Indoor Search and Rescue Using a 3D Indoor Emergency Spatial Model

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FOR MY DEAREST PARENTS

WHO INSPIRE ME AND GUIDE ME TO BE A BETTER PERSON IN LIFE
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Abstract

Buildings are becoming a major subject of recent disasters resulting in huge amounts of casualty and damage costs for both public and emergency managers. In the context of emergency management, the Search and Rescue procedures in indoor environments face various complications and uncertainties due to increasing urbanization and complexity of urban structures. In case of an indoor disaster it is unknown to emergency managers how many first responders are required and how the routes should be assigned to them prior to entering the scene in order to have the most efficient plan.

An important factor in enabling effective search route assignment to first responders on scene is the existence of an indoor model addressed at emergency applications. Currently, most of the information from inside the structures is unrevealed to emergency managers prior to physical entrance to the scene exposing their lives to risk and danger and complicating decision making. Unfamiliarity with the indoor environments, limited visualization due to smoke, and collapsed and blocked areas all increase the difficulty of emergency response and rescue as well as unwanted wandering and uncertainty routing in indoor environments. A key limitation is that the current indoor spatial models do not fit emergency response requirements and thus cannot be effectively used for decision making in this area leaving the Indoor Search and Rescue Problem a challenge for first responders. Thus, an effective indoor search and rescue solution needs to be based on a detailed 3D indoor model consisting of both the geometric and semantic information of the structure which can be leveraged to build the indoor search and rescue navigation model.

This thesis addresses this knowledge gap by first developing a new 3D Indoor Emergency Spatial Model (IESM) aimed at emergency response operations that contains geometric and semantic information of building utilities required by first responders. And second, formulating and solving the indoor Search and Rescue Problem (SRP) by leveraging IESM for creating the indoor navigable network. IESM and the SRP Algorithm form the two main contributions of the research. The study uses a data modelling technique, a mathematical formulation, and an evolutionary optimization for developing the IESM model and SRP Algorithm.
The underlying IESM is based on mission critical information required on-scene by fire fighters which is developed as a data model using the BIM (Building Information Modelling) representation of the building. To develop the Search and Rescue Algorithm, an integrated geometric/semantic indoor route network is extracted based on IESM to support emergency response routing requirements. Using the indoor navigable model, the indoor Search and Rescue Problem is formulated mathematically. The Search and Rescue Problem is proved to be in the category of integer linear programming problems, making it an NP-hard problem. Thus, an ant colony based algorithm is developed to solve the problem for both the initial state of the algorithm considering the building settings are intact, and for the dynamic state of the problem in which the algorithm has the ability to adapt the assigned routes to conform to the new conditions of the problem where the search area is changed due to real time updated information.

To evaluate the feasibility and applicability of the proposed 3D indoor situational awareness model, the model was evaluated using an observational case study and descriptive scenario method at The Department of Infrastructure Engineering at The University of Melbourne under various scenarios. In addition, experimental simulation and analytical methods are used for evaluating the performance of the SRP algorithm. To prove the effectiveness of the proposed model, the results are validated with current practice strategies of fire fighters using an agent based simulator. These fire fighter decision strategies were collected through a series of interviews with the Dandenong Country Fire Authority (CFA) of Victoria in Australia.

The research proved that availability of IESM based model of the structure consisting of detailed geometric and semantic information required by emergency responders allows the SRP approach to identify the number of crew and the designated 3D routes for each person (including which entrance/exit and ingress/egress path to use) to minimize total response time; saving critical on-scene investigation and planning time. While IESM was proved to facilitate indoor emergency response by enabling 3D seamless indoor/outdoor visualization, spatial analysis, routing, and situational awareness; the empirical analysis from the SRP algorithm proved that the total response time and number of rescuers can be significantly improved using the SRP solution approach compared to the usual first responders’ strategies. Also, the results prove that the SRP algorithm finds paths that are balanced in terms of on-route travel time and distance, thus distributing the workload evenly amongst the rescuers which is very helpful for effective resource management. In addition, the dynamic SRP approach was shown extremely efficient as it adapts the assigned routes to the new circumstances of the structure without violating the constraints and conditions of the problem.
Overall, based on the obtained results it can be inferred that while the current firefighters’ practice systems carry a lot of uncertainties, utilizing the proposed 3D indoor situational awareness model can present a much more certain, robust, and reliable solution. Availability of such information could help decision makers interact with building information and thus make more efficient planning prior to entering the disaster site.

Keywords

3D Indoor GIS, Search and Rescue, Ant Colony Optimization, BIM, IFC, Indoor Situational Awareness
Declaration

This is to certify that:

i. The thesis comprises only my original work towards the PhD
ii. Due acknowledgement has been made in the text to all other material used
iii. The thesis is fewer than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices

______________________________
Hosna Tashakkori Hashemi

[Signature]

Melbourne, June 2017
Thesis Preface

The following is a list of published works that has been produced as part of this thesis:

i. Journals


ii. Peer Reviewed Conferences


iii. Book Chapters


iv. Other

The following is a list of awards received during the research:

• RHD Best Journal Paper Award, Geomatics Discipline, Department of Infrastructure Engineering, The University of Melbourne, 2015

• 2015 Thomas Ewing Memorial Scholarship

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• 2015 Infrastructure Engineering Departmental Travel Grant

• Nominated for Best Poster Presentation in the 2nd International Symposium of Disaster Management (ISDM2015)

• 2015 Fresh Scientist of Victoria, Fresh Science Victoria, July 2015

• 2015 APCO Australasia Young Public Safety Innovation Award, April 2015

• Semi-finalist of 3 Minute Thesis Competition, Aug 2015

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<td>2D</td>
<td>Two Dimensional</td>
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<td>3D</td>
<td>Three Dimensional</td>
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<td>Ant Colony Optimization</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>IESM</td>
<td>Indoor Emergency Spatial Model</td>
</tr>
<tr>
<td>IFC</td>
<td>Industry Foundation Classes</td>
</tr>
<tr>
<td>LBS</td>
<td>Location Based Services</td>
</tr>
<tr>
<td>LoD</td>
<td>Level of Detail</td>
</tr>
<tr>
<td>MAT</td>
<td>Medial Axis Transform</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
</tr>
<tr>
<td>SRP</td>
<td>Search and Rescue Problem</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>TSP</td>
<td>Travelling Salesman Problem</td>
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<tr>
<td>UML</td>
<td>Unified Modeling Language</td>
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<tr>
<td>VG</td>
<td>Visibility Graph</td>
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<tr>
<td>VRP</td>
<td>Vehicle Routing Problem</td>
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Chapter 1

Introduction
1.1 Research Motivation

Buildings are becoming a major subject of recent disasters resulting in huge amounts of casualty and damage costs for both public and emergency managers. Only in US, 3,000 people are killed, 16,000 civilians are injured, and 27,000 firefighter are injured on the fire ground each year with structural fires playing the leading role (FEMA 2014) while at the same time Australia experiences 300 deaths and 3000 injuries per year (Ashe et al. 2009). Emergency management for these indoor environments is quite challenging due to increased complexity of buildings, high rise structures and underground facilities (Safety Health and Survival Section International Association of Fire Chiefs 2012) where much of the information stays unrevealed to emergency managers prior to entering the incident scene; exposing their safety and lives to danger.

While time is the most critical factor in emergency response, research have shown that travel times required to reach a disaster site inside multi-story buildings can be much longer than the actual time it takes the first responders to reach that disaster building from outside the structure (Kwan & Lee 2005). Also indoor navigation is much slower than outdoor navigation due to slower walking speed and unavailability of elevators in emergency situations and also uncertainty of paths. In addition, smoke distribution and blocked areas in many of disaster incidents increases the probability of rerouting inside structures which decreases emergency response speed (Jeon et al. 2011).

The success of the emergency response operations depends on establishment and utilization of Situational Awareness of existing and dynamically created data in the field, the first responders’ level of awareness of the incident surrounding, their knowledge of the situation they are responding to, and their capability to efficiently communicate amongst each other (Dilo & Zlatanova 2011; Li, Yang, et al. 2014; Berger et al. 2016; Holmberg et al. 2013). Having access and communicating such information would improve the first responders’ situational awareness to a high extent and therefore would improve safety and reduce property loss (Holmberg et al. 2013). However, currently no additional information is known about the disaster building and the environment around it which makes emergency planning difficult prior to entering the structure (Holmberg et al. 2013).

Inexistence of the indoor information also complicates the Search and Rescue procedures which are a major task undertaken by first responders after an incident occurs. Search and
Rescue as a widely used term among fire services refers to the act of locating fire or potential victims and removing them from the scene which consists of a primary and secondary search (Bricault 2006). Most importantly, chances of saving victims in residential buildings under dangerous situations depends on the speed of the primary search (Bricault 2006). However, unavailability of accurate indoor maps and detailed information on building features and utilities aimed at indoor emergency response makes this quite a difficult task where the decisions on the number of crew required and the way they should be dispatched in the building considering the various entrances, exits, and ingress/egress paths of a building in a way that optimizes the overall search and response time is something that is left to previous knowledge of the environment and incident commanders’ experience.

In the current practice systems, when an indoor incident occurs, a 360-degree size-up of the incident and an assessment of the structure and the blueprints of the buildings and physical spaces are conducted rapidly after arrival of the emergency crew and an action plan is developed accordingly on site. Although, some building owners provide the fire brigades with their 2D CAD maps, these maps are difficult to interpret quickly, lack detailed emergency information and are not available for all the structures and residential areas. For the primary search operations, firefighters are trained to use the right or left hand technique to keep them oriented. They unreel special ropes called lifelines and fire hoses to find routes along the way and occasionally use thermal cameras in poor visual conditions (Safety Health and Survival Section International Association of Fire Chiefs 2012). Still, getting lost in buildings, disorientation, miscommunication of locations and spaces, and not knowing the paths cause huge amounts of casualties in indoor structures (Safety Health and Survival Section International Association of Fire Chiefs 2012).

1.2 Research Background

As mentioned above, decision making and search and rescue operations for indoor emergency situations face various challenges. Unavailability of detailed geometric and semantic maps is what plays a major role in these complications and as Evans (2003) discusses, first responders should not have to physically enter a burning building to gain critical information regarding that building and in fact this information should be readily available to them in their trucks while approaching the scene; providing them detailed situational awareness of the inci-
dent area (Tashakkori, Rajabifard, Kalantari, et al. 2016). Provision of detailed indoor spatial, geometric, and semantic information to decision makers can assist them with orienting crew members in indoor environments and help them navigate through the structures using best paths in order to reduce the overall response time (Tashakkori et al. 2015; Isikdag et al. 2013). However, since the concept of indoor space is very different from that of outdoor space in various ways (Winter 2012), provision of such detailed indoor information requires a redefinition of the data models, concepts, and standards to be able to meet the requirements of specific indoor location based services, indoor route analysis, and indoor geo-tagging services (OGC et al. 2014).

3D city models that are able to represent building structures including their entry/exit points, building elements and furniture have been proven to improve disaster, evacuation, and navigation services for indoor emergencies (Kwan & Lee 2005; Kolbe et al. 2008; Isikdag et al. 2008; Zlatanova & Li 2008; Jun et al. 2009). In fact, accurate building and visual information are known necessary for structural fire scenarios and thus, building models and firefighter tracking systems have been recognized as invaluable tools by emergency responders for improving the safety of individual firefighters in structural fires (Berger et al. 2016). More specifically, 3D indoor models have proven to enhance the localization, orientation, and visual cognition of the indoor environments (Rakkolainen & Vainio 2001) as well as improve the speed of rescue for indoor operations (Kwan & Lee 2005; Tashakkori et al. 2015) and help in more efficient decision making in indoor environments. Thus, geographical information systems have been integrated with geometric and semantic information of building utilities from 3D Building Information Models (Eastman et al. 2011) in an attempt to improve indoor situational awareness and assist in indoor way finding (El-Mekawy et al. 2012; Isikdag et al. 2013; Thill et al. 2011). However, what has complicated the use of such models in the real world applications, is their lack of appropriate and applicable representations of the indoor geometry and semantics (Lee & Zlatanova 2008). The problems with these models are they are not geo-referenced, are usually defined with complex geometries like CSG, are either too complex, or don’t have enough semantic support that can be used for indoor navigation (Isikdag et al. 2013). Moreover, most of the indoor spatial models proposed thus far, are not targeted to emergency responders, and thus can’t be used directly for emergency response applications.

Accurate indoor situational awareness and route finding for emergency crew depends on availability of detailed indoor information aimed at first responders that will meet their specific
needs which are different from that of evacuation and building construction applications. Information of floor plans, gathering points, staircases, elevators, building type, location of emergency utilities such as fire panels, utility shutoffs, and hazardous materials, as well as information on occupancy and real time information collected through environmental detectors all play a major role in the emergency planning and decision making and should be seen in the developed indoor models (Holmberg et al. 2013).

Most of the indoor models proposed thus far have primary focuses on specific purposes such as network modelling and indoor routing (Umit Atila, Karas & Rahman 2013; Rakip et al. 2012; Lee 2007; Meijers et al. 2005; Kwan & Lee 2005); or visualization purposes (Kim & Wilson 2015; Goetz 2013; Kolbe 2009) and thus, have limitations in highlighting the other important information required for emergency response. Image based methods (Luhmann et al. 2013), laser scanning techniques (Lafarge & Mallet 2012), and integrated approaches (Xiao & Furukawa 2012) are becoming very common for acquiring 3D data used for 3D indoor construction. However, automated reconstruction of detailed LoD4 (Level of Detail) models of buildings using such approaches is quite a challenge (Díaz-Vilarriño et al. 2015). Detecting the common elements such as doors, walls, stairs, etc. are absolutely essential and beneficial for knowledge of the interiors, navigation, and evacuation planning. Although efforts have been taken for finding solutions that can automatically extract some building features like doors (Díaz-Vilarriño et al. 2015); these approaches have limitations in modelling the elements that are inside the walls such as gas pipes and electrical facilities, as well as semantic and cellular information of the inside environments. Therefore, other approaches such as CityGML and Building Information Modelling are popular alternatives used to overcome some of these known limitations by focusing more on indoor spatial modelling (Kolbe 2009; Eastman et al. 2011).

CityGML is an open data model and XML-based format for the storage and exchange of virtual 3D city models (Gröger et al. 2012) with high potential for emergency response applications (Kolbe et al. 2008). CityGML presents the graphical appearance of city models whilst also presenting the semantic, thematic, and aggregations of the models. On the other hand, Building Information Models (BIM) (Underwood et al. 2007) are semantically rich digital facility models that carry comprehensive geometric and semantic information of building elements (Eastman et al. 2011) which are obtaining attention in the architectural, engineering, construction, facility management, urban planning, emergency response, and energy planning communities due
to their ability to ease the discussions amongst its users (Tang et al. 2010). The most popular BIM standard and schema is the Industry Foundation Classes Model (IFC) (Liebich 2009) which is an open, international, and standardized specification containing advanced semantics and geometries of building elements and spaces inside buildings (BuildingSmart 2008). BIMs have been variously used in the literature to improve indoor localization (Li, Becerik-Gerber, et al. 2014), route planning (Teo & Cho 2016), and decision making (Chen & Huang 2015) for in-building emergency response.

