BIM-based disaster response: Facilitating indoor path planning for various agents

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ABSTRACT: During path planning, rescue operations in buildings are often hindered due to the lack of critical building information. This paper proposes a real-time navigational platform combining various information sources to mitigate this problem. Various operating agents such as first-responders and UGVs receive specialized assistance by integrating semantic information from digital building models with incident-related real-time data. The proposed methodology includes three steps: (1) Pre-configuration of conditions influencing path choices according to agents' capabilities and safety preferences. (2) Representation of the building geometry using a navigation graph. Inclusion of semantic information by weighting the graph with incident-related information, compared with the conditions per agent type and semantic information from the digital model. (3) Development of a knowledge database containing conditions for various types of agents. Evaluation in a real-world scenario revealed that paths calculated by the planning module were faster, shorter, and safer than those determined by first responders.

1 INTRODUCTION

An indoor disaster scene consists of areas dynamically changing in accessibility and safety during incidents, which poses a challenge for operating first responders. The lack of accurate real-time information (e.g., disaster location and its spread, crowd density and room occupancy, structural damages, etc.) often reduces the efficacy of disaster response. The current challenges are magnified by the growing size and complexity of modern built environments. Currently, there are no platforms that can enable a remote administrator to assimilate the real-time status of the building and acquire important evacuation details to identify the safest and speediest path to the destination for various agents and disaster types.

Recent developments in the architecture, engineering, and construction (AEC) industry regarding building information modeling (BIM) have unfurled new opportunities to meet disaster situations with more detailed support for first responders using digital tools and methods. The availability of new technologies, such as unmanned vehicles, and the increased access to digital information due to the digitalization of the construction industry, have opened up new opportunities to address those challenges (Directionsmag, 2019). The utility of path planning in outdoor areas has already been proved with mapping solutions, such as Google Maps or Open Street Maps, throughout the last decades. Indoor areas can also be of interest with regard to path planning, as demonstrated by Google Maps' recent indoor mapping and path planning solutions (Google, 2022). Though, the generation of indoor mapping and path planning is not new (Liu, et al., 2021). Geometry-based solutions range from simple ones that only consider the connectivity between different areas to more complex ones that also consider properties such as the agent's size. In this work, an agent is regarded as an object or person that can move through space, depending on its locomotion type, physical abilities, and constraints. In the case study of this paper, first responders, unmanned aerial vehicles (UAVs), and unmanned ground vehicles (UGVs) are used as agents. Solutions that rely not only on geometric but also semantic sources can take into account differing abilities of agents (Khan, 2015). Semantically rich building models form the basis for such advanced mapping approaches. BIM is a methodology for generating and using those comprehensive, informative representations of built facilities consisting of three-dimensional components and a vast amount of additional non-geometrical information (Borrmann, et al., 2015).

Disaster management is one area of application requiring indoor mapping and path planning. Various researchers (Beata, et al., 2018) have already investigated what information is to be collected, how to collect it, and how to present it efficiently to operating first responders. While significant efforts have been made to present as much information as possible to first responders, how this information is to be processed, to provide first responders with easily manageable information, remains under-researched. Existing solutions focus on a limited amount of obstacle avoidance, such as avoiding fire ignition points, and providing solutions only for first responders (Chou, et al., 2019; Wang, et al., 2019). State-of-the-art solutions also commonly overlook how disaster-related support must be provided for UAVs and UGVs as well, since they are expected to operate with first responders in future incidents (Directionsmag, 2019).

This paper addresses the above-mentioned research gap and fuses the rich disaster-related information with semantically rich building models and various operating agents' abilities and priorities.

A novel method for planning paths through disaster scenes is proposed, combining wide-ranging information from digital building models to address the challenge of large, complex buildings for various types of agents while also considering varied disaster types. In preparation for this study, expert interviews and surveys were conducted with robot manufacturers and first responders. A qualitative list of relevant incident-related obstacles and their effects on operating agents was generated (Dugstad, et al., 2021). It was determined that both direct and indirect effects of incidents on agents must be considered. A direct effect is the deadly threat that fire has to humans. An indirect effect of fire is its impact on the functionality of building elements, decreasing the safety of areas connected to these building elements. BIM can be used to generate a geometric representation of the environment and provide semantic information to determine the effects of incidents on the built environments and thus indirectly on first responders. A knowledge database developed in this study allows the collection of agent-related properties. These properties can be used to compare real-time information from the incident with the geometric and semantic information of the built asset and the agent's priorities regarding accessibility, safety, and distance of a path through the incident. The environment-abstraction methodology, knowledge database, and weighting function were implemented. Finally, the methodology was tested in a case study where a selected number of parameters was implemented. The time for first responders to orient themselves in a disaster scene and plan a path, which represents the conventional procedure in a disaster scenario, was compared with the time of the tool to plan a path through the scene while taking into account the determined parameters. The path planning module was found to determine faster and safer paths more quickly than the first responders.

