used from the generated parameter list from the building perspective is *fire resistance of material*. The following information is needed to check this parameter: First of all, the fire location and duration in each location of the building is needed. This information will be given with the incident-related information. Furthermore, the material of the building in each location is required. This information can be retrieved from a BIM model, which would be representative of the building model. To check whether the building stability is in danger or not, the fire resistance is quantitatively stored in the building-related parameter list. By checking duration of the fire on a specific location, the material on a specific location and the fire resistance of this material on the specific location, the stability of this location can be determined. When one area is of material with low fire resistance, this information will be given to the path planning module, which will consider it by planning a path around this location.

A human-related example can be described in an aligned scenario. The incident-related information in a fire scenario may be the temperature distribution in the building. The human model may contain information of the type of first responder and its protection equipment, such as fire fighting equipment. The person-related parameter list contains information on the temperature resistance of different kinds of fire fighting equipment. By comparing the temperature in each location with the temperature-resistance of the fire fighting equipment, which depends on the type of firefighter, areas in the building can be determined as non-safe and excluded in the path planning.

6 Discussion and Outlook

This paper presented a concept to derive path planning parameters for first responders operating in four different disaster scenarios from qualitative expert interviews. The parameters were presented and described in Chapter 4 and summed up in Table 1 - 5.

Chapter 5 complemented the results by presenting an exemplary prototype that can use the determined parameters. Compared to existing research, this prototype does not only use one exemplary obstacle description but enables to include several different types of obstacles in a disaster scenario. These obstacles can furthermore be treated with different weighting depending on how they influence the safety of an operating first responders.

The determined parameters are the first step to generate a holistic path planning system. While they are, until now, only based on the first elaboration of parameters, further research will focus on completing the list. Moreover, a further necessary next step is the generation of a set of quantitative parameters based on the qualitative parameter set. The implementation of the presented prototype, including its testing in real-life disaster scenarios, is planned as a next step in the project that is aligned to this research.

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References

[1] National Fire Protection Association. *NFPA 1971: Standard on protective ensembles for structural fire fighting and proximity fire fighting*. National Fire Protection Association, Quincy, 2006.

[2] Craig L Beyler and Leonard Y Cooper. "Interaction of sprinklers with smoke and heat vents". In: *Fire technology* 37.1 (2001).

[3] André Borrmann et al. *Building Information Modeling: Technologische Grundlagen und industrielle Praxis*. Springer-Verlag, 2015.

[4] A. Braun et al. "Improving progress monitoring by fusing point clouds, semantic data and computer vision". In: *Automation in Construction* 116.C (2020), pp. 1–16. DOI: 10.1016/j.autcon.2020.103210.

[5] Albert Y Chen and James C Chu. "TDVRP and BIM integrated approach for in-building emergency rescue routing". In: *Journal of Computing in Civil Engineering* 30.5 (2016), p. C4015003.

[6] Albert Y Chen and Ting Huang. "Toward BIM-enabled decision making for in-building response missions". In: *IEEE Transactions on Intelligent Transportation Systems* 16.5 (2015), pp. 2765–2773.

[7] Pavan Kumar Chitumalla et al. "Emergency response applications: Dynamic plume modeling and real-time routing". In: *IEEE Internet Computing* 12.1 (2008), pp. 38–44.

[8] Jui Sheng Chou et al. "Optimal path planning in real time for dynamic building fire rescue operations using wireless sensors and visual guidance". In: *Automation in Construction* 99.November 2018 (2019), pp. 1–17. ISSN: 09265805. DOI: 10.1016/j.autcon.2018.11.020. URL: https://doi.org/10.1016/j.autcon.2018.11.020.

[9] Abdoulaye A. Diakité and Sisi Zlatanova. "Spatial subdivision of complex indoor environments for 3D indoor navigation". In: *International Journal of Geographical Information Science* 32.2 (2018), pp. 213–235. ISSN: 13623087. DOI: 10.1080/13658816.2017.1376066. URL: https://doi.org/10.1080/13658816.2017.1376066.

[10] ISO. *Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries*. Standard. Geneva, CH: International Organization for Standardization, 2018.

[11] Thomas H Kolbe and Andreas Donaubauer. "Semantic 3D City Modeling and BIM". In: *Urban Informatics*. Ed. by Wenzhong Shi et al. Singapore: Springer Singapore, 2021, pp. 609–636. ISBN: 978-981-15-8983-6. DOI: 10.1007/978-981-15-8983-6_34. URL: https://doi.org/10.1007/978-981-15-8983-6_34.

[12] Liu Liu et al. "Indoor navigation supported by the Industry Foundation Classes (IFC): A survey". In: *Automation in Construction* 121.October 2020 (2021), p. 103436. ISSN: 09265805. DOI: 10.1016/j.autcon.2020.103436. URL: https://doi.org/10.1016/j.autcon.2020.103436.

[13] Yuling Liu, Michinori Hatayama, and Norio Okada. "Development of an adaptive evacuation route algorithm under flood disaster". In: *Annuals of Disaster Prevention Research Institute, Kyoto University* 49 (2006), pp. 189–195.

[14] Holger Maiwald and Jochen Schwarz. "Berücksichtigung der Fließgeschwindigkeit bei Hochwasser-Schadensmodellen". In: *Bautechnik* 86.9 (2009), pp. 550–565.

[15] Elise Miller-Hooks and Theodor Krauthammer. "An intelligent evacuation, rescue and recovery concept". In: *Fire technology* 43.2 (2007), pp. 107–122.

[16] Rajkishore Nayak, Shadi Houshyar, and Rajiv Padhye. "Recent trends and future scope in the protection and comfort of fire-fighters' personal protective clothing". In: *Fire Science Reviews* 3 (Dec. 2014), pp. 1–19. DOI: 10.1186/s40038-014-0004-0.

[17] Deutsches Institut für Normung. *DIN 18095: Rauchschutztüren*. Berlin: Beuth Verlag GmbH.

[18] Deutsches Institut für Normung. *DIN 4102: Brandverhalten von Baustoffen und Bauteilen*. NABau im DINe. V.

[19] Ronald Pape, Kim R Mniszewski, and Anatol Longinow. "Explosion phenomena and effects of explosions on structures. II: Methods of analysis (explosion effects)". In: *Practice Periodical on Structural Design and Construction* 15.2 (2010), pp. 141–152.

[20] Markus Pulm. *Einsatztaktik für Führungskräfte: Praxiswissen für Gruppenführer*. Kohlhammer Verlag, 2017.

[21] Jacek Roguski et al. "Comparison of Requirements and Directions of Development of Methods for Testing Protective Clothing for Firefighting". In: *Fibres & Textiles in Eastern Europe* 5 (119) (2016), pp. 132–136.

[22] I Visser. "Route determination in disaster areas: Using predictions and introducing the option to wait to improve routing results". In: (2009).

[23] Zhiyong Wang, Sisi Zlatanova, and Peter Oosterom. “Path Planning for First Responders in the Presence of Moving Obstacles With Uncertain Boundaries”. In: *IEEE Transactions on Intelligent Transportation Systems* PP (Jan. 2017), pp. 1–11. DOI: 10.1109/TITS.2016.2634079.

[24] Lynn J White et al. “Continuous core temperature monitoring of search and rescue divers during extreme conditions”. In: *Prehospital Emergency Care* 2.4 (1998), pp. 280–284.

[25] Wolfgang M Willems et al. *Formeln und Tabellen Bauphysik*. Springer, 2007.

[26] Jürgen Wohlrab. *Einsatztaktik für den Zugführer*. Kohlhammer Verlag, 2020.