Most of the models that are based on CityGML and BIM either have complex architectural engineering aspects (Li 2008) or are designed for visualization reasons; lacking information required for emergency management (Kolbe 2009; Goetz 2013). Even indoor modelling methodologies proposed for facilitating indoor navigation and orientation for emergency situations (Isikdag et al. 2013), still lack much of the indoor information required by first responders on scene. Information such as real time information collected from detectors, location of emergency utilities, ownership and accessibility information, etc. In addition, while it is important to have a seamless spatial model between the indoors and outdoors, most of the models proposed thus far, consider buildings as autonomous systems; independent of how they interact with their surrounding buildings and environment. To enable exchange of information between building objects and geospatial objects, efforts have been taken to integrate BIM and CityGML to enable cross spatial analysis between the indoors and outdoors (El-Mekawy et al. 2012). Although, some valuable information regarding the interaction among the indoor and outdoor objects could be retrieved, still this model carries all the complexities of the IFC and CityGML and has limitations presenting all the information that is necessary during emergency management such as position of main shutoffs, hazardous materials, etc.

The Search and Rescue Problem is also affected by this inexistence of an accurate indoor spatial model aimed at emergency responders. That is why, solutions such as that proposed by (Wu & Chen 2012) for finding the search and rescue routes face a main drawback of not considering the buildings as 3D environments containing multiple entry/exit points and various ingress/egress ways with indoor elements that impact the routing decisions and thus resulting in unrealistic solutions. Furthermore, they see the problem as a TSP (Travelling Salesman Problem); searching the entire area by one person in the building which is an impractical assumption. Although, other researchers have tried to increase the accuracy of the solution approach by using BIM for the indoor routing network (Chen et al. 2015) still, BIM is only used for graph
extraction using the Medial Axis Transform; not taking into consideration the semantic and geographic information for solution construction.

1.3 Problem Description

Considering the importance of a quick thorough search inside the buildings by first responders after an incident occurs (Bricault 2006), an important research problem is how the first responder crew should be dispatched inside the building in order to minimize the search and rescue time which is referred to as the **Search and Rescue Problem (SRP)**. SRP is defined as finding the optimum routes for the minimum number of first responders to search and visit all rooms inside a building for possible victims in the quickest time possible. Considering the various settings of the building and multiple entrances and exits that a building can have, SRP should suggest best routes including which door to enter and which door to exit for each responder to optimize the overall performance of all the responders in the scene. To address this problem and to be able to present an effective solution approach for it two major aspects need to be considered. First, accuracy of the proposed solution depends on proposing a precise 3D indoor/outdoor geometric and semantic spatial model aimed at emergency response which will enable the creation of the underlying navigable indoor graph to fit first responders’ routing needs inside the structures. Second, the proposed model should be leveraged for designing the indoor network model and formulating the problem moving towards a solution approach that will fit indoor emergency operations. The combined indoor spatial model along with the search and rescue routes would increase indoor situational awareness in case of indoor incidents as well as increase response speed.

1.4 Research Problem and Aim

According to the research description, emergency response and search and rescue operations are faced with a lot of difficulties in indoor environments due to lack of indoor situational awareness of the incident scene and knowledge of the area. Most of the indoor information regarding the building elements and utilities are unavailable to first responders before physically entering the building which makes emergency planning and decision making complicated and reliant on previous knowledge of the environment. Furthermore, decisions on num-
ber of crew required and the way they should be dispatched inside the building for an efficient search is quite challenging.

Accordingly, the research problem is defined as:

Despite the considerable amount of research done in the area of indoor spatial modelling, the current data models are not effective in indoor search and rescue operations and thus indoor decision making is a challenge for first responders.

Therefore, the main aim of this research is to:

Develop a new 3D indoor spatial model that contains geometric and semantic information of building utilities and is integrated with the outdoor environment aimed at emergency response operations and leverage it for formulating and solving the indoor search and rescue problem.

The following research questions are addressed in this research:

• What building information is critical for emergency responders in case of structural disasters that should be integrated into the model?

• How should the 3D indoor spatial model be developed in order to address the first responders’ decision making requirements? And how would the model affect situational awareness, spatial analysis and routing for indoor areas and be integratable with outdoor spatial models?

• Can a new solution to the Indoor Search and Rescue Problem be provided? how should the problem be formulated based on the 3D integrated indoor spatial model and solved to find the optimized search and rescue routes for an indoor area in order to minimize the response time?

• How well does the proposed model perform compared to the current practice systems, does the proposed indoor spatial model and search and rescue algorithm
improve situational awareness and emergency response time compared to current procedures and practice systems?

The hypothesis of this research is accordingly:

A 3D indoor emergency spatial model targeted at first responders can improve the situational awareness of the incident building and surrounding environments and will allow accurate formulation and solution provision for the Indoor Search and Rescue Problem resulting in quicker and more efficient response time.

The expected research outcome is:

A 3D indoor spatial model tailored at emergency response operations that will allow presenting a solution to the Search and Rescue Problem (SRP). While the 3D indoor spatial model will be integrated with the outdoor environment to enable seamless 3D indoor/outdoor situational awareness and spatial analysis of the incident scene, the SRP solution will help in finding the minimum number of first responders required to search an entire building, finding near optimum routes for each one in order to cover the entire building in the shortest time, considering the multiple entrances and exits to the building and providing indoor situational awareness to first responders.

1.5 Research Objectives

Based on the research description, questions, and aims of this thesis, the following objectives were identified (Table 1-1). Each of these objectives answers one or more of the above mentioned questions.
Table 1-1 Research Objectives and Outcomes

<table>
<thead>
<tr>
<th>Objective</th>
<th>Description</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective 1</td>
<td>Assess current indoor disaster management models to identify the gaps and limitations of current indoor models and search and rescue procedures to establish a theoretical framework for the research</td>
<td>Foundation of the research</td>
</tr>
<tr>
<td>Objective 2</td>
<td>Design and develop a 3D indoor spatial data model based on mission critical information for indoor emergency response</td>
<td>3D Indoor Spatial Data Model for Indoor Emergency Response</td>
</tr>
<tr>
<td>Objective 3</td>
<td>Formulate the Search and Rescue Problem based on the 3D indoor spatial model and solve the problem using a heuristic approach</td>
<td>Algorithm for optimized Search and Rescue routes</td>
</tr>
<tr>
<td>Objective 4</td>
<td>Develop a 3D indoor situational awareness prototype system based on the designed indoor data model and SRP solution approach, consisting of indoor emergency spatial services and path finding</td>
<td>Proof of concept case study and prototype system for the indoor situational awareness model</td>
</tr>
<tr>
<td>Objective 5</td>
<td>Test the system and evaluate its efficiency based on quantitative methods</td>
<td>Results and Improvements</td>
</tr>
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1.6 Research Approach

According to Kothari (Kothari 2004) “a research process or research approach consists of actions or steps necessary to effectively carry out research and the desired sequencing of the steps”. A scientific research process can be generally defined in the context of the phases and steps shown in Figure 1-1. As Kothari (Kothari 2004) discusses, the steps and activities in a research process overlap continuously and are not considered as exclusive or distinct. However, the following steps can set a guideline for the journey of a successful research: 1) Definition and formulation of the research problem; 2) comprehensive literature review; 3) hypothesis development 4) preparation of research design; 5) data collections; 6) project execution; 7) data analysis and system evaluation; 8) hypothesis testing; 9) interpretations of results and 10) formal presentation and writing of findings.
To address the stated research problems and achieve the research objectives; based on the scientific research approach phases given above, five stages are conducted in the research with each addressing one of the objectives of the research. These five stages are given in detail in Figure 1-2:

1. Defining the research problem, conceptualization of the research, and establishing the theoretical framework of the research

2. Designing the 3D Indoor Emergency Spatial Data Model (IESM) using the identified emergency mission critical data

3. Formulating the Search and Rescue Problem (SRP) based on the 3D IESM and proposing an ant colony inspired metaheuristic solution for solving the static and dynamic problem

4. Developing the 3D IESM prototype model for a case study building to evaluate the efficiency of the model for cross spatial analysis and routing purposes

5. Analyzing and evaluating the performance and efficiency of the proposed solution to SRP and validating the results by comparing it with current practice procedures.
**Research Methodology**

Activities and Steps Involved

1. **STAGE 1:** Defining the Research Problem
   - Review previous literature and practice systems on indoor modelling and search and rescue

2. **STAGE 2:** Designing the 3D Indoor Emergency Spatial Model (IESM)
   - Investigate current indoor modelling methodologies
   - Review concepts and theories and identify research gaps in the context
   - Formulate research questions and objectives
   - Establish the theoretical framework and design the research

3. **STAGE 3:** Formulating the Search and Rescue Problem (SRP) based on the 3D IESM and
   - Model the Search and Rescue Problem (SRP)
   - Analyze indoor mission critical data requirements for first responders
   - Design the 3D Indoor Emergency Spatial Data Model
   - Design a geometric/semantic based network model

4. **STAGE 4:** Developing the 3D IESM Prototype Model
   - Develop an ant colony metaheuristic solution approach for solving the problem
   - Develop the dynamic SRP algorithm for real time changes in problem setting
   - System design of the 3D Emergency Spatial Model
   - IESM system implementation using a case study prototype (desktop and web based)

5. **STAGE 5:** Analyzing and Evaluating the IESM based SRP
   - Implement the IESM based SRP algorithm in Python
   - Evaluate the algorithm’s performance and efficiency using simulation for the case study
   - Evaluate and validate the proposed solution with practical procedures using pedestrian based simulation

**Research Objective**

- **OBJECTIVE 1**
- **OBJECTIVE 2**
- **OBJECTIVE 3**
- **OBJECTIVE 4**
- **OBJECTIVE 5**

Published in (Tashakkori, Rajabifard, Kalantari, et al. 2016; Tashakkori et al. 2015)

Published in (Tashakkori, Rajabifard & Kalantari 2016)

Published in (Tashakkori et al. 2015)

Figure 1-2 Research approach and its link to research objectives
While most research is generally based on the scientific approach discussed above, research in information systems follows the more specific behavioral science or design science paradigms (Hevner et al. 2004). While behavioral science is focused on human and organizational behavior, design science generates novel and innovative artifacts for expanding the human and organizational capabilities. Furthermore, the artifacts allow creation of innovative ideas, products, or technical capabilities where using the information systems can improve proficiency and efficiency. Design science research in IS results in an IT artifact that is addressed to solve an organizational problem (Hevner et al. 2004). IT artifacts are defined as constructs, models, methods, and instantiations (Hevner et al. 2004). Constructs consist of vocabulary and symbols; while models are basically abstractions and representations; methods involve algorithms and practices; and instantiations are implemented and prototype systems.

Design Science (DS) can be used to analyze the feasibility of a proposed approach in IS by creating and evaluating IT artifacts. To give a more standardized format to the DS research in IS Peffers et.al. (2008) develop a Design Science Research Methodology (DSRM) for presenting and evaluating such kind of research. The methodology is based on six major steps: 1) problem identification and motivation, 2) objective definition for a solution, 3) design and development, 4) demonstration, 5) evaluation, and 6) communication.

**Problem Identification** is where the research problem is defined based on the broad knowledge of the state of the problem and the significance of the solution is highlighted. In the **Solution Objective Definition**, the objectives of the proposed solution are defined either quantitatively or qualitatively. The proposed artifact (construct, model, method, or instantiation) is created in the **Design and Development** stage. The developed artifact is solved for one or more instances of the problem using simulations, experimentations, case studies, proof, etc. in the **Demonstration** step. Lastly, the artifact is observed for the performance measures to evaluate the efficiency and feasibility of the proposed solution in the **Evaluation** phase and then the importance and novelty of the developed solution is communicated in the **Communication** phase and future improvements are proposed.

This research’s methodology best fits the requirements and procedure of the Design Science approach. DS and the details of the undertaken design and methods used in the thesis are discussed thoroughly in Chapter 3. Based on the Design Science, the stages of this research can be classified into the following phases:
1.6.1 Research Problem Definition, Hypothesis and Objective Formulation

The first stage of the research consists of building the foundation and the theoretical framework of the research. This includes an extensive literature review of indoor modelling and search and rescue systems in the domain of indoor emergency response. Based on the wide range of books, journals, conference papers, reports, and discussions with practitioners and experts in the field, the problem is investigated and the research gap is highlighted. This stage allows establishing the research problem and setting the aims and objectives of the thesis; which in this thesis is stated as limitations of indoor spatial models for emergency response requirements and thus, the open question of how search and rescue should be undertaken in indoor environments.

After a thorough investigation of the literature, the working hypothesis of the research should be clearly stated. The hypothesis is a tentative assumption that should be tested and evaluated logically and empirically (Kothari 2004).

The hypothesis of this research is:

“a 3D indoor emergency spatial model targeted at first responders can improve the situational awareness of buildings and surroundings and will allow accurate formulation and solution provision for the indoor Search and Rescue Problem resulting in quicker and more efficient response time “.

The hypothesis sets the delimitation of the research and helps in designing the research for testing the hypothesis which is the next stage of the research aiming at developing a solution targeted to solve the problem and prove the hypothesis.

1.6.2 Research Design and Development

Subsequent to conceptualization of the research and defining the research problem, the research design defines the conceptual structure within which the research will be undertaken (Kothari 2004). Having the research problem in mind, this stage designs a method to solve the problem and overcome the objectives of the research.

To be able to present a solution for the Search and Rescue Problem two main aspects need to be covered in the research. First, the indoor environment needs to be modelled accurately to
present the information requirements of first responders on scene. Second, the presented
indoor model can then be leveraged for designing the indoor network model and formulation
of the problem moving towards a solution approach that fits indoor emergency operations.
Therefore, the structure of this research is based on design, development, and evaluation of
both of these aspects alongside one another.

To address the first aspect which is proposing an accurate indoor modelling approach for
emergency response, after extensively analyzing current indoor modelling methodologies and
search and rescue procedures, a 3D indoor emergency spatial data model (IESM) is designed
based on indoor mission critical data requirements of first responders. According to the limita-
tions of current methods for indoor GIS and urban modelling (refer to Chapter 2), the pro-
posed 3D IESM presents a new method for modelling the indoor areas and integrates the out-
door environments (see Chapter 4). While the model brings together the emergency critical
aspects of both BIM and CityGML, it removes complicated, constructional aspects that are not
related and instead adds other related first response criteria.