2 STATE OF THE ART

This section provides a comprehensive literature review about indoor mapping, their applicability to planning paths for various agents, and possibilities to integrate BIM-based information into disaster technologies and, more precisely, path planning methods.

2.1 *Indoor map generation*

Typical approaches for indoor map generation based on BIM are the grid-based map-generation (Lin, et al., 2013), and the graph-based map generation (Cheng, et al., 2014; Teo & Cho, 2016; Hamieh, et al., 2020), as well as combinations of those (Zhou, et al., 2020; Liu, et al., 2021). Grid-based maps allow precisely setting start and end points for fine-granularity path planning. Their efficiency with algorithms like A* (Hart, et al., 1968) is, however, low due to their comparably high grid-resolution (Yao, et al., 2010). By contrast, graph-based maps are generated based on some logic, such as topology. Topological indoor mapping approaches overcome the inefficiency of grid-based maps (Zhou, et al., 2020). They are typically generated by skipping the height on each floor and applying Poincaré Duality (Liu, et al., 2021). Nodes may represent spaces that are connected depending on their connectivity through transition elements (Hamieh, et al., 2020). Topological maps allow no precise selection of start and end points and optimal shortest path planning due to their usually comparably lower resolution (Zhou, et al., 2020). A graph-based example for overcoming in-precise path generation with a logic-based approach is presented by (Kneidl, et al., 2012).

2.2 *Path planning for various agents*

Maps are generated based on the idea of representing the connectivity of an environment’s accessible areas. It is important to note that the accessibility differs for different types of agents. (Khan, 2015) investigated how the accessibility of an indoor environment is different for flying, rolling, and walking locomotion types. Not only is this accessibility constrained by the moving object's size but also by its moving ability, involving parameters such as whether it can climb stairs and ramps or use windows. In their study, they define a navigable space for each locomotion type.

2.3 *BIM-based disaster technologies*

BIM-based disaster technologies can be sub-categorized into three stage. In the first stage, BIM is used to visualize the environment in which incident-related parameters are detected (Beata, et al., 2018). First responders can use those visualization environments to orient themselves, where specific gas concentrations of, for example, carbon monoxide are high or low and where fire is located. Some researchers wanted to visualize the status quo of disaster-related parameters and how the situation may develop (Chen, et al., 2018; Wang, et al., 2021). Their approaches include using BIM with a fire simulation software to visualize how incidents may develop during a disaster.