To address the second aspect of the research which is presenting a solution approach for SRP,
the indoor GNM (Geometric Nework Model) extracted from the model is used to mathemati-
cally formulate the problem and a heuristic ant colony based algorithm is designed for SRP for
both the static and dynamic states of the problem (will be discussed in detail in Chapter 5). The
solution considers the constraints of the problem where the aim is to search the entire build-
ing in minimum time with minimum number of first responders, visiting all points of interest,
while minimizing the overlap in the network in both static and dynamic settings (see Chapter
5). Ant colony optimization (ACO) is a strong category of metaheuristic algorithms based on
the real ants behavior to forage food (Maniezzo et al. 1991). ACO algorithms have promising
results for TSP (Dorigo et al. 2010) and its generalized form, Vehicle Routing Problems
(VRP)(Gambardella et al. 1999), which more recently is being used for optimizing evacuation
routes inside buildings (Amalina et al. 2016). The ACO based algorithm is developed for both
the initial/static state of the problem where no further information is available on the dynam-
ics of the indoor situation and the dynamic state where routes need to be updated based on
timely information received.
1.6.3 System Demonstration and Data Collection

To demonstrate the feasibility of the developed artifact proposed in this research, the artifact instantiation is used which for this research is basically a software tool developed for implementing the Indoor Emergency Spatial Model (IESM) and the SRP algorithm aiming to improve the process of information system development. This instantiation provides “proof by construction” (Nunamaker et al. 1991).

For the artifact instantiation of the proposed indoor situational awareness framework, first a case study building at The University of Melbourne is chosen to enable a consistent demonstration of the proposed solution. The 2D indoor CAD floor plans from the case study building are converted to a geo-located 3D building model using the Revit Software. Using the case study building, a proof of concept demonstration of the Indoor Emergency Spatial Model is presented in Chapter 6. The IESM model is implemented in ArcGIS’s ArcScene platform creating an integrated indoor/outdoor geo-information model to support indoor emergency response and management. This would allow demonstrating various emergency management functions that will be enabled by the model for different scenarios confronted by emergency responders.

Once the 3D IESM’s effectiveness has been proven, the SRP algorithm is implemented in Chapter 7 based on the 3D presented indoor GNM using python 2.7. This includes the proposed ant colony based algorithm for both the static algorithm; that is the initiation of the problem, before arrival at the scene, where no further information of fire progression and blockage is available and also the dynamic algorithm; where the building is prone to environmental changes received through sensors or other forms of communication. This is where changes occur in the search plan, due to areas becoming inaccessible, dangerous, or blocked and there is need for dynamically updating the already assigned paths to first responders to avoid passing through endangered areas.

The implemented simulation environment allows simulating the case study for various experimental settings and scenarios which enables quantitative analysis of the results and the performance of the algorithm.

1 www.autodesk.com
1.6.4 Research Analysis and Evaluation

The last phase in the research approach before reporting and communicating the research is to analyze the results, evaluate the performance, and validate the hypothesis. For this purpose, a twofold evaluation of the proposed and developed indoor situational awareness model is undertaken; 1) demonstrating and evaluating the proposed 3D IESM, and 2) evaluating and validating the Indoor Search and Rescue Problem.

For the first part, an observational case study and descriptive scenario method is used to evaluate the demonstrated 3D IESM in Chapter 6. Various scenarios and uses cases that first responders would need on the incident scene are applied to the system and the analysis outputs are used for evaluation of the proposed model.

For the second part, which is the evaluation and validation of the SRP, the developed and implemented algorithm was simulated for various parameters and indoor settings to evaluate the efficiency of the proposed algorithm for both static and dynamic conditions in Chapter 7. Once the algorithm is robust, to validate and prove its efficiency compared to current procedures, a series of face to face interviews were conducted with experts from Country Fire Authority (CFA) Dandenong to simulate their strategies and search and rescue procedures in an agent based pedestrian simulator named Pathfinder\(^2\) for the same case study building. The results and outcomes of the proposed SRP algorithm was also simulated in Pathfinder and then compared with the current regulations to test if the aim of the research was achieved.

1.6.5 Interpretation and Communication

In the final phase, the research problem, our solution and its novelty along with the findings are presented to the academic community and relevant audiences using a dissertation, a number of publications, as well as presentations to the key relevant industry bodies and public safety authorities.

\(^2\) http://www.thunderheadeng.com/pathfinder/
1.7 Delimitation of Scope and Key Assumptions

The focus of this research is on first responder assistance and situational awareness improvement for indoor incidents. Indoor incidents can cover a big range of events such as fires, earthquakes, chemical spills, gas leakages, terrorist attacks, etc. Although modelling the indoors spatially can increase indoor situational awareness for all such incidents and assist decision makers to have a better view of the incident scene and is an absolute necessity for the next generation of GIS; since the research is unable to encompass the entire indoor disasters, this research is mostly focused on incidents such as fires in which the structure doesn’t collapse right after the occurrence of the incident; leaving time for on-scene emergency response and rescue operations. In addition, the research is targeted at first responders specifically fire fighters and their requirements for indoor incident management in such situations.

Although the proposed 3D IESM and SRP can play a major role in increasing indoor situational awareness and improving the knowledge of indoor areas even without localization systems due to creating a 3D conceptualized model; indoor path finding and navigation is reliant on an accurate indoor positioning system. However, the localization techniques are beyond the scope of this study and the assumption here is that the proposed model sits on top of any indoor localization approach.

The reader should bear in mind that the main aim of the research is to model the indoors geometrically and semantically to improve the Search and Rescue procedures and although the dynamic changes in the accessibility of areas and their effects on the rescue routes are considered, other factors such as fire dynamics, smoke movement, etc. are not taken into consideration for this research.

Finally, as there is already various solutions to modelling the outdoor urban areas (Biljecki et al. 2015), the focus of this research is mostly on the indoor environments and how it should be connected and integrated with the outdoor areas to allow seamless spatial analysis, visualization, and pathfinding.

Lastly, the indoor routing and search and rescue procedures are based on the creation and existence of the indoor route graph which allows movability and path finding in the network. Automated derivation of graphs is an entire different research domain that still faces its own strengths and challenges (Mortari et al. 2014) and lies beyond the scope of this study. Thus,
the indoor geometric network model of the case study used here is extracted manually based on the requirements discussed in Chapter 4

1.8 Thesis Structure

This dissertation is structured in four major parts; Introduction, Design & Development, Implementation & Evaluation, Conclusion & Future Work. The eight chapters of this thesis are structured under these four parts to target the research problem and achieve the aforementioned objectives of the research. The order and overall contents of each chapter are given in Figure 1-3.

Chapter 2 will provide an overview of complexities of indoor emergency management procedures by looking at current procedures and practice systems through both literature and interviews with practitioners. Furthermore, the need for indoor situational awareness and 3D Indoor GIS models for the urban context is evaluated. Also, the Search and Rescue Problem is more deeply analyzed from both practice and literature. Thereafter, a critical review of the literature and practice is given and their limitations and the major research gaps are highlighted.

Chapter 3 outlines the research design and methodology used to answer the research questions. Moreover, it explains in detail the steps and methods used for undertaking the research.

Chapter 4 discusses the issues with current indoor modelling methodologies and their limitations for application to indoor emergency situations. Accordingly, the critical information required by emergency responders for indoor incident management is examined and the Indoor Emergency Spatial Model (IESM) is presented by developing a new data model for Indoor/Outdoor spatial presentation. The chapter then continues by presenting an approach for extracting an integrated geometric/semantic network model from IESM for seamless pathfinding in indoor environments detailing the graph construction and cost computation of routes for emergency applications. The model then allows it to be used for formulating and solving the Indoor Search and Rescue Problem in Chapter 5.

Chapter 5 delves deeply into the Indoor Search and Rescue Problem. It first defines the problem for complex indoor environments and explains current practice methods. Then, using the proposed indoor GNM extracted from IESM, SRP is formulated and an ant colony inspired algo-
Algorithm is proposed for solving the problem. Also, the dynamic version of the algorithm which adjusts itself based on changes in the environment for updated rescue routes is presented.

Chapter 6 evaluates the feasibility and capabilities of IESM through a case study scenario based development. Thus, looking at different scenarios that first responders are confronted with, the performance of the proposed model is analyzed for enabling seamless 3D visualization, seamless spatial analysis, seamless routing and decision making. Chapter 4 and Chapter 6 are mainly based on the paper published in the Journal of Building and Environment (Tashakkori et al. 2015). The proven proficiency of the system then allows evaluating SRP which is based on IESM in Chapter 7.

Chapter 7 explains the implementation details of the proposed SRP algorithm, discusses the experimental design properties and presents the results of running the algorithm under various settings. Furthermore, the performance of the algorithm for initial route finding and route adjustment after dynamic changes is evaluated. Finally, using the interviews from practitioners, their decisions for search and rescue routes are modelled in an agent based pedestrian simulator and is compared with the results achieved from the ACO based solution for validation and efficiency analysis of the algorithm.

Finally, Chapter 8 discusses the outcomes of the research, concluding on the findings and achievements of the research, and lastly presents the recommendations for future research.
Chapter 1: Introduction

- Research Description
- Research Problem, Hypothesis, and Aim
- Research Objectives
- Research Approach

Chapter 2: Indoor Situational Awareness and Indoor GIS for Emergency Response

- Need for Indoor Situational Awareness
- Indoor Emergency Operations in Practice
- 3D GIS for Urban Context
- 3D Indoor GIS
- Indoor Routing and Evacuation
- Indoor Search and Rescue

Chapter 3: Research Design and Methodology

- Research in Information Systems
- Design Science Research Methodology
- Dissertation Research

Chapter 4: A new 3D Indoor Outdoor Emergency Spatial Model (Paper 1 and 2)

- Indoor Information Requirements for Indoor Incident Management
- 3D Indoor Emergency Spatial Data Model
- 3D IESM Integrated Geometric/Semantic Network Model

Chapter 5: Spatially Enabled 3D Indoor Search and Rescue (Paper 3)

- Search and Rescue in Complex Structures
- Current Practice and Requirements
- 3D Indoor Geometric and Semantic Aware Network Model
- SRP Formulation
- Ant Colony Based Algorithm for SRP

Chapter 6: IESM Implementation and Evaluation Analysis

- IESM System Design
- IESM Emergency Management Capabilities
- Integration and with Outdoor Environment
- Web Based IESM

Chapter 7: SRP Implementation and Evaluation Analysis

- Implementation Settings
- Proposed SRP algorithm results
- Algorithm Performance under Dynamic Environmental Changes
- Agent Based Simulation for CRP Validation with

Chapter 8: Conclusion and Future Work

- Discussion on IESM and the Ant Colony Inspired SRP Algorithm
- Conclusion
- Recommendations for

Figure 1-3 Structure of the thesis
1.9 Chapter Summary

A key problem in indoor emergency management is that the current indoor spatial models do not fit emergency response requirements and thus cannot be effectively used for decision making in this area leaving the indoor Search and Rescue Problem a challenge for first responders. This thesis intends to address this problem which relies on first developing a new 3D indoor spatial model that contains geometric and semantic information of building utilities targeted at emergency response applications. And second, leveraging the proposed model for solving the indoor search and rescue problem. The two contributions form the overall structure of the thesis in hand.

To address the research problem and achieve the aims and objectives of the thesis, this chapter provided the foundation of the research presented in this dissertation. A background to existing challenges and issues in indoor incident response was given, and accordingly the non-existence of indoor spatial models aimed at first responders and the problem of indoor search and rescue were highlighted. Based on the research problems, the hypothesis of this thesis, objectives for achieving the aims, and the scope of the research were discussed. Furthermore, the methodology and research approach and the various phases involved for achieving the objectives of the thesis were briefly explained and will be given in more detail in Chapter 3. The chapter was concluded by delineating the overall structure of this dissertation to guide the reader throughout this document.

The next chapter provides a thorough overview of the problem domain by looking at indoor situational awareness in both literature and current practice and reviews the challenges and gaps faced by emergency responders for on-scene decision making.
Chapter 2
Shifting Towards Indoor Situational Awareness for Emergency Response and Search and Rescue
2.1 Introduction

As was discussed in Chapter 1, indoor emergency operations and search and rescue procedures face various difficulties and uncertainties and the solutions proposed thus far are not targeted directly to the indoor applications from the first responders’ point of view. To address the research problem and objectives outlined in the thesis, this chapter forms the knowledge base and presents an overview of the principles and current status of the research. Moreover, a thorough systematic investigation of the current practice systems and literature is undertaken to identify the gaps in the area of indoor emergency response and search and rescue operations to highlight the significance of the problem and the proposed solution.

The current chapter first highlights the complexities and challenges faced by rescuers and decision makers in indoor emergency response operations in Section 2.2. The general rules and regulations used by first responders in handling indoor incidents and search and rescue operations are investigated in Section 2.3 to give a better understanding of the problem in the real world settings. To have a deeper grasp of the strategies used by decision makers on-scene and for the case of preparing the case study and evaluation purposes later in the thesis, more detailed and practical view of the current practice systems and procedures for search and rescue are investigated from the Australian context by a series of interviews undertaken with the fire brigade team at the Dandenong Country Fire Authority (CFA). The chapter then gives an overview of the state of the art models and solutions proposed in literature to assist public and first responders in gaining indoor situational awareness of the incident scene and navigating the structures in Section 2.4. The various approaches used by literature to model the indoor environments, how the models are used for public/first responder navigation inside the buildings, and how these models are utilized for solving the search and rescue problem are discussed; emphasizing the gaps and limitations these approaches face and discussing the reasons none of the current methods can be applied to the indoor search and rescue operations.

2.2 Complexities of Indoor Emergency Response and Search and Rescue Operations and Necessity of Indoor Situational Awareness

The US fire administration statistics show that around 1,290,000 fires are reported in US each year causing fatalities and injuries of thousands of firefighters and civilians on the fire
grounds, with structural fires playing the leading role as shown in Figure 2-1 (FEMA 2016). Only the statistics in US reveal that a total of 29,130 firefighters were injured on the foreground in 2015 and 75 were killed on duty. These reports show that foreground duties are the most common type of duty for firefighters killed. Of the 26 firefighters that were killed on the foreground in 2015, 17 were at the scene of a structural fire; proving how dangerous indoor structures could be for rescuers (Fahy, Rita, LeBlanc, Paul, Molis 2015). The main reasons of the fatalities included stress/overexertion, getting lost or disoriented, being caught or trapped, collapse of the structure, or falling.

When responding to emergencies such as fires, first responders’ safety and ability to save people’s lives and reduce the cost associated with the damages depends on the following factors: 1) their level of awareness of the incident surrounding, 2) their knowledge of the situation they are responding to, and 3) their capability to efficiently communicate amongst each other (Dilo & Zlatanova 2011; Li, Yang, et al. 2014; Berger et al. 2016; Holmberg et al. 2013). Moreover, the availability and access to existent and timely information regarding the incident scene in a reasonably short time impacts the efficiency and decision making of the emergency situation.
vastly (Dilo & Zlatanova 2011). However, in the current practice it is difficult to access all this information in a reasonably short time as this information is either incomplete or gathered by multiple sources that aren’t organized (G Guven et al. 2012). Things are even more complicated in indoor incidents where Information regarding the damaged building, its contents and occupancy conditions is not entirely available to emergency response teams before arrival (Walter W Jones et al. 2005; Evans 2003; G. Guven et al. 2012). As a result, emergency response planners face various complications, complexities, and uncertainties when planning the search and rescue operations.

2.2.1 Indoor Search and Rescue Complexities

Search and Rescue as a widely used term among fire services is defined as the act of firefighters looking for something which could be the location of fire, potential victims, or interior fire conditions. And Rescue is defined as the act of firefighters removing a victim physically from the dangerous area to a safe location which consists of the primary and secondary search (Bricault 2006).

The emergency responders undertake the search operations for finding victims using three main strategies: physical search, canine search, and electronic search (FEMA 2013). The physical void strategy requires the first responders to make vocal and visual searches for casualties. There is limited access to all voids in this method, exposing the responders to more danger and having limitations in finding unconscious and weak people. Fiber optics, search cameras, and infrared/thermal imaging could be used for assisting with the physical void search. The search area in this method is restricted to safe areas that are searchable. The other strategy is using canine teams which can be effective in locating unconscious victims. The canine search strategy is however reliant on weather conditions, temperatures, surface type, and search area. Lastly electronic listening devices can increase the search range where the areas are inaccessible to canines. Acoustic/seismic devices are used to find sounds and vibrations from victims. These devices still have limitations in detecting unconscious victims and deployment at the site.

In the primary search, the aim is to quickly locate victims that are in danger. Time is critical in this search and fire fighters need to check all locations with possible victims relying on sight, sound and touch. In the secondary search, a thorough search is conducted once the situation is
under control to search the locations that weren’t searched in the primary search tending to cover all the areas using multiple teams of firefighters to include all of the areas of the building (Fire Service Resources Network 2006). The main objective is for the firefighter to search the area thoroughly while keeping themselves oriented with the environment. The sooner and quicker the primary search is executed, the chances of rescuing more live people increases (Bricault 2006).

Search and rescue operations for indoor areas are challenging due to structural complexities, unfamiliarity with the environment, and environmental conditions (Safety Health and Survival Section International Association of Fire Chiefs 2012). In the current practice, a 360-degree size-up of the incident and an assessment of the structure and the blueprints of the buildings and physical spaces are conducted rapidly after arrival of the emergency crew and an action plan is developed accordingly on the site. Although, some building owners provide the fire brigades with their 2D CAD maps, such maps are difficult to interpret quickly, lack detailed emergency information and are not available for all structures and residential areas and in fact the NIOSH firefighter fatality reports have declared lack of a comprehensive size-up as the leading factor contributing to firefighter deaths (The National Institute for Occupational Health and Safety (NIOSH) 2010).

For the primary search operations, firefighters are trained to use the right or left hand technique to keep them oriented. They unreel ropes called lifelines and fire hoses to find routes along the way and occasionally use thermal cameras in poor visual conditions (Safety Health and Survival Section International Association of Fire Chiefs 2012). Still, getting lost in the building, disorientation, miscommunication of locations and spaces, and not knowing the paths cause huge amounts of casualties in indoor structures (Safety Health and Survival Section International Association of Fire Chiefs 2012).

Contrary to the outdoor environments, unavailability of detailed geometric and semantic information from the buildings adds further complication to the decision making strategies for indoor incidents. Moreover, planning the number of crew needed and the area that needs to be covered from inside the building is unknown to decision makers before entering the building. Thus, the effectiveness of the search, rescue, and attack strategies are quite reliant on the situational awareness of the indoor environment which allows planning for search routes inside the structures.
2.2.2 Role of Situational Awareness in Indoor Emergency Response

Typically, there is a very short time between the dispatch of first responders and arrival at the scene. However, since detailed information about the disaster building and the environment around it is mostly unavailable before entering the structure, emergency planning is complicated and time consuming (Holmberg et al. 2013). Furthermore, much of the necessary building emergency information is left unrevealed to first responders until after arrival to the site where they have to quickly evaluate the situation and take actions accordingly. In fact, lack of timely information reduces their preparedness ability to act rapidly when confronted with an incident (Evans 2003). Though, as Evans states “first responders should not have to go into a burning building to obtain critical information and situational awareness” (Evans 2003).

Situational awareness is defined by the International Association of Fire Chiefs (Safety Health and Survival Section International Association of Fire Chiefs 2012) as:

“The level of understanding and attentiveness one has (the firefighter) regarding the reality of a set of conditions (fire conditions and fire ground operations). When situational awareness is high, there are rarely surprises. When situational awareness is low or absent, “unexpected” events occur (that can injure or kill firefighters)”.

In other words, situational awareness is relating between the cognition of the event and the reality of what is happening. Situational awareness is affected by lack of information of the incident, lack of knowledge, and lack of cognition. Firefighters need to observe and be aware of their surroundings at all times by noting landmarks, windows, exits, and the route he/she or the crew have taken to enter the building to reach the current point which is required in case of getting lost and getting out of the building. Thus, the landmarks and accurate location descriptions are critical especially when declaring a May Day (Safety Health and Survival Section International Association of Fire Chiefs 2012).

Situational awareness data consisting of information delivered to Incident Commanders (IC) and information delivered directly to fire fighters should be relayed in a quick and digestible way since the time in a fire emergency is very limited and they are already flooded with heaps of information (Berger et al. 2016). Thus, decision on which data should be delivered must be
Shifting Towards Indoor Situational Awareness for Emergency Response and Search and Rescue

taken carefully. For this reason, Holmberg et al. (2013) identify the various categories of information deemed necessary by first responders during building emergencies as follows:

- Emergency utilities’ information such as location of electric shutoffs, fire department hook-ups for sprinkler systems and standpipes, fire hose rack cabinets, fire hydrants, etc.
- Building construction information such as construction type, material of doors, fire resistance, etc.
- Architectural information such as floor plans, staircases, entrances and exits to the building, etc.
- Semantic information such as building occupancy, ownership of spaces, accessibility of areas during various time periods (some spaces are locked or inaccessible even in emergency situations), etc.
- Hazardous materials inside the building or in the surrounding outdoor environment such as gas lines, propane tanks, chemical materials, gas stations, etc.
- Real time information gathered from ubiquitous systems such as heat and smoke sensors.
- Incident precinct outdoor information such as surrounding buildings, road information, hazardous stations, and water resources around the incident location.

High rise buildings have different aspects and difficulties compared to residential and other complex structures. The main difference is the building heights which might be beyond the reach of aerial ladders. Thus, victim removals using ladders are eliminated and interior attacking strategies are required (Keogh & Lord 2012). In addition, there are many other situations that the fire can’t be extinguished with an outside master stream. Thus, the search and rescue will have to be achieved from inside stairways and the fire extinguishing process requires an interior extinguishing strategy. Inability to use exterior accessing methods, results in frequent use of elevators and stairways which causes extended time and physical effort. Also, extended evacuation times due to size and occupancy of such structures, pronounced stack effect due to temperature differentials between inside and outside, need for supplemental water pumps inside the buildings due to water supply limitations of fire department pumpers, and finally mixed occupancy types of the building, all make high rise disasters much more challenging to first responders (Keogh & Lord 2012). Therefore, knowing the information required during emergency prior to entering the building; for example, knowing which level the fire hook-ups or hose racks are located and their exact location on the floor can decrease the trial and error navigation time spent indoors to find those utilities. This could be clearly seen in cases such as
the Shanghai fire where firefighters were ill equipped due to the size of the fire and the height of the building which resulted in hours of fire battle (Times 2010).

According to W. Jones et al. (2005) firefighters can only enter the building if there is backup crew for rescue. However, if building information was available, then in cases without IDLH (immediately dangerous to life or health), intervention could occur without the need for a backup crew. As stated in the outcomes of this workshop (Walter W Jones et al. 2005) huge amount of money is spent on decreasing the time it takes to send the fire truck to the location rather than taking information available before the fire and making that available to the incident commander. Fire departments are moving towards using electronic pre-emergency plans (e-plans) of buildings derived from stored information. However, the recent developments in telecommunications enable the provision of real time and more detailed information about the building and the location incident. Having such information available will speed up the decision planning and fire extinguishing process. A standard building data delivery solution will integrate the capacity of the building fire safety systems with the capabilities of the fire service, resulting in an improvement in firefighter safety and a reduction in commercial property losses due to fire. Remote access to these data would provide greatly improved situational awareness for emergency responders, reducing response times as well as time to size up and mitigate building fires (Holmberg et al. 2013).

Therefore due to the necessity of accurate building and visual information for structural fire scenarios, 3D building models and firefighter tracking systems have been recognized as invaluable tools by emergency responders for improving the safety of individual firefighters in structural fires (Berger et al. 2016). Fire departments are thus looking for ways to store their information into GIS databases to be used at any emergency incident. They are looking to integrate floor plans and emergency plans of urban buildings into the system to be available for downloading to relevant bodies such as fire departments in the incident time (Evans 2003).

Knowing the positions of all firefighters and tracking them during an incident reduces the risk of injury and death and is also critical for keeping them communicated and safe. Although tracking can be achieved with GPS on wild land and urban areas, and there are some working solutions for standalone tracking systems, position tracking in pre-existing emergency systems, and indoor unmanned aircraft vehicles (UAV); there is no robust method currently that can be used for structural use cases. This is mainly due to the requirement of high precision and accuracy of tracking systems for indoors where floors are differentiated clearly and information is
communicated to incident commanders and firefighters with distances and directions to each position (Berger et al. 2016).

The above mentioned complexities and challenges faced by emergency responders in indoor incidents and search and rescue operations highlight the importance of making indoor information available to decision makers. Information consisting of static floor plans, building elements, occupancy information, real time environmental changes, etc. To have a better understanding and more detailed view of how the indoor emergency operations and search and rescue procedures are undertaken for indoor environments by practitioners, the next section overviews the current practice and strategies taken by first responders on scene. This information was gathered through our series of interviews with the fire brigade team at CFA Dandenong for our case study and will later be used for simulating the practical search and rescue procedures in the thesis and comparing it with the proposed solution of the research.

2.3 Current Practice Indoor Emergency Response Tactics - Australian Practitioners Perspective

Fire is a significant hazard to people in Australia causing approximately AUD$8,500 million per year (Ashe et al. 2007) and although, bushfires contribute to most of the fire related disasters in Australia, structural fires are recently becoming more common due to development of more complex and high rise buildings consisting of 19% of the total fire incidents (NSW Fire Brigades 2007).

To better understand the indoor first response and search and rescue operations as well as the indoor situational awareness strategies undertaken by rescuers and firefighters, this section investigates the emergency response procedures specifically for indoor areas in the Australian context from the viewpoint of the CFA fire brigade. CFA (Country Fire Authority) is the Victorian volunteer and community based fire and emergency organization with 1,219 brigades in 21 districts and 5 regions. A series of meetings and face-to-face interviews were conducted with
the fire brigade at CFA Dandenong. CFA Dandenong is responsible for the south east region of Victoria.

The main objective was to identify how current indoor incidents are handled in terms of locating the facilities inside the building, managing crew number, dispatch, and search and rescue procedures. The interactive workshop with the CFA Dandenong team (an incident commander, a sector commander, and two firefighters) addressed the following questions regarding their regulations which are briefed below.

1. Availability of indoor maps and information
   a. What maps or information is currently available for use?
   b. How do they plan when no indoor plans are available?
   c. How are the main facilities and utilities located inside the building?

2. Indoor search and rescue decisions
   a. How many crew members are chosen for the operation?
   b. How are the crew dispatched, which point of entry do they use and how are the routes assigned to them?
   c. Do rescuers move individually or do they move in groups?
   d. How is the search and rescue operation undertaken?
   e. How long can each first responder spend searching inside the building or incident scene?

3. Indoor navigation and keeping oriented
   a. How are routing decisions affected in case of collapse?
   b. How do firefighters keep oriented?
   c. How does the Incident Commander keep track of his crew?

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3 CFA, www.cfa.vic.gov.au
2.3.1 Availability of indoor maps and information

The CFA Dandenong experiences around 8-10 calls per day consisting of both outdoor and indoor emergencies. Some of the main premises and structures provide the fire station with alarm sheets and 2D map sheets of the building along the entrance key to that building which is held in several cabinets inside the fire station (Figure 2-2). On receiving a call regarding a structural fire, unless the alarm sheet is available, there is no way to access information regarding that building. At the moment, detailed maps of the structures are not available and only for a limited number of buildings a fairly rudimentary block diagram is available. The maps are available via built-in fire truck tablets while on the route towards the fire (Figure 2-3). Unfortunately, only a small percentage of building layouts, usually belonging to main shopping malls or complex structures where owners have provided the maps, are available, and among those many are not updated and the maintenance and updating is done by fire brigades which is impractical and time consuming.

![Figure 2-2 Main premises (a) key cabinets and (b) maps](image-url)
Each map provided, contains a very coarse level of detail of information regarding that premise. As seen in Figure 2-4, this map consists of the name, address, fire station region, availability of keys to the structure, occupancy times and numbers. The map also holds an image of the premise with information of location of the pumpers, FIP (Fire Indicator Panel) (Figure 2-5) and sometimes a satellite or street view image of the premise to have a better view of the building with location of sprinkler controllers, and hydrants (Figure 2-5). Furthermore, these maps are usually very coarse (as seen in figures below), lacking detailed indoor information.

Most of the information sheets available at the moment to fire stations are exclusive protected premises where an alarm sheet is available with a basic map that doesn’t cover all information that matters to the first responders. Buildings that are equipped with fire alarms are required to have building maps available at the fire panel. Thus, first responders need to physically enter the building to reach the fire panels for accessing the maps. This is not always the case as buildings without fire alarms usually don’t have such maps unless they are a certain
type of building such as chemical plants which according to the legislations are required to have a map of the premise available in front of the building.

Figure 2-4 Map of the premise with facility access locations
In the case where no information is available to first responders before entrance, knowledge of the environment is based on observations of the windows, the sides, google map, etc. This knowledge is progressed as the crew continues with on-site operations. The incident commander will not enter the building personally and will rely on the crew members’ information and descriptions for decision making. Descriptions could be in the form of “second stairwell on the left, two stories up, fourth door to the right” which is obviously difficult to comprehend without the detailed map and even more difficult for route planning and tracking of the crew inside the building.

The CFA Dandenong team highlighted the main information required in a fire incident to be the location of fire hydrants and points of entry. The rest of the information is gained dynamically through time and operations based on the situation and the crew’s point of view from inside. Information such as switchboards, gas isolations, water isolations, hydrant locations, extinguisher locations, building type, and occupancy information are other critical information required by the first responder team. To them, the most important thing is to know where exactly the fire is, what is on fire, the type of the fire, how big it is, how far it is, and where the hydrants are. Usually two crew members will do an initial size up of this information and then the rest of the crew would bring in the equipment. The initial size up might lead to a decision of entering the building from the back to avoid running hose lines in unnecessary points.
2.3.2 Indoor Search and Rescue Planning

After the incident happens, a primary search is first undertaken which is planned by the incident commander based on the type of the building (residential, office, commercial, etc.), time of occurrence, and exit ways where people are more likely to reside. After this search is complete, it is turn for the secondary/exhaustive search which aims at searching the entire building.