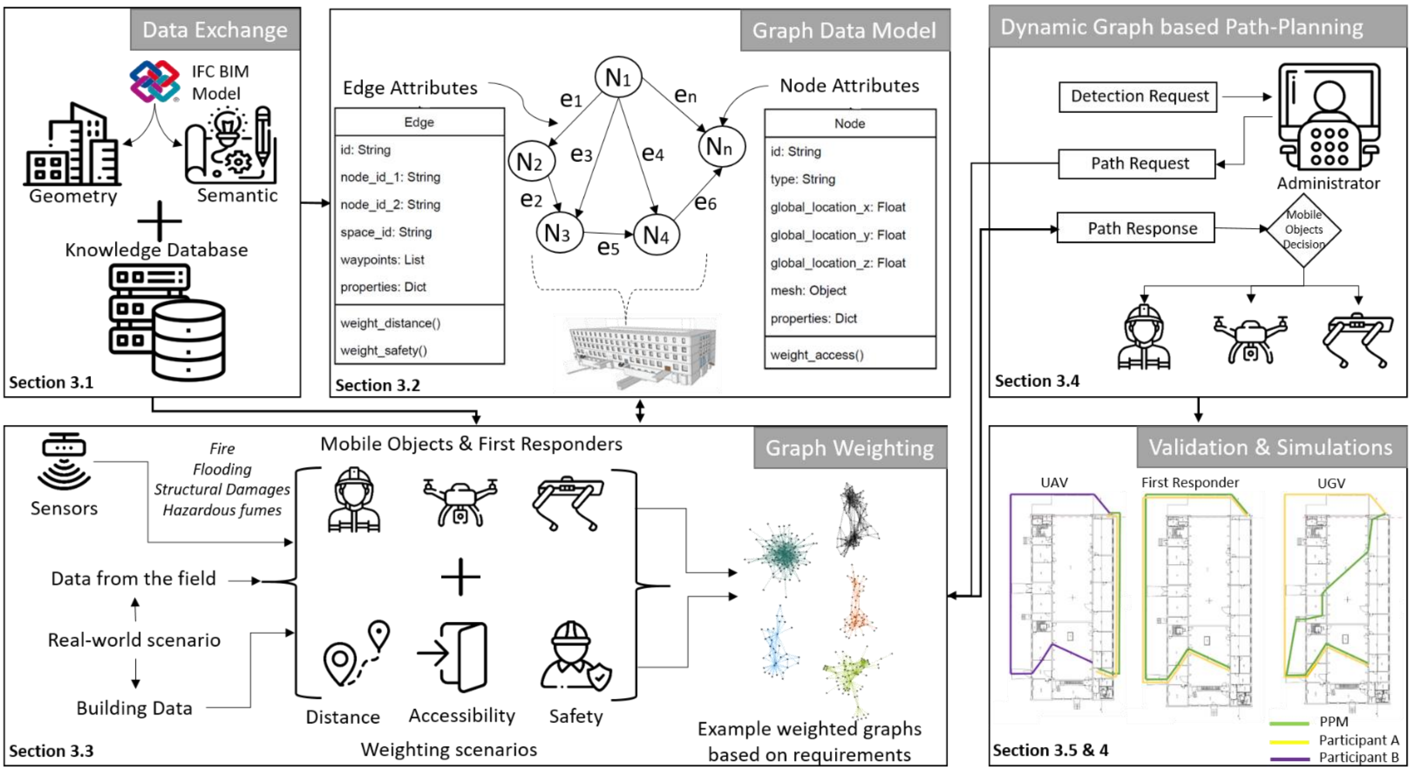


Figure 1 Framework Overview. Workflow presenting all developed modules and their interactions.

2.4 *Path planning tools*

A common approach to planning paths through a disaster-related environment is to either only visualize hazardous situations and plan the shortest path independently (Rueppel & Stuebbe, 2008), or generate a graph-based map as explained in Section 2.1 and weight this graph with information that goes beyond distance information. A path planning algorithm searches for a path with the optimal weight. Thus, hazardous situations can be bypassed by adjusting the weights of nodes and edges corresponding to a hazardous area. (Chou, et al., 2019) introduce such a weighting-based approach to determine safe paths for first responders in fire scenarios. They generate a graph where the nodes are set based on the location of Bluetooth sensors that can detect fire ignition points in an indoor environment. The weight of the edges is initially set according to the distance of the nodes to each other. When a fire is located by a Bluetooth sensor, the weight of the edges connected to the corresponding node increases, forcing the algorithm to search for an alternative path around fire ignition points.

3 METHODOLOGY

This study proposes an end-to-end real-time path planning approach that considers both the direct and indirect effects of incident-related obstacles on first responders and various agents operating in disaster scenarios. The proposed method consists of five parts, as demonstrated in Figure 1. The data source and exchange depicted in Section 3.1 sums up the information existing before an incident. It consists of a semantically rich building model, in Industry Foundation Class (IFC) format in the frame of this study, and information gathered from first responders stored in a knowledge database, which was developed within this study. The graph data model described in Section 3.2 was designed to hold every information necessary to represent the indoor environment within a weighted graph. The weighting framework Section 3.3 uses the information from the data exchange and real-time information from sensors from the field to weight the graph with the graph structure according to the graph data model. The path planning module's dynamics are described in Section 3.4. It consists of the functionality that the graph is constantly re-weighted according to any newly fetched information from the sensors from the field, and paths can be dynamically planned accordingly. The usability of the approach is validated in Section 3.5.