Decisions on crew number and dispatch strategies inside the building for search and rescue operations are mostly reliant on experience and available resources. From what was learned from the practitioners, a fire station with 10 crew members and 2 trucks have more flexibility compared to a station with only one truck and 4 crew members. The incident commander at CFA Dandenong however explained a basic strategy to be sending two firefighters to quickly observe the situation and detect the number of people needing rescue, what situation they are in, and how they need to be rescued. And then another couple of firefighters are sent inside for rapid intervention and to back up the previous two members. They use the right hand or left hand technique in general to search the floors.

The crew members usually work in pairs to back up each other, though, not side by side. That is, they will navigate to the same floor, search different rooms separately and meet back at the corridor. Staying together is a safety measure, however is inefficient in terms of time and effective use of resources. Therefore, crew members tend to stay in line of sight of each other as the preferred method. This is especially the case when the visibility and passability are under normal situations. Otherwise, if the conditions are not stable, for example for a room that is full of smoke, at least two people are required to attend to it.

After the primary search is done, another team would enter the building for the detailed secondary search of all the locations and rooms inside the building.

2.3.3 Indoor Navigation and Keeping Oriented

Keeping orientation requires a systematic approach between peers where a certain decision is made to either move to the right or left and then keep the consistency. This would allow for switching to new crew members to avoid disorientation. This would mean, taking any right turn making sure not to miss any doors. In the case of complex building searches, the
“marking technique” is used to indicate areas that have already been searched. This could be any pre-communicated strategy such as leaving an upside down chair at the doorway or using a chalk to highlight the visited rooms.

Thermal cameras are also used as an equipment to ease the view for indoor areas. However, proper training is required not to mistakenly misinterpret what can be seen in the cameras such as hand/foot prints left from previous body heat or window reflection, with mirror or additional areas behind the window (see Figure 2-6).

Figure 2-6 Thermal camera showing (a) thermal handprint shown seconds after touching the area (b) reflected picture in the window

To summarize, as access to premises’ indoor maps is very limited and the ones available are mostly 2D map sheets that lack enough details of the critical utilities inside and outside the structure; search and rescue planning is a time consuming procedure which is decided on-scene as the knowledge of the building progresses. Thus, decisions on crew dispatch in terms of point of entry, routes, and points of exit are not made in the most efficient way. Factors such as the type of building, location of main utilities, victim and occupant locations, and accessibility of areas inside the building all affect the planning strategies which are currently
mostly hidden from decision makers and they can only partially gain it dynamically from the crew’s point of view from inside after the operations are initiated.

Therefore, as indoor emergency response is quite limited to the basic techniques explained above, a lot of uncertainties exist when responding to an indoor incident. Thus, research is targeting this domain vastly to overcome and facilitate the issues highlighted above. For any solution to be effective in the domain of indoor search and rescue, it needs to be based on a detailed representation of the indoor environment that allows accurate formulation of the problem. 3D city models are gaining vast attraction as the popularity of three dimensional virtual reality models increases. The models show increased efficiency when utilized for urban planning, tourism, navigation, and evacuation. The same popularity is increasing for applications that need detailed 3D indoor building models such as emergency response applications, architectural planning, energy analysis, managing crowd and movement inside buildings, etc. (Biljecki et al. 2015).

In the rest of the chapter, the most prominent solutions proposed in the area of indoor incident response will be discussed and analyzed.

2.4 Research and Development for Indoor Emergency Response

Due to the limitations and complexities discussed above, new models and solutions should be proposed for addressing the search and rescue problem in order to facilitate the decision making and route planning for crew dispatch operations inside the buildings. However, accurate modelling of the problem depends on the availability of an underlying indoor spatial data model that provides geometric and semantic information of the building that could be integrated with the current geographical information systems forming what is referred to as Indoor GIS. Indoor GIS proves to be effective in analyzing static and dynamic variables in small regions such as indoor environments which rise opportunities for indoor applications and decision making (Tang & Ren 2012; Li 2008).

There are four main components that are key to having an applicable indoor service (Liu Liu & Zlatanova 2011; Tashakkori et al. 2015):

1. **A Building Modeling Standard** consisting of floor plans, building elements, and semantic information
2. **An Indoor Spatial Model** for navigation and indoor routing purposes
3. **An Indoor Positioning System** to compensate the lost GPS signals inside the structures for localization purposes
4. **A Route Finding Algorithm** for routing the occupants/emergency responders through the building

Similar to the rest of the indoor services, the accuracy of the indoor search and rescue service relies on the accuracy and applicability of the above four components. That is, having a building model that fits the emergency responders’ requirements, an indoor spatial model that enables navigability, a formulation and solution approach for the route assignment algorithm, and finally the indoor positioning system for tracking and navigation purposes.

The rest of this section will give an overview of approaches taken by literature in these four areas focusing on their applicability to the indoor emergency response and search and rescue domain. It is important to note that as stated before, the indoor positioning technique is beyond the scope of this research, however due to the role that building models play in new positioning techniques and for the sake of completeness, a concise review of prominent technologies is presented in Section 2.4.4.1

### 2.4.1 City Models and Indoor Representations of Built Environments

The current development trend in technology highlights the importance and improvement of three dimensional data acquisition techniques. In fact, the 3rd dimension is what differentiates the indoor areas from outdoor spatial representations (Winter 2012). 3D visualization provides better perception and conceptualization for humans and can help in more efficient decision making especially in indoor environments (Rakkolainen & Vainio 2001).

High demand of 3D in geospatial related applications (Biljecki et al. 2015) such as cadastre information management, city planning, evacuation, emergency response, facilities and utilities management, entertainment, virtual reality, etc. heavily rely on existence of three dimensional building models (Kim & Wilson 2015). Photogrammetry and computer vision techniques allow reconstruction of high quality 3D scenes (Müller Arisona et al. 2013) and there has been significant effort in automating these approaches in order to reproduce 3D city models. Indoor
scenes have also been a key target of 3D reconstruction (Biber et al. 2004; Xiao & Furukawa 2012). However, most of these models could only be used for visualization purposes and can’t be utilized for indoor spatial analysis. Large companies such as Google and HERE are also enhancing their maps to cover indoor spaces, but what is available to public mostly resembles 2.5D maps where floor plans are stacked above each other and information on utilities and semantics is missing (Figure 2-7, Figure 2-8).

3D models are mostly used for specific purposes such as 3D network modelling, improving routing algorithms, or evacuation route visualization (Kwan & Lee 2005; Rüppel et al. 2010; U Atila et al. 2013; Meijers et al. 2005). These studies’ approaches and platforms are proprietary to their applications (Figure 2-9 - Figure 2-12). Another application where 3D city models are proved to be a necessity is for the emergency response applications; which is due to the fact that 3D city models enhance emergency managers’ knowledge of the incident scene (Kolbe 2009; Zlatanova & Holweg 2004). However, for 3D geospatial data to be effective in emergency decision making, new models are required to fit the specific needs of emergency applications (Lee & Zlatanova 2008) and thus the research community has had a great focus on this area which will be covered in the rest of this section. Each of the proposed approaches model the city and building objects to a certain Level of Detail (LoD) which could be used for comparing the various methodologies.

![Figure 2-7 Google Indoor Maps](image-url)
Shifting Towards Indoor Situational Awareness for Emergency Response and Search and Rescue

Figure 2-8 HERE Venue Maps

Figure 2-9 Indoor Emergency System (Rueppel and Stuebbe, 2008)

Figure 2-10 Indoor Emergency Navigation System Proposed by (Inoue et al., 2008)
The five Levels of Detail (LoD) which were first presented by (Kolbe et al. 2005) to represent the city objects in 3D are illustrated in Figure 2-13. LoD0 is the coarsest level which basically presents a 2.5D of the Digital Terrain Model (DTM). The next level is LoD1 which presents buildings as block models with vertical walls without presenting any texture or roof surfaces. LoD2 adds differentiated roof surfaces and textures for the building. Architectural components like walls, roofs, balconies, doors, windows, and other projections are added in LoD3. This level is the highest level of exterior detail of the building. Finally, LoD4 includes the interior elements and representations of the building like rooms, interior walls, doors, and furniture. As Kolbe (2005) highlights, the different Levels of Detail also vary in their positional and height accuracy. Whereas this accuracy in LoD1 could be somewhere between 5 meter or less, it should be no more than 2 meters for positional accuracy in LoD2 and less than 1 meter for height accuracy. This accuracy would shift to 0.5 meter in LoD3 and must be 0.2 or less for
LoD4. The LoDs are the base of assessing and comparing the quality of 3D city models. Below, the most popular city modelling strategies are analyzed.

2.4.1.1 Terrestrial Laser Scanning

One of the leading approaches in modelling the city environments is based on terrestrial laser scanning techniques which use image-based methods, point cloud-based techniques, and integrated approaches for acquiring 3D data.

The image based approaches are based on stereo image pairs and photogrammetry of series of overlapped images which are then used to reconstruct 3D models (Xiao & Furukawa 2012). Reconstruction of objects is done using the triangulation principle in these approaches. The development of digital imaging technologies have allowed close range photogrammetry to be improved vastly on its efficiency in time and cost and ability to be used on either very small machine objects to large buildings (Luhmann et al. 2013).

The laser scanning approaches are used for fast and accurate 3D data acquisition. They generate 3D point clouds by using non-contact laser pulses that can measure the surface features of the objects. Based on the maximum distance range a laser scanner can cover, they can be
grouped into the close range (2-3 mm), medium range (500-1000 m) or long range (several kilometers). Laser scanners have been used for reconstruction and modelling of both the indoor and outdoor surfaces. Large urban environments can be reconstructed from 3D point data by using realistic semantized descriptions of urban scenes where various elements such as the buildings, ground surfaces with topological complications, trees, etc. are reconstructed at the same time as shown in Figure 2-14 (Lafarge & Mallet 2012).

Laser scanning can also be used for collecting 3D data of the assets inside a structure (Lee et al. 2013). The 3D point cloud data captured can then be processed, analyzed, and converted into 3D models of the facilities. To generate accurate indoor 3D models, the data cloud processing includes data registration, noise filtering, and finally 3D modelling. The produced 3D model scan can then be exported as multipatch geometry formats which is the known GIS ready format for using in Geographical Information System environments.

Lastly, in the integrated approaches, hybrid point clouds and images are used simultaneously for reconstruction of the 3D models. The point clouds in this approach are used for constructing the geometries of the objects while the photos will add the textures to the surfaces. Ground level photographs and 3D laser points can be integrated in such approaches using algorithms like the Inverse Constructive Solid Geometry (Xiao & Furukawa 2012) for modeling large 3D indoor environments such as museums where the photorealistic maps are a necessity (Figure 2-15).

Applications for indoor reconstruction require the models to determine both the geometric and the semantic content of the buildings. However, automated reconstruction of detailed LoD4 models of buildings is quite a challenge (Díaz-Vilariño et al. 2015). Detecting the common elements such as doors, walls, stairs, etc. are absolutely essential and beneficial for knowledge of the interiors, navigation, and evacuation planning. Díaz-Vilariño present the workforce for detecting doors using the point clouds and imagery of interiors based on the generalized Hough transform (Díaz-Vilariño et al. 2015). Even without automatic extraction, laser scans of interior environments can be very beneficial in providing information of elements such as object measurement, shape, and position. Such information can then simplify the 3D modelling process and integration with semantic information of the elements (Lee et al. 2013).

Although, the laser scanning approaches have advanced vastly recently, still they have limitations in modelling the semantic and cellular information of the indoor environments as well as
modelling elements that are inside the walls such as gas pipes and electrical facilities; all of which are critical for indoor emergency response planning. Therefore, other approaches such as CityGML and BIM are gaining more popularity for indoor services as they overcome some of these limitations which is discussed next.

Figure 2-14 Reconstruction of 1 Km2 area urban scene (Lafarge & Mallet 2012)
2.4.1.2 CityGML

CityGML is an open data model and XML-based format for the storage and exchange of virtual 3D city models (Gröger et al. 2012). CityGML aims to develop a shared definition of the entities, attributes and relationships between objects of a 3D city model. Furthermore, CityGML presents the graphical appearance of city models whilst also presenting the semantic, thematic, and aggregations of the models.

CityGML is based on a geometry model and a thematic model in a modular structure (Figure 2-16). The geometry model enables defining the 3D objects in the city model using their geometrical and topological attributes. The thematic model uses the geometry model for defining the thematic fields such as the Digital Terrain Models, sites like building and bridges, transportation facilities, city furniture, vegetation, water bodies, and land use (Gröger et al. 2012). CityGML is an application schema of GML3 (Geography Markup Language), where a _CityObject is defined as a subclass of the GML class _Feature which all CityGML objects inherit their properties from (Figure 2-17). CityGML models are differentiated based on their Levels of Detail (LOD) where objects become more detailed moving from LoD0 to LoD4 as described in 2.4.1.
The **Building module** as one of the most detailed thematic concepts of CityGML allows the representation of both thematic and spatial aspects of building elements in one of the five LoDs. As can be seen in Figure 2-18, **Abstract Building** is the main class which typically inherited from the _CityObject_ consists of building and building parts. This class holds some basic semantic information of the function, usage, year of construction, etc. of the building. In LoD1 the generalized geometric representation of the outer surface of the building is presented. The _BoundarySurface_ and _BoundaryInstallations_ are added to LoD2 to present modelling the outer architectural elements. The _Opening_ is added to LoD3 to represent the doors and win-
dows and finally the Room and BuildingFurniture bring in the interior objects to CityGML in LoD4.

CityGML mostly aims at visualization of the city objects, thus many building elements such as beams, slabs, stairs, and other structural properties are not clearly modelled or are all represented as the generic BuildingInstallation object and details of that element and its semantic
properties are not defined. Figure 2-19 shows the CityGML representation of a building. As can be seen, objects like floor, room, wall are represented as surfaces and thus the full geometry, material, and semantic attributes are not presented.

To include application specific requirements to CityGML, the extensible structure of CityGML allows to do so by using either the generic features and attributes or the Application Domain Extension (ADE) (Kim et al. 2013; Van den Brink et al. 2013; Schulte & Coors 2008) which enable definition of new objects or extending current CityGML modules for extended features.

![Figure 2-19 Building representation using CityGML surfaces (Nagel 2014)](image)

Automatic generation of 3D models of buildings is necessary for creating large city models and landscapes that will be used for further analysis. Simple exterior representations of city models with LoD2 can be easily generated automatically from airborne LiDAR point clouds (Rottensteiner 2003), aerial images (Hammoudi & Dornaika 2010), and 2D building footprints (Aringer & Roschlaub 2014). Automatic generation of CityGML LoD3 and LoD4 can be achieved using crowdsourced geodata from IndoorOSM data (Goetz 2013). However due to the limited tags of OSM and lack of real 3D geometries and the Manhattan-World assumption of IndoorOSM where detailed information is limited, the automatic generated models differ from reality and don’t completely fit the LoD4 description.

Although, LoD2 models are quite simple, they have a wide range of applications such as shadow modelling (Alam et al. 2013), noise pollution analysis (Stoter et al. 2008), urban planning (Buhur et al. 2009), etc. However, only LoD4 supports indoor geometries and models the buildings interiors. These higher levels of detail increase the applicability of the models significantly.

In an attempt of automatic generation of higher levels of detail of indoor geometries and building features, Nguatem et al. (2016) propose an automatic building generation from 3D point clouds with the CityGML levels of detail 1 to 3 by segmenting the 3D point cloud into planes. Automatic generation of LoD2+ from LoD2 is presented in (Boeters et al. 2015) which refers to LoD2 models that consist of storeys within a building; allowing a further range of applications such as urban inhabitant estimation for cities.

For the city models to be applicable to the indoor emergency management domain, a higher level of detail for the building interiors is required to present the objects and utilities and their geometries in the structure to allow a more accurate route planning, thus Building Information Models are more favorable in this domain.

2.4.1.3 Building Information Models

Among the indoor modelling methodologies, Building Information Models (Underwood et al. 2007) carry comprehensive geometric and semantic information of building elements and are believed to be an important source of managing the building information during its lifecycle (Eastman et al. 2011). As the NBIMS Committee (2007) describes, “A BIM is a computable representation of all the physical and functional characteristics of a building and its related project/lifecycle information, which is intended to be a repository of information for the building owner/operator to use and maintain throughout the lifecycle of a building”.

Building Information Models (BIM) are semantically rich digital facility models that are obtaining attention in the architectural, engineering, construction, facility management, urban planning, emergency response, and energy planning communities due to their ability to ease the discussions amongst its users (Tang et al. 2010). Contrary to traditional CAD models, BIMs represent facilities in a semantically rich manner where each element is defined as a set of surfaces with defined relationships with the other entities in the building as well as proper identification of the object itself.
The most popular BIM standard and schema is the Industry Foundation Classes Model (IFC) (Liebich 2009) which is an open, international, and standardized specification containing advanced semantics and geometries of building elements and spaces inside buildings (BuildingSmart 2008) (see Figure 2-20). IFC was developed by BuildingSmart as a common language to improve communication, quality, productivity, cost, and delivery time during the design, construction and maintenance of buildings (Isikdag 2015). The IFC model architecture consists of a modular structure for the development of the components by use of ‘model schemata’ (Figure 2-21). Each conceptual layer in the IFC representation consists of a set of model schemata. The resource layer is the lowest level which contains resource classes that are independent of the application type and can be used by the higher levels. In the core layer, a core project model, the kernel, and product extensions are provided. The interoperability layer provides objects and concepts that can be shared amongst multiple construction industry domains by providing schematas that define concepts that are shared between different domains. And lastly, the domain layer as the highest conceptual layer delivers modules that are specific for a construction industry or application type. At each layer, a class can only reference a class at the same or lower layer, but not the higher level.

Figure 2-20 Building representation with IFC objects (Nagel 2014)
Although the typical way of generating a BIM is from a CAD-based model of a facility’s design and the process can be automated (Dore & Murphy 2014; Barki et al. 2015), usually the created model in this way can’t represent what Tang et al. (2010) refer to “as-built” conditions of the building. That is, due to various reasons such as changes of construction versus design phase, changes during subsequent renovations, or absence of a design model of an existing structure, BIMs generated from CAD don’t present the building as it exists or its current condition. Therefore, the methods for creating an as-built BIM should be automated and this would involve identifying the geometries and appearance of an existing structure and converting it into a semantically rich representation. A popular approach in generating as-built BIMs is laser
scanning techniques due to their quick and precise measurements of 3D objects in the environment (Tang et al. 2010). The process involves three steps: 1) data collection; 2) data preprocessing; and 3) Building Information Modelling (BIM). The data collection phase gathers the dense point measurements using laser scans that can collect hundreds of thousands of point measurements in each second (Figure 2-22). The scanning should be taken from multiple positions to capture all the surfaces. Thus, usually digital cameras are used for 3D data fusion in the later stage. In the data preprocessing stage, the data is filtered from artifacts and registered as a single point cloud in the global coordinate system. Finally, in the last phase the BIM happens which consists of modelling the geometries of each of the components, giving them an object category and material features and setting the relationships between those components. This would mean for example defining the shape of a door, assigning its texture and identifying which wall it connects to. Various algorithms and solutions have been proposed to simplify this tedious process (Liu et al. 2010; Tang et al. 2010; Jung et al. 2014).

Figure 2-22 laser scanning approach and a laser scanned data of a building under construction (Tang et al. 2010)

2.4.1.4 Integration of BIM and GIS for Seamless Indoor Outdoor Spatial Awareness

GIS and BIM cover different domains of geometric and semantic information based on their specific application needs. While one tends to focus mostly on outdoor and urban features, the other concentrates on structural and architectural elements. However, In order to better plan for 3D urban infrastructures, knowledge is required on both the building structures and their environments in the city (El-Mekawy et al. 2012). Researchers mostly tend to view structures as independent components and don’t consider their relations with the sur-
rounding objects (Li 2011; Lin et al. 2013; Rueppel & Stuebbe 2008; Rakip et al. 2012). Rich data from both indoor and outdoor structures could be beneficial in urban planning, emergency planning and response, insurance, real estate and construction management.

Integrated geometric models and harmonized semantics between the domains of GIS and BIM are required to overcome the interoperability challenges between the geospatial information and AEC domain (van Oosterom et al. 2005). However this integration faces various difficulties such as semantic mismatches between the two domains, differences in granularity (IFC is a finer granularity compared to CityGML), redundant objects, and problems with bidirectional transfer between the two models (Isikdag & Zlatanova 2009).

To integrate semantic information from IFC into CityGML, a CityGML ADE named GeoBIM was developed in (Laat & Berlo 2011). Getting full IFC semantics in CityGML is quite difficult as CityGML is not originally generated for internal structures. Their proposed model still doesn’t allow full integration of IFC into CityGML and also the inverse conversion is not covered. To overcome this issue, El-Mekawy et al. (2012) suggest the full integration of Building Information Modelling (BIM) using the reference IFC model standard (Industry Foundation Classes) with CityGML. IFC models are used to represent the building industry technology and the topological and semantic properties of geographical areas including buildings while the urban geospatial information is provided by CityGML. By integrating these two concepts, the authors allow exchange of information between building objects and geospatial objects. The integration allows having queries that integrate both indoor and outdoor information for example windows that could be used as exiting points from the building (Figure 2-23). Although, some valuable information regarding the interaction among the indoor and outdoor objects could be retrieved, still this model carries all the complexities of the IFC and CityGML and has limitations presenting all information necessary during emergency management such as position of main shutoffs, hazardous materials, etc.
Several studies demonstrate how IFC models could be converted to CityGML and due to the importance of automating the process of integration, research has studied how buildings can be generated automatically in CityGML using IFC models (Isikdag & Zlatanova 2009; Donkers et al. 2015). Also, there has been efforts in integrating GIS and BIM to fit special domains such as indoor incident management for seamless spatial analysis and navigation in the incident (Tashakkori, Rajabifard, Kalantari, et al. 2016). As the conversion of data between the two domains has a high risk of information loss, Daum et al. (Daum et al. 2015) propose a spatio-semantic query language (QL4BIM) which is an intermediate layer and supports integrated processing of data sets from both the geospatial domain and AEC without the need of conversion between IFC and CityGML. This way, the original data is untouched and reserves its properties and instead an integrated data processing approach is undertaken to ease the spatial analysis amongst the two domains.

Most of the approaches mentioned above target specific aspects of indoor modelling and since they are not designed for emergency applications, these models can’t be used in their current format in this domain. Thus, the next section looks at how indoor models have been used for facilitating emergency response in literature.
2.4.2 Necessity of 3D Indoor Semantic/Geometric Model for Emergency Response

3D city models are a necessity for emergency response as they enhance emergency managers’ knowledge of the incident scene (Zlatanova & Holweg 2004; Kolbe et al. 2008). The success of orientation, way finding and navigation activities is determined by a person’s knowledge and spatial awareness of his/her location (Klippel et al. 2010) and this is especially of high importance in case of indoor incidents where time is critical and room for error is small. Thus, the indoor space should be the first target of spatial information services (Li et al. 2010).

Complex structures are highly vulnerable to various disasters such as human induced fires, bush fires, pollution incidents, explosions, etc. which result in tragic consequences for people, their assets and the environment (NFPA 2013). Research has proved that travel times required to reach a disaster site inside multi-storey buildings can be much longer than the time it takes first responders to reach the disaster building from outside the structure (Kwan & Lee 2005). Furthermore, due to slower walking speed and unavailability of elevators in emergency situations and also uncertainty of paths, indoor navigation is much slower than outdoor navigation. In addition, smoke distribution is an inevitable event that occurs in many disaster incidents and results in decreased movement speed and increased travelled distances (Jeon et al. 2011). Such visual distractions combined with blocked areas and inaccessible spaces inside structures all increase the probability of rerouting inside structures which decreases emergency response speed. Thus, having situational awareness about both interiors of buildings as well as their interactions with other nearby buildings and surrounding outdoor environments is crucial for minimizing the unnecessary wandering in the building caused by route uncertainty to reach the disaster sites or main utilities. Having remote access to such information would improve the first responders’ situational awareness to a high extent and therefore improve safety and reduce property loss (Holmberg et al. 2013). However, in the current practice systems, much of the necessary building emergency information is left unrevealed to first responders until after arrival at the site which increases the risk of life threats to rescuers and complicates decision making.

Most of the studies thus far, model the indoors for way finding and navigation purposes, and thus disregard the information required by first responders during indoor emergency situations. Currently, after receiving an alarm, firefighters are dispatched to the incident location with minimal information about the buildings and the fire precinct. Thus, a significant amount of time is spent to assess the fire area upon arrival (Yang et al. 2009). Nevertheless, precise
information about the buildings, their utilities, etc. is unknown to first responders up until arrival at the scene which increases the risk of life threats to rescuers and complicates decision making.

In order to assist first responders in their emergency decisions, many of the studies proposed have focused on indoor way finding and navigation based on indoor travelled distances (Inoue et al. 2008; Chen et al. 2011; Fallah et al. 2013). These studies have either simply used floor plans to identify the shortest paths towards exits (Inoue et al. 2008) or dynamic information such as data gathered from congestion detectors, is used to expedite the evacuation process by finding less congested paths (Chen et al. 2011). There has also been some attempt to use important BIM (Building Information Modeling) information such as gas pipes and high voltage panels to help fire fighters in better mitigation and safer navigation inside buildings (Rueppel & Stuebbe 2008).

Most of the mentioned indoor navigation systems are either 2D or 2.5D representations of the environment. However, the 3rd dimension is the main difference and essential factor of indoor spatial information (Winter 2012) and 3D visualization of geographical data is attracting much attention in urban studies and residential development (Xu & Coors 2012). Thus, new approaches should be proposed based on 3D aspects of multilevel structures (Kwan & Lee 2005; Umit Atila, Karas & Rahman 2013). Furthermore, the current development trend in technology highlights the importance and improvement of three dimensional data acquisition techniques (Lee et al. 2013). Most importantly, 3D GIS representations of internal structures have proved to significantly improve speed of rescue operations (Kwan & Lee 2005).

In order to model inside the structures in 3D, an interactive evacuation system has been developed for human way finding in Rakip et al. (Rakip et al. 2012). Their proposed system contains a 3D network analysis and simulation component which calculates the optimum path towards the exits. However, less accurate routes are suggested due to imprecise floor plans and building information. In order to have more detailed indoor models, there has been some effort to use BIM and CityGML for indoor spatial modelling, yet these models are not completely feasible as they are either too architectural or designed for visualization purposes or lack necessary emergency information required about the incident and its precinct (Isikdag et al. 2008; Isikdag et al. 2013; Lin et al. 2013; Kolbe 2009). It is important to note that methods used to present building information should be kept simple and as the emergency responders have very short times to spend using the model for situational awareness before entering the
incident scene, the information added to the model should be selected carefully (Walter WW Jones et al. 2005).

To enhance the applicability of existing indoor modelling frameworks to applications such as emergency response, delivery, and facility management, Isikdag et al. (2013) suggest integrating semantic and geometric information included in intelligent building models. Due to the complexity of the current BIM’s structure, their study suggests a new BIM oriented indoor modelling methodology (BO-IDM) which modifies BIM to facilitate indoor navigation and orientation inside buildings. Although it contains some information regarding material type and existence of hazardous materials in the building, it still lacks much of the indoor information required during emergency response; such as real time information collected from detectors, location of emergency utilities, ownership and accessibility information, etc. In addition, buildings are viewed as autonomous systems; independent of how they interact with their surrounding buildings and environment. In order to integrate both indoor and outdoor information, IFC and CityGML are integrated in El-Mekawy (El-Mekawy et al. 2012) to enable information exchange between the geospatial and building objects, thus providing cross spatial analysis on the model. Still, the proposed model carries all the complexities of both IFC and CityGML. Furthermore, indoor/outdoor information necessary during emergency response is missing.

summarizes the main features of each of these indoor modelling approaches. As it can be seen in this table, most of the 3D models developed represent floor plans and building structure to some extent and can be used for limited indoor analysis and navigation applications. However, the main reason these models cannot be used in real emergency situations is their lack of detailed building and semantic information aimed at emergency responders that are geo-referenced and would enable simple querying and spatial analysis as well as integration with outdoor geographical information systems.

Considering the lack of comprehensive 3D indoor data models developed systematically to consist of critical emergency information about the buildings and their surroundings, this thesis will recommend a new 3D indoor data model that aims at facilitating the integration of existing and dynamic building information which will result in improved situational awareness for first responders and the public in Chapter 4. The proposed model is then leveraged for precise formulation and solution proposal for the indoor search and rescue problem.
Table 2-1 Comparison of emergency indoor models (Tashakkori et al. 2015)

<table>
<thead>
<tr>
<th>Research</th>
<th>3D</th>
<th>Real time Data</th>
<th>Indoor Situation Awareness</th>
<th>Navigation Approach</th>
<th>Positioning Systems</th>
<th>Floor Plan Information</th>
<th>Structural Information</th>
<th>Building Emergency Information</th>
<th>Integrated with Outdoor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency Evacuation (Inoue et al., 2008)</td>
<td>×</td>
<td>✓</td>
<td>Environmental sensors (temperature, humidity, ...)</td>
<td>Dynamic routes using sensor data management</td>
<td>Radio beacons</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Indoor Emergency Navigation (Chen et al., 2011)</td>
<td>×</td>
<td>✓</td>
<td>Congestion detection sensors</td>
<td>Intersection deployed sensors</td>
<td>N/A</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>3D Indoor GIS (Kwan and Lee, 2005)</td>
<td>✓</td>
<td>✓</td>
<td>Blocked areas</td>
<td>Shortest path considering blocked areas</td>
<td>Multi method, WLAN, UWB, and RFID</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>Indoor Navigation for Firefighting (Rüppel et al., 2010)</td>
<td>×</td>
<td>×</td>
<td>Integrates fire operation data and fire protection installations</td>
<td>N/A</td>
<td>N/A</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Indoor Network Modelling for Navigation (Rakip et al., 2012)</td>
<td>✓</td>
<td>✓</td>
<td>Real time data from detectors and information about people</td>
<td>N/A</td>
<td>N/A</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Indoor Modelling and Navigation (Lin et al., 2013)</td>
<td>✓</td>
<td>×</td>
<td>Uses IFC building models</td>
<td>Shortest path based on the fast marching method</td>
<td>N/A</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Indoor Modelling (Isikdag et al., 2013)</td>
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<td>×</td>
<td>Modified BIM for emergency management</td>
<td>N/A</td>
<td>N/A</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Indoor Routing and Visualization (Kim and Wilson, 2014)</td>
<td>✓</td>
<td>×</td>
<td>N/A</td>
<td>Shortest path considering routing preferences</td>
<td>N/A</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
</tr>
</tbody>
</table>
2.4.3 Indoor Navigation Models

Another main component of an indoor application service is the underlying indoor spatial model that retains the indoor representation to support the routing algorithm. The recent developments in positioning systems and ubiquitous computing systems enable the enhancement of novel indoor spatial services from mobile robot mapping to indoor location based services (LBS) and context-aware navigation services for indoor environments. Though, the success of orientation, way finding and navigation activities in such applications is determined by a person’s knowledge and spatial awareness of his/her location (Klippel et al. 2010). The building floor plans are usually approximated with geometric networks, regular and irregular cell subdivisions, or symbolic based models, which are referred to as navigation models.