3.1 *Data Exchange*

The BIM methodology is suitable for generating building models providing this project's necessary information. It allows for creating semantically rich building models that provide detailed information such as fire resistance. BIM is a standard methodology used in the construction industry to generate building models. Most newly developed construction processes base on the BIM methodology, and BIM models are thus available for disaster response for many buildings. They will be extensively available in the future. BIM models can be produced with software such as Autodesk Revit and exported in various data formats. IFC is a commonly used export data format that makes building information easily accessible via libraries such as Ifcopenshell in Python.

The knowledge database, which was developed within this study, is based on a line of expert interviews that were conducted to gain an overview of the needs of first responders (Dugstad, et al., 2021). The interview results contain qualitative situations that the first responders would consider positive or negative in different disaster scenarios. The specified situations can directly or indirectly impact the first responder's path choices. Fire is, for instance, considered both, impacting first responders' path choice directly and indirectly. The direct component may be the inability of first responders to cross fire. The indirect component is that a fire impacts an agent's path when the functionality of the building construction is threatened under fire. Furthermore, the importance of avoiding or preferring different situations differs. Four different cases are to be distinguished: A path with a specified situation *is preferred, can be used, should be avoided or must be avoided*. For instance, a preferred path is a path via stairways or emergency routes in a fire incidence. A path with no special occurrences is a path that can be used. A path with a specified temperature may be defined as a path that should be avoided, and a path with fire is, for instance, a path that must be avoided.

Direct conditions can be considered by gathering the information from the field on where a specified parameter such as fire is occurring, and comparing it with the information on how this parameter should be handled for a specified agent. Here the applicability of the methodology for various agents comes into the picture. A database that defines how different occurrences shall be handled for a first responder, UAV, or UGV can adjust paths for the specified agent. Indirect conditions can be considered by gathering the field information on where a specified parameter such as fire is occurring and comparing it with how this impacts the building. For instance, the impact of fire on a building can be analyzed by using the semantic information about the fire resistance of building elements such as walls from the semantically rich BIM Model. The fire resistance holds the information on how long a standard fire can penetrate a building element until it loses its functionality. The database stores how the resulting effect should be handled. Users can, for instance, choose that they would like to avoid areas where the duration of fire exceeds the guaranteed fire resistance of the connected building elements.

3.2 *Graph Data Model*

The study considers empty multiple-floor indoor environments with straight floors. Operating agents are considered intelligent, meaning they are able to navigate around small obstacles on their own. The interviews conducted in (Dugstad, et al., 2021) revealed three significant requirements for paths in disaster environments. Paths must be short, accessible, and safe (Dugstad, et al., 2021). Thus, the indoor map generated for path planning has to be of a type that allows the calculation of short, accessible, and safe paths for various agents. To do so, the map must hold information about (1) the connectivity of different locations to each other, (2) the distances between different connected locations, (3) the accessibility of the different areas for specific agents, and (4) the safety in different connected areas for various agents. A weighted graph-based approach was found to be useful in aligned studies (Chou, et al., 2019) and will also be applied in this study.

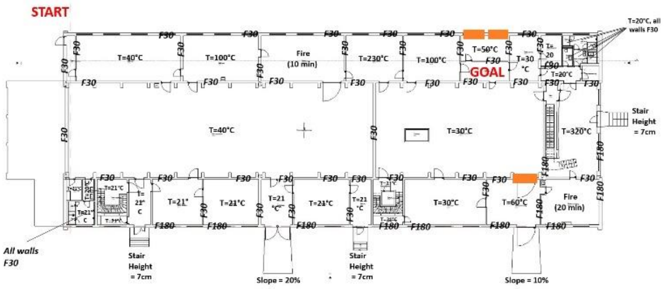
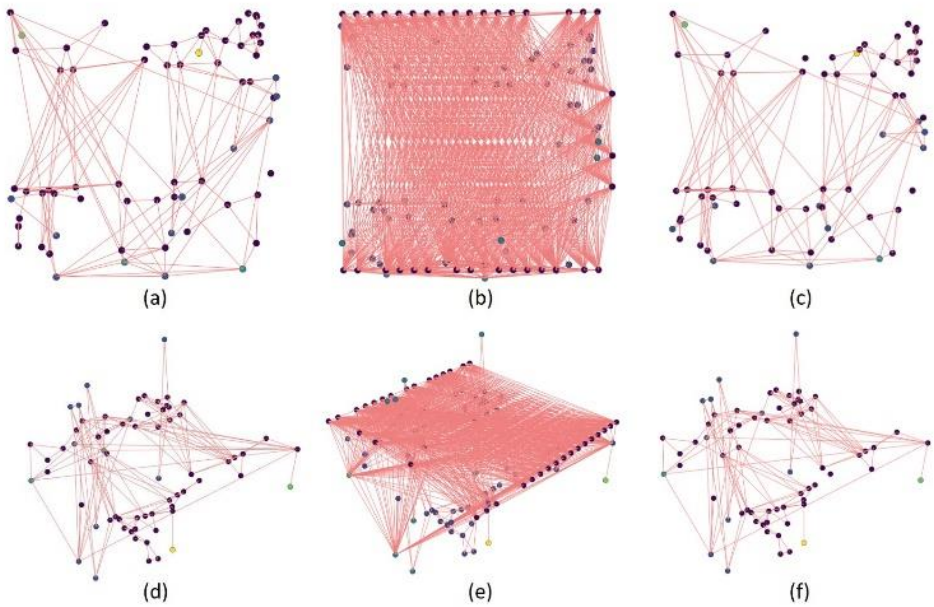