2.4.3.1 Context-Aware Spatial Models

Integration of real time information gathered from the structures enables provision of diverse context aware services which can affect services such as human way finding and navigation in built environments. Therefore, the spatial models could be developed from a context-aware perspective (Afyouini et al. 2012). Although, there are few research that consider how deviation from predefined paths should be corrected and adapted using continuous real-time tracking of the moving objects (Xu et al. 2010), these approaches are mainly based on time and distance while context aware spatial models allow adaptive and context aware navigation under dynamic situations (Afyouini et al. 2012).

To be able to deliver indoor context aware services, an appropriate data model is required for representing location of objects in the environment. Two main classes of approaches exist in this sense: the symbolic and the geometric models. The geometric spatial models consider the space as either continuous or discrete and are mainly cell-based (grid based, quad trees, free space tessellation, voronoi tessellation) or boundary based (using extracted object boundaries) representations (Figure 2-24). The symbolic approaches model the indoor areas using topological-based, graphs, and hierarchy representations (Figure 2-25). The main advantage of using symbolic models is that object positions can be given semantically like room number, etc. and their topological relations are also presented. The symbolic models are categorized in two classes of set-based models (place-based sets and object oriented model) and graph-based models (place graphs, visibility graphs, generalized voronoi graphs, fine-grained graphs, and sensor based graphs) (Afyouini et al. 2012).
To combine the benefits of both the geometric and symbolic techniques, another category of classes for modeling the indoor environments called hybrid spatial models exists. The hybrid models integrate on one hand the metric properties of the geometric approaches; which generate precise location and distance information, and on the other hand the abstract human understandable symbolic approach (Lorenz et al. 2006; Jiang & Steenkiste 2002; Becker et al. 2009). To increase the usability of the indoor spatial models for route planning and localization and tracking within indoor navigation systems, a multilayer representation of the indoor spaces is presented in (Becker et al. 2009). Their model integrates the 3D building decompositions of topographic space and transmitter/sensors where each layer is presented independently and changes to one layer don’t affect the other layers. An N-partite graph is suggested in their work to connect the states/nodes of different layers using joint state edges. To increase the applicability for routing and indoor evacuation, the integration of sensor graph and route graph in an indoor environment coupled with dynamic risk assessment allows route planning aware of predicted risks (Wang et al. 2015). To improve mobility for users with specific needs such as people with vision disability, Ge et al. (2016) propose an indoor spatial model that consists of fine-grained accessibility semantics including real time environment context awareness, information on obstacles, and detailed operation of door openings. Further, they provided a systematic approach for automatic creation of path descriptions for users.
Square and hexagonal grid based approaches

Free space tessellation techniques (triangulation and trapezoidal)

Voronoi diagram of indoor area (Wallgrün 2005)

Boundary based model of a floor plan

**Figure 2-24 Geometric spatial models** (Afyouni et al. 2012)
Shifting Towards Indoor Situational Awareness for Emergency Response and Search and Rescue

2.4.3.2 IndoorGML

CityGML and IFC standards describe the 3D geometry and semantics of buildings for both indoor and outdoor spaces. However, they lack the important features that are necessary for indoor navigation applications (OGC et al. 2014). IndoorGML overcomes this limitation by adding encoding features specifically designed for indoor navigation. The OGC standards for IndoorGML contain two data models; first a core data model for describing the topological
connectivities such as sensor and topographic space and second; a data model for indoor navigation.

The current IndoorGML version 1 is aimed at indoor LBS routing and emergency services and doesn’t cover facility management applications. As IndoorGML consist of geometric and semantic information that is required for indoor navigation, it is considered as a complementary standard to CityGML, KML, and IFC for navigational location support and thus to avoid duplication, only contains a limited amount of construction components. Based on OGC, IndoorGML defines the following information regarding the indoor environment: navigation context and constraints; space subdivisions and connectivity types amongst spaces in the indoor environment; geometric and semantic properties of spaces; and lastly navigation networks and their relationships (OGC et al. 2014).

Indoor constraints differ from those of outdoor constraints where IndoorGML’s focus is not on the architectural components, but in fact on how the architectures create the spaces and indoor constraints which can be seen from the cellular space, semantic, geometric, topological, and multi-Layered aspects.

Each cellular space has an identifier such as name/number in IndoorGML and has boundaries with other cells, however the cells can’t overlap. The identifiers can then be used to position a space inside the premise. Each of the cellular spaces can obtain semantics, geometric, and topological information attached to it. Attaching semantic properties to the cellular spaces allows classification and identification of the various cells and their connectivity. Although IndoorGML allows the inclusion of the geometric 2D/3D information of the spaces, it doesn’t put its main attention on this aspect since it is already defined clearly in CityGML and IFC (Figure 2-26). And finally, the network and topology representation of cellular space is the essential component of IndoorGML for enabling the indoor navigation which is based on the Node-Relation Graph (NRG) concept (OGC et al. 2014). The NRG can be implemented as a graph with adjacency and connectivity. If the nodes and edges have coordinates then the graph is a geometric NRG, while if no geometric properties are considered, it is called a logical NRG.
IndoorGML uses the concept of multi-layered space representation which consists of multiple space layers and inter-layer relations. Space layers represent the topographic cellular space (composed of rooms, corridors, etc.), sensor space (environmental sensors like smoke detectors), Wi-Fi coverage space, etc. While the inter-layer connections represent the relationship among two cells of different space layers. Thus, each space layer will decompose the indoor area differently and how they relate is dependent on the IndoorGML presentation (Figure 2-27).

As IndoorGML can be used in combination with current indoor models such as BIM and CityGML, automatic construction of the IndoorGML dataset from either of these models can enable navigation structure enablement on the current models for different types of locomotion (Khan et al. 2014). To enable the seamless connection and navigation between the indoor and outdoor areas, the concept of anchor node is defined which is basically using the entrance/exit point to the building as an additional topology element to enable the seamless indoor to outdoor connection.
2.4.3.3 Indoor Spatial Models for the Emergency Context

While the context-aware spatial models are mainly based on obstacle detection and semantics of the environment, they are not necessarily based on the building models and utilities, and thus neglect many of the main building utilities that can affect the route planning decisions. Although IndoorGML adds the navigational properties as a complementary standard to building models such as IFC, still the standard is based on the public routing perspective and can’t be used for first responder dispatch inside the structures in the current format. The same limitation is valid for most of the other graph based approaches used for modelling evacuation and routing in indoor navigation platforms (Karas et al. 2006; Jun et al. 2009; Rüppel et al. 2010).

CityGML (Kolbe 2009) and most 3D visualization problems use Lee’s Node-Relation Structure model (Lee 2001) which integrate the topological model of the network with the geometric information to form the geometric network model given in Figure 2-28 enabling visualization and cost (based on distance or optimality) computation. Chen and Huang (2015), propose using BIM as the data input for automatic construction of a hybrid MAT-VG (Medial Axes Transform- Visibility Graph) network graph which allows quicker execution times for network analysis. However, their model doesn’t completely cover complex geometries and weight assignment on edges based on edge factors such as length, flow, risk, etc. Research such as
(Tashakkori et al. 2015; Teo & Cho 2016) have also integrated BIM data with the indoor GNM in order to make the indoor spatial models more reflective of the real building environments. While the proposed IESM (Indoor Emergency Spatial Model) integrates semantic and geometric information of building elements into the GNM (Tashakkori et al. 2015), the MGNM (Multipurpose Geometric Network Model) automates the process of extracting a BIM oriented indoor Graph from the building representation (Teo & Cho 2016). Both these models allow detailed indoor network models based on opening elements such as doors and windows and enable seamless navigation by integrating the indoor model with the outdoor road network.

To conclude, the indoor emergency response and search and rescue problem requires an indoor spatial model that meets the requirements of first responders’ movement in the structure and thus should be developed for this purpose and can’t be based on current models. Also, it is important to note that the structure of the network consisting of the number of nodes and edges impact the complexity and computation time of the problem and thus should be considered when designing the indoor spatial model. Therefore, Chapter 4 proposes a new indoor spatial model based on emergency requirements and Chapter 5 discusses how the model should be used for solving the indoor search and rescue problem.

![Figure 2-28 Building the geometric network model](image_url)

Figure 2-28 Building the geometric network model (a) 3D building model (b) topologic model (c) geometric network model (Lee 2001)
2.4.4 Positioning and Navigation for Indoor Environments

Mautz (2012) gives the following definition of positioning and localization:

“Positioning is the general term for determination of a position of an object or a person, and localization used initially for position determination, in general literature means positioning emphasizing the fact that positioning is carried out in ad-hoc and cooperative manner”

While in his definition, navigation is defined as:

“1) Determination of position, speed, and heading of a subject, 2) finding the optimal path from start to end, and 3) guidance along the path and handling deviation from planned path”

There are three main techniques for automatic positioning: triangulation, scene analysis, and proximity (Liu 2007b). The triangulation method uses the triangle geometries for calculating the location of the object. The triangulation could be based on lateration (distance measurement), angulation (angle measurement) or bearing measurements. The scene analysis methods use features inside the observed scene from the viewpoint of the subject (vehicle, pedestrian) to determine the location of the observer and thus is not reliant on geometric angles and distances which are sometimes hard to capture. And finally, the proximity positioning techniques depend on being sensed in the limited range of a physical phenomenon such as being sensed in the range of a wireless access point or RFIDs (Jeffrey Hightower 2001).

Global Navigation Satellite System (GNSS) positioning is widely used for locating and navigating pedestrian and vehicles in outdoor and city environments. Although, there are problems with positioning accuracy in urban canyon environments where GPS signals are blocked or reflected due to high rise buildings, the problem has been mostly overcome by various techniques such as constrained methods (Cui & Ge 2003), shadow matching using 3D city models of nearby buildings (Wang et al. 2013), and Bayesian filters based on sensor fusion algorithms (Jo et al. 2012).

While the area of road and outdoor positioning has been well established, indoor positioning is still quite challenging due to unavailability of GPS signals in indoor environments, multipath from signal reflection off walls and obstacles, non line of sight conditions, quick changes in people and indoor settings, need for high precision, and high attenuation and signal scattering (Mautz 2012). Indoor positioning is becoming inevitable in many of the modern way of life applications such as police, firefighters, intelligent transportation (seamless navigation to in-
door parkings, etc.), social networking, environmental monitoring, museums, logistics and optimization, navigating disabled people, augmented reality applications, underground construction sites, etc. (Mautz 2012).

There is rapidly growing literature on indoor positioning which detect various GPS-less approaches and technologies for locating occupants and objects in indoor environments. The main technologies consist of cameras, infrared, tactile & polar systems, sound, WLAN/Wifi, RFID, ultra-wideband, high sensitive GNSS, Pseudolites, inertial navigation, magnetic systems and infrastructure systems which have been surveyed in (Mautz 2012) based on their accuracy and coverage (Table 2-2).

<table>
<thead>
<tr>
<th>Technology</th>
<th>Accuracy</th>
<th>Coverage(m)</th>
<th>Method</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cameras</td>
<td>0.1mm-dm</td>
<td>1-10</td>
<td>Angle measurement from images</td>
<td>Metrology, robot navigation</td>
</tr>
<tr>
<td>Infrared</td>
<td>cm-m</td>
<td>1-5</td>
<td>Thermal imaging, active beacons</td>
<td>People detection, tracking</td>
</tr>
<tr>
<td>Tactile &amp; Polar Systems</td>
<td>μm – mm</td>
<td>3-2000</td>
<td>Mechanical, interferometry</td>
<td>Automotive, metrology</td>
</tr>
<tr>
<td>Sound</td>
<td>cm</td>
<td>2-10</td>
<td>Distances from time of arrival</td>
<td>Hospitals, tracking</td>
</tr>
<tr>
<td>WLAN/WiFi</td>
<td>m</td>
<td>20-50</td>
<td>Fingerprinting</td>
<td>Pedestrian navigation, LBS</td>
</tr>
<tr>
<td>RFID</td>
<td>Dm-m</td>
<td>1-50</td>
<td>Proximity detection, fingerprinting</td>
<td>Pedestrian navigation</td>
</tr>
<tr>
<td>Ultra-wideband</td>
<td>cm-m</td>
<td>1-50</td>
<td>Body reflection, time of arrival</td>
<td>Robotics, automation</td>
</tr>
<tr>
<td>High sensitive GNSS</td>
<td>10m</td>
<td>Global</td>
<td>Parallel correlation, assistant GPS</td>
<td>LBS</td>
</tr>
<tr>
<td>Pseudolites</td>
<td>cm-dm</td>
<td>10-1000</td>
<td>Carrier phase ranging</td>
<td>GNSS challenged pit mines</td>
</tr>
<tr>
<td>Inertial Navigation</td>
<td>1%</td>
<td>10-1000</td>
<td>Dead reckoning</td>
<td>Pedestrian navigation</td>
</tr>
<tr>
<td>Magnetic systems</td>
<td>mm-cm</td>
<td>1-20</td>
<td>Fingerprinting and ranging</td>
<td>Hospitals, mines</td>
</tr>
<tr>
<td>Infrastructure systems</td>
<td>cm-mm</td>
<td>Building</td>
<td>Fingerprinting, capacitance</td>
<td>Ambient assisted living</td>
</tr>
</tbody>
</table>

As the positioning and localization technologies are beyond the scope of this research, the techniques will not be described in detail here and the reader is advised to refer to the various research and surveys overviewsing the state of the art methods (Mautz 2012; Ijaz et al. 2013; Liu 2007a). However, it is important to note that localization for indoor emergency response
applications faces very dynamic environments and needs special consideration as described in Section 2.4.4.1.

Although, most of the indoor positioning technologies require pre-installation of local infrastructure such as deployment of sensor beacons, a class of localization methods which have high accuracy range rely on detecting objects in images and matching them with objects in a building data base such CityGML or IFC. For example range imaging cameras are integrated with LoD4 CityGML in (Kohoutek et al. 2010) to find the location and orientation of the camera. Thus, the accuracy of positioning in this class relies on detailed/up to date digital spatio semantic interior building models which again highlight the importance of the research done in this thesis.

2.4.4.1 Indoor Localization for Building Emergency Response Operations

For building emergency response operations, localization should be justified to another level with first responder requirements. The deployed indoor localization solutions should be accurate, easily deployable on scene, resistant to heat/water/ other physical damages, have high calculation speeds, be carriable in terms of size and weight, have reasonable pricing, be independent from building infrastructure/ prior data collection/ on-scene data input, scalable to a large number of people, and easy to assemble before dispatching the team (Li, Becerik-Gerber, et al. 2014). Thus, various new indoor localization approaches have been proposed that target first response operations.

One of the most demanded requirements of fire services is to localize victims in the scene as quick as possible. Thus, researchers have used users’ smartphones to estimate location and physical status of victims inside the building (Lee & Cho 2011; Yoon et al. 2016). Yoon et al. (Yoon et al. 2016) suggest the use of an integrated Victim Positioning System (VPS) and Victim Assessment System (VAS) to find the location of the person inside the building by using the received Wi-Fi RSSI of the phone and estimating the victim’s activity by using the acceleration and the magnetic field sensor using Naïve Bayes classifiers respectively. The authors have shown promising accuracy of victim position and status.

Building Information Models have proven to increase accuracy of indoor positioning algorithms when integrated with Radio Frequency Identification (RFID) tracking (Costin & Teizer 2015) or on scene ad-hoc deployment (Li, Becerik-Gerber, et al. 2014). Among the many localization
techniques aimed at first responders, Li et al. (Li, Becerik-Gerber, et al. 2014) suggest what they call the EASBL (Environment-Aware radio frequency beacon deployment algorithm for Sequence Based Localization) algorithm which provides the ability to set up an ad-hoc radio frequency network on scene to locate first responders and people that are trapped inside the building. The algorithm is based on BIM geometric information for calculating the space division quality and correct estimation of room and levels which eliminates the need for pre installation of positioning infrastructure which is usually the case under emergency situations. They suggest adding hazardous information and location of hydrants, and other relevant information for rescuers in their future work. The robustness and efficiency of EASBL is field tested and is shown to have promising accuracy and robustness in location determination and is easily deployable on-scene (Li et al. 2015).

Such approaches highlight the importance of existence of underlying indoor data models for effective indoor positioning and routing decisions.

2.4.5 Indoor Routing and Evacuation

Once the interior of the building is modelled, and a spatial indoor model is designed for it, and assuming an indoor localization system is in place; what enables a smooth navigation and route guidance inside the building, is the routing algorithm. While indoor services require accurate path finding algorithms to direct occupants towards their destinations; indoor emergency situations require quick evacuation of occupants in the building to safe locations as well as quick guidance of emergency crew inside the building. Fire is with no doubt one of the main threats to high rise building and complex structures and their thousands of occupants. And thus, evacuating people from the safest shortest paths in extraordinary circumstances has become a main focus of research in the recent years (U Atila et al. 2013; Kamkarian & Hexmoor 2012). There are many types of disasters and emergency situations which need quick evacuation of the indoor environments which can either occur inside the structure or have an outdoor source (Figure 2-29).
Many of the emergency situations such as indoor fires, outdoor fires that affect indoors, earthquakes, chemical releases, etc. require quick evacuation of the indoor environments. Also, emergency response teams need to have access to real time navigation information in the quickest time. However, in the current practice it is difficult to access all this information in a reasonably short time as this information is either incomplete or gathered by multiple sources that aren’t organized (G. Guven et al. 2012).

Many causes lead to loss of life or injury during building disasters specially fires, such as asphyxiation or lung damage due to smoke inhalation, structural collapse on people unable to get out of the building quickly, and physical injury caused by trampling of evacuating people caught in the crowd (Ahn & Han 2012). Generally, public behavior could be different from what is expected in emergency situations. For example evacuees that are already familiar with the building are more likely to choose habitual routes in emergency situations which might lead them to dangerous or blocked areas (Wang et al. 2014). A main factor causing these scenarios are the length of time it takes for occupants to evacuate the building as well as unavailability of indoor situational awareness of the indoor areas. Thus, decreasing this time increases the chances of safe survival from the situations (Ahn & Han 2012).
Response delays inside multilevel structures caused by “indoor route uncertainty” may be much longer than delays that happen due to “street network uncertainty” (Kwan & Lee 2005). Kwan and Lee propose the use of real time 3D GIS for the development and implementation of GIS-based intelligent emergency response systems (GIERS) to assist in quicker emergency response for multi-level structures. Their results prove that extending conventional 2D GIS to 3D GIS representations of the indoor environments of multi-level structures can improve the overall speed of rescue operations. This type of findings motivates geospatial scientists to develop intelligent emergency evacuation systems for complex buildings called Intelligent Building Evacuation (IBE) system which integrates 3D GIS with Intelligent Transportation System technologies (Meijers et al. 2005).

Graph networks are used for modelling evacuation and routing in many indoor navigation platforms proposed (Karas et al. 2006; Jun et al. 2009; Rüppel et al. 2010) while CityGML (Kolbe 2009) and most 3D visualization problems use Lee’s Node-Relation Structure model (Lee 2001). IndoorOSM data can also be used for generating detailed floor plans, evacuation plans, route graphs, and mass evacuation simulation plans (Goetz & Zipf 2012) since IndoorOSM contains detailed information about the topology and geometry of each building. However, IndoorOSM also has its shortcomings. First, real population figures can’t be derived from it, thus real time data sources such as linked geodata (Auer et al. 2009) and Live Cities (Resch et al. 2012) need to be integrated with it. Second, information about individual inhabitants such as age, sex, and health conditions of the buildings is missing. Third, barriers and obstacles inside buildings are not defined. Generally speaking, evacuation simulations that are solely based on crowdsourced OSM data will not be accurate as they lack dynamic and population information about the buildings. Due to BIMs importance in emergency response decision making, BIM can be used as the data input for automatic construction of a hybrid MAT-VG (Medial Axes Transform- Visibility Graph) network graph which allows quicker execution times for network analysis (Chen & Huang 2015). This model has limitations in covering complex geometries and weight assignment on edges based on edge factors such as length, flow, risk, etc.

Ubiquitous computing systems allow the real time information gathering in indoor environments and this information could be used for dynamically navigating people in the buildings (Huang et al. 2009). Monitored and controlled sensors are making buildings and structures increasingly smart and intelligent. Although some research use tracking strategies to monitor user’s progression to avoid deviations or help in recovering from deviation, they mostly focus
on time and distance (Berger et al. 2010; Xu et al. 2010). However, other preferences or events that could highly affect the answer are left unconsidered. Sensor graphs are integrated with route graphs in (Wang et al. 2014) to enable sensor tracking and risk aware evacuation planning for indoor emergencies. The model discusses how activated sensors in the building can affect the accessibility of vertices and edges on the route graph. (Tang et al. 2014) propose using stochastic models for modelling real time change in the network and calculating evacuation routes quickly. The data gathered from sensors deployed in the structure can be employed as a source of real time information about the building’s situation (Kwan & Lee 2005).

Use of GIS-based Intelligent Emergency Response Systems (GIERS) that are capable of collecting and disseminating data in real time can analyze disaster events and communicate decisions and actions among affected community (Kwan & Lee 2005). As structural events also affect their immediate outdoor environment, the GIERS proposed in this work aims at integrating Intelligent Transportation Systems with Intelligent Building Systems since they both have real time data collection and dissemination technologies that can help in gaining knowledge about disaster environment. The results of their study show that a 3D network that integrates the street network with the building network saves more than one third of the travel time that is needed otherwise for reaching the disaster site. Therefore, real time information gathered from sensors detecting emergency situations is integrated into maps to guide people to safer areas in (Inoue et al. 2008) but the dynamic update of paths is not covered. Chen et al. (2011) propose the use of moving speed detector sensors to estimate the congestion of people in corridors and thus navigating people according to congestion not necessarily the shortest paths.

Emergency incidents are dynamic and variable events in contrast to static events (Rakip et al. 2012) and thus dynamic evacuation processes should be proposed to deal with them, contrary to the previous work which have mainly disregarded this fact. Developing an Intelligent Building Evacuation (IBE) system model, which incorporates indoor geospatial data about both the emergency situation and changes in evacuation status during time could help in dynamically evacuating the structures (Lee 2007). Also, Rakip et al. (2012) propose the Optimum Evacuation System (OES) which aims at obtaining accurate information during the incident as well as considering the status of individuals and groups and providing evacuation information to occupants accordingly. Rakip et al. (2012) describe that important information such as damaged areas, chemical and gas leakages, smoked zones, electricity cuts, location of people, population density, stairways, disabilities, etc. should be constantly updated. Figure 2-30 shows their
proposed framework. Based on this idea they examine the use of 3D indoor pedestrian navigation systems for route finding in indoor environments.

![Diagram of Components of Optimum Evacuation Systems](image)

**Figure 2-30 Components of Optimum Evacuation Systems** (Rakip et al. 2012)

During disasters, many unknown problems can occur to a building, leading to change in the environment. Furthermore, as French et al. (2012) states, “a number of the current issues that arise during emergency incidents are due to the uncertainty and transiency of environmental conditions”. Projects like FireGrid are focusing on next-generation emergency response systems especially in built environments (Berry et al. 2005; Han et al. 2010). The key idea of such projects is to gather real-time data from intelligent buildings and proactively provide decision support information for emergency responders. The transient and uncertain environmental conditions are modelled as flow problem in time-dependent networks and evolutionary optimization algorithms are used to solve the problem in (French et al. 2012). In addition, Pu & Zlatanova (2005) suggest using adaptive search trees for finding the evacuation routes in such
unstable conditions to consider real time factors; as fixed search trees would not be useful and could cause wrong navigation instructions.

To summarize, when dealing with indoor emergency situations, we are confronting non-fixed and changeable situations. Thus, pre-plans, routing and decision making based on obsolete data are not effective. The research currently is on intelligent building systems to monitor and integrate data from a variety of sensors (temperature, movement or occupancy sensors, pressure pads, smoke or gas detectors, fire detectors) for detection, alarming and controlling other systems (heating, ventilation, air flow, lock/unlock doors, lighting, etc. (Reyes et al 2001). In the near future, these intelligent buildings will be connected to backbone infrastructures to forward up to date information about the building to external emergency responders allowing clearly observing and predicting progression of incidents to make more knowledgeable decisions (French et al. 2012).

2.4.6 Search and Rescue Operations in Research

Having discussed all the components of an indoor application service and highlighting the gaps and challenges for the indoor emergency applications, this section overviews the most recent solutions developed for the indoor search and rescue application.

As discussed in Section 2.2 and 2.3, the indoor search and rescue operations face various difficulties and challenges in the current practice systems. Moreover, the unavailability of indoor maps and building information targeted at first responders complicates the decision planning for crew number and their dispatch routes inside the building; resulting in more wasted time and delay due to uncertainty, rerouting, and lack of knowledge of the environment. Studies have shown only a small delay of 5-10 minutes can hugely impact the fire damage and risk to people and first responders’ lives in structural fires (Mattsson & Juås 1997). In fact, firefighter injuries are a main concern of emergency bodies (NFPA 2013) with the lack of comprehensive size-up and information contributing to the leading firefighter deaths (The National Institute for Occupational Health and Safety (NIOSH) 2016). Although there has been great focus in research on public evacuation in buildings (Tang et al. 2014), importance of models aimed for navigating first responders through built environments and providing them with emergency critical information has been underestimated.
In the current practice, firefighters know little about the fire and the building until they get to the scene where they have to quickly evaluate the situation and take actions accordingly. In fact, lack of timely information reduces their preparedness ability to act rapidly when confronted with an incident. However, first responders should not have to physically enter a burning building to gain critical information regarding that building (Evans 2003) and such information should be readily available to them in their trucks while approaching the scene, giving them detailed situational awareness of the incident area (Tashakkori, Rajabifard, Kalantari, et al. 2016). From the point of emergency response, the incident commander is required to know about the building layout (such as the stairs, exits, occupant number, etc.), location of the crew members in the incident and the parts of the building that have already been searched to avoid multiple visits of the same room and failing to visit another. Valuable time could be wasted for searching the same room twice or failing to search another. The rescue team should be able to locate a firefighter if he/she signals a distress call and the incident commanders are required to have information of the building elements. There are various incidents of firefighter deaths due to disorientation and running out of air. Thus, several reports highlight the importance of tracking and navigation systems for buildings as well as sharing building information with fire departments and using Computer Aided Dispatch Systems (CAD) for pre-incident planning\(^4\),\(^5\).

Searching the incident building for possible victims and location of fire is one of the major tasks undertaken by first responders after an incident occurs. In fact chances of finding live victims in residential buildings under dangerous situations depends on the speed of the primary search done in the building (Bricault 2006). Considering the importance of this thorough search in the building, an important research problem is how the first responder crew should be dispatched inside the building in order to minimize the search and rescue time. This could be quite a complicated task due to various entrances, exits, staircases, and elevators in the building which creates various choices and difficulties in choosing the paths for rescuers and as of now, decisions on dispatching the crew depends on previous knowledge and experience of the incident managers.

\(^4\) http://www.cdc.gov/niosh/fire/pdfs/face200718.pdf
\(^5\) http://www.cdc.gov/niosh/fire/pdfs/face201314.pdf
The case of routing several rescuers to perform tasks at multiple static locations is a common case that takes place when a major disaster strikes. Because of the limitation of the time, quantity and quality of the resources, an optimal scheduling of resources in space and time should be used by emergency managers (Fiedrich et al. 2000). To find the best assignment of available resources to operational areas for the initial search and rescue. Fiedrich et al. (2000) propose a mathematical optimization model and a simulated annealing (SA) metaheuristic for solving the problem after an earthquake hits. The problem allocates resources (machines and equipment) to work at operating areas (depots, hospitals, crossroads) towards searching and rescuing victims with the objective function aiming to minimize the total number of fatalities during the search and rescue period after an earthquake hits. The problem is restated as a Multiple Travelling Salesman Problem (MTSP) and a genetic algorithm, ant colony optimization, and neural network solution is suggested for finding the optimal tours in the network (Kulich et al. 2004). The effect of static and dynamic obstacles on path finding algorithms for emergency response operations has been discussed in (Wang & Zlatanova 2013) and navigation cases for single/multiple rescuers routed towards single/multiple static/dynamic destinations with single/multiple static/dynamic obstacles have been analyzed. Victims’ smartphones can also be used to quickly locate them to plan the search and rescue operations for outdoor areas where locating the victims’ location is easier compared to the indoor areas (Costantini et al. 2012).

Indoor search and rescue resource assignment is quite different compared to the urban environment. Various researches have focused on new approaches to facilitate indoor emergency operations (Fischer & Gellersen 2010; Bliss et al. 1997; Diez et al. 2016). Indoor navigation systems are becoming more advanced