Figure 2 The floor plan, given to the participants, contains all information about the scene. Fire resistance is indicated as F30 -- F180, standing for 30 and 180 minutes fire resistance, respectively. Temperature is given per room. The existence and duration of a fire in a room are given. Blocked doors and windows are marked in orange. All other doors and windows are considered open. Stairs have stair height, and ramps have slope properties. Start and goal position are indicated.

The logic described in the following section explains how a graph must be built to allow it to be weighted according to the abovementioned criteria. In Section 3.3 the weighting of the graph according to those criteria is described.

(1) and (2) The shortest path within a room is always the direct one from the entering point of the room to the exit point. If the two transition points are visible to each other, the shortest path is a straight line between the two points. For cases where the transition points are not visible, a vertex-based graph-generation approach by (Kneidl, et al., 2012) can be used. Together with a path search algorithm such as A* or Dijkstra, the shortest path within a room can be determined. The proposed methodology to get the shortest path between two points in a building is thus, to represent all transition points in the building as nodes, connect them when they are associated with the same room, and store the waypoints retrieved as the room-based path search in a list of waypoints within the edge. The correct distance can then be calculated by retrieving the distance between these waypoints. This graph data model represents the geometric connectivity of the building.

(3) The type of transition elements determines whether an agent can access an area that is delimited by this transition element or not. A rolling agent may,


(a) (b) (c)

(d) (e) (f)

Figure 3 Graphs representing the connectivity of the area, depicted in Figure 2, reduced by the edges and nodes which must be avoided for a first responder (a) and (d), a UAV (b) and (e), and a UGV (c) and (f). Purple nodes represent doors. Blue nodes represent stairs, dark green nodes represent ramps. The start position of a requested path is depicted as a light green node and goal position as a yellow node. The view of the graph in the first row corresponds to the view of the floor plan in Figure 2.

for instance, not be able to access stairs. Storing the information about a transition type in the corresponding node allows weighting the node according to the accessibility for a specified agent afterward. Further information, which is relevant to determine an agent's ability to use this transition point may be the transition elements' size and geometry.

(4) Multiple edges always correspond to only one space in a building due to the nodes representing transition elements, that are located on geometrical space boundaries. The definition of a safety level per room allows weighting every edge according to the corresponding safety occurrences in the room. Every node is thus fitted with a function to calculate the accessibility weight, and every edge is thus fitted with a function to calculate the safety and distance weight. here listing facts use either the style tag List signs or the style tag List numbers.

3.3 *Graph Weighting*

The graph weight consists of three parts: distance, accessibility, and safety. Each of these three categories is conducted per agent on each node and edge of the graph.

The distance weight is applied to the edges, which connect the nodes (transition elements). While there is no path request, this weight is the distance.

The accessibility weight is applied to the nodes, which represent transition elements. The weight is either 1 if this transition element represents a preferred one for the agent, 2 if the agent can use the transition element, 3 if the agent prefers to avoid the transition element, or 4 if the agent cannot use this transition element at all. The weighting algorithm considers not only varying types of transition elements but also their properties, such as the blockage of a door or window, the slope of a ramp, and stair height. The weighting is conducted with the information collected for each agent's abilities in the knowledge data bank.

The safety weight is applied to the edges. Each room holds one safety weight and corresponds to multiple edges. All edges located in one room hold the same safety weight. The safety weights are similar to the ones of the accessibility weight, of values between 1 and 4, which describe whether the respective area is to be avoided. For this first development stage, a building fitted with sensors that can detect fire and temperature in every room is assumed, and the information measured by them is the following: whether or not there is a fire in a room, how high the room temperature is, and the duration of a fire. The building model holds the information on the fire resistance of walls (i.e., how long a wall can withstand a fire until it loses its functionality). The knowledge database holds the information about the preferences per agent per incident. The safety weight is determined by comparing building model information with agent preferences and the real-time information from the scene. Both the direct impact (i.e., fire affecting the safety level of a room for the agent) and indirect impacts (i.e., fire affecting the stability of the walls in a room and thus the safety level of a room for the agent) are taken into account in this weighting step.

When a path is requested for a specified agent, the weights of the graph are dynamically updated based on the agent and real-time information from the scene. The graph is reduced by all edges and nodes, which hold a weight of 4. The path planning tool searches through the reduced graph, which is weighted according to the distance for the x shortest paths. The x shortest paths are re-weighted according

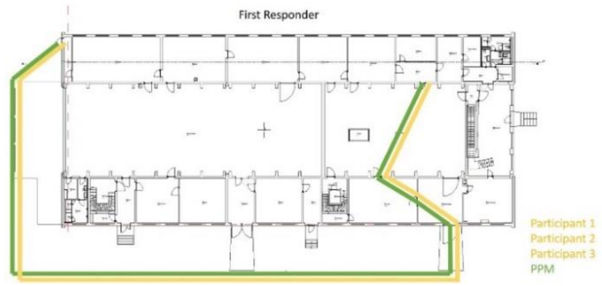


Figure 5 Paths, which were found by the path planning module (green) and the participants (yellow) for first responders.

to their safety- and accessibility weight, which at this point only consists of values between 1 and 3, due to the exclusion of all inaccessible nodes and edges. The re-weighting is conducted by checking the properties that store the safety and accessibility information per agent. Each node and edge can contain multiple weights due to numerous incidents (fire and temperature, for instance) influencing the weight. The highest weight per edge and node is selected. The shortest x paths get assigned the averaged safety and accessibility weight over all edges and nodes. To incorporate the distances of the paths, their weight is interpolated to a value between 1 and y depending on whether their value is equivalent to the shortest distance between start and goal node or y = t times the shortest distance. Each path consists of a distance, accessibility, and safety weight between 1 and 3. The first responders can conduct the prioritization, for instance, accessibility over safety in the step of editing agent-based information in the knowledge database. Based on this prioritization, the paths are weighted, and the most optimal one is proposed.

3.4 *Dynamic Graph*

Technologies are considered deployed to report information on windows' and doors' opened or locked status. Similar to the data from the sensors that determine fire and temperatures, this information is a “new detection”. Every agent-related graph is constantly re-weighted per new detection, activating the dynamic path planner per the current situation in the building. The dynamics of the path planning consist of the real-time update of graph weights with real-world information via the sensors and intelligent technologies.

A client can request a path from the path planning module specifying the agent for which the path should be planned as well as the start and the goal position. The path planning module reduces the graph according to the methodology described in Section 3.3. The closest node to the start and goal position is searched and connected to the graph. The shortest x paths from the start to the goal position are generated using the Dijkstra Algorithm (Dijkstra & others, 1959). We used Dijkstra path-planning algorithm mainly due to its easy implementation and linear time complexity. Paths are weighted according to the safety, accessibility, and distance with respect to the corrected distance, described in Section 3.3. The path with the lowest weight is suggested.

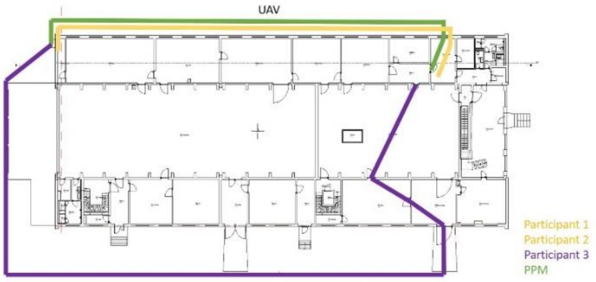


Figure 4 Paths, which were found by the path planning module (green) and the participants (yellow and purple) for UAVs.

3.5 *Validation & Simulations*

A prototype of the developed concept was implemented and validated in a study involving a complex, extensive building at the inner-city campus of the Technical University of Munich (TUM), which was prepared for a possible fire event. The prototype allows for a generation of graphs based on built environments automatically. Correct paths for transition points per room that are not visible to each other were incorporated manually in this version. The building model was prepared with Revit 2022 and exported into IFC4 format. Properties such as the slope of ramps, heights of stairs, and the fire resistance of walls were adjusted in the model. The current implementation of the module checks which rooms share the same wall to weigh the impact of fire on the safety of an adjacent room depending on the fire resistance of a wall separating these rooms. Thus, one wall is required to be shared by only two spaces in this implemented version. Outdoor areas are one space.

The case study aims to test the performance of firefighters to plan paths to different goal positions in a building that is affected by a fire incident to validate the possible assistance which can be achieved with an approach proposed within this study. To avoid confusion between the use of the terminology for firefighters representing the participants and the firefighter representing agents for which the paths were planned, the firefighters within this study are from now on referred to as the participants.

A mock-up of fire incidents was simulated using a pictorial representation on a 2D drawing of a floor plan. The participants were given floor plans of the scene that were enriched with information about the scene and the abilities of three different agents for which paths should be planned. The three different types of agents considered are a UAV, which can transition to any transition element despite closed ones; a UGV, which can use doors, stairs, and ramps but is constrained by ramp slopes and stair heights and a first responder, which is also able to use stairs, ramps, and doors, but is not constrained regarding ramp height. While the building is five storeys high, the scenario was prepared for one storey to compare

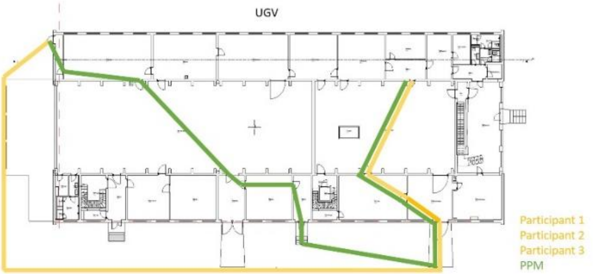


Figure 6 Paths, which were found by the path planning module (green) and the participants (yellow) for UGVs.

the developed methodology with the participants' ability in an easy scenario.

The participants' speed was counted by measuring their time from receiving the floor plan to planning a path. The result was split up into the gross time, which includes the time participants used to orient themselves and check the properties of the agents, and the net time, which was the time participants only used to orient themselves within the scene. The study was recorded to measure this time correctly. The determined paths by the participants and the path planning module were compared by their weights. To keep it comparable, the parameters measured in the scene were *temperature*, and *fire* as well as blocked windows and doors. Fire is processed regarding its direct impact on the safety of a path and its impact on the functionality of walls using the difference between the duration of a fire and the minutes that the wall should be able to persist the fire. The accessibility was weighted according to the type of the transition elements and, for ramps, according to their slope, and stairs, according to the stair height that an agent can climb. A further parameter used in the weighting schema was whether a door was opened or closed.

4 SIMULATION AND RESULTS

To make the graph clear to the reader, the BIM model was reduced to one storey. The graphs which were produced for the three types of agents based on accessibility and safety (both weighted<4) are presented in Figure 3. The different colors of the nodes represent transition elements. It can be seen that the graphs (a) and (d), representing the connectivity graph for the implemented first responder, and the graphs (c) and (f), representing the connectivity for the implemented UGV, are very similar due to the similar abilities of the implemented *first responder*, and *UGV*. The graph for the UGV is accessibility-wise reduced by one node, representing a slope that is too steep for the UGV, and further nodes due to its lower temperature resistance. Due to the UAV's ability to use windows, graphs (b) and (e) consist of more nodes and edges than the other graphs. The reduction of the UAV's graph with regards to accessibility due to two blocked windows in the upper right of the floor plan in Figure 2 can be detected in Figure 3 upper right corner.

Agent	Path planner	Calculation time [min]		Path length [m]	Weight [-]			
		Total	Net		A	S	D	Total
FR	Participant 1	05:37	02:45	116.06	2.00	2.00	2.19	2.06
	Participant 2	03:13	01:49	116.06	2.00	2.00	2.19	2.06
	Participant 3	08:20	04:36	116.06	2.00	2.00	2.19	2.06
	PPM	<00:01		116.06	2.00	2.00	2.19	2.06
UAV	Participant 1	02:57	02:01	70.14	2.00	2.00	1.34	1.78
	Participant 2	02:30	01:00	70.14	2.00	2.00	1.34	1.78
	Participant 3	01:52	01:45	116.06	2.00	2.20	2.19	2.13
	PPM	<00:01		70.14	2.00	2.00	1.34	1.78
UGV	Participant 1	03:28	02:19	116.06	2.00	2.20	2.19	2.13
	Participant 2	02:45	01:27	116.06	2.00	2.20	2.19	2.13
	Participant 3	03:43	02:30	116.06	2.00	2.20	2.19	2.13
	PPM	<00:01		108.05	2.00	2.17	2.04	2.07

Table 1 Comparison of the paths found by the path planning module and the participants during the case study. Agent indicates who the path was planned for. Path planner represents the planning person or computer. Calculation time refers to the time which was used to plan the path. Gross time stands for the time in total, including the time which was used to look up parameters by participants. Net time stands for the time that was solely used to search for a path in the scene. The path length of the defined paths is given in meters. The weight consists of the accessibility weight of the nodes, the safety weight of the edges and the distance weight of the edges of each path. The total weight averages all three weights.

The path planning module was implemented with x=10,100,1000, representing the number of the shortest paths during step 1 of the planning. Factor x was introduced in Section 3.3. Factor t, introduced in Section 3.3, was chosen as 3, such that a path three times as long as the shortest distance between start and goal node is weighted with factor 3. The shortest distance between start and goal was determined as 53 m. Any path, which is 53m long, is thus weighted with 1. Any path, equal or more than 53m times 3=159m long, is weighted with 3. The values in between were interpolated. The optimal path for all three types of agents is depicted in green in Figure 5, Figure 4, and Figure 6. The calculation time to determine the paths was under 1 second when using x=10 and x=100 shortest paths in the algorithm, and 7 seconds when using x=1000.

The participants in the case study needed, on average, 03:49min gross and 02:14min net to plan a path. The net time is more accurate since it excludes the time used to check for agents' parameters such as a maximum slope. Operating first responders are expected to know those parameters and thus won't need to look them up. With 03:03min, participants took the most time to search for the path for the first responders, which may, however, also correlate to the fact that this was the first one they searched for. The shortest time (01:35min) was used for finding a path for the UAV, which is able to use windows and can thus be considered easier than the other cases. On average, 02:05min were used to plan a path for UGVs. Please refer to Table 1 for the complete simulation results.

While the participants successfully found the safest, shortest, and most accessible path for the first responders, the path planning module outperformed their results for the UAV and UGV. The paths which were chosen by the participants are depicted in yellow and purple in Figure 5, Figure 4, and Figure 6.

5 CONCLUSION

This paper presents an end-to-end path planning approach for various agents in disaster scenarios, which allows first responders to decide upon the abilities of the agents as well as include building-related information and compare it with disaster-related information. A first version of the module was implemented and tested in a case study. The results promise valuable support for first responders with this tool. Instead of being overwhelmed with information that is not easy to process in a complex situation, the presented methodology allows first responders to focus on their operations effectively.

There are three limitations to the proposed framework. (1) Currently, the algorithm takes a simplistic approach during the safety-level assignment for a wall that continues along multiple rooms. The proposed algorithm that compares a wall's fire resistance concerning a fire in its connected room assigns a lower safety level not only to the adjacent room but also to all other rooms that are connected via this wall. Doing this may be inaccurate and lead to errors due to the false weighting of the graph. (2) A further drawback is a connection between two transition element points that are not visible. The actual distance between such transition elements was computed manually in this study. (3) The proposed method further depends on the information gathered from a limited number of first responders to develop a knowledge database framework. To generalize the framework, we aim to conduct crowd-sourced experiments with a large and diverse set of first responders in the future.

6 ACKNOWLEDGEMENT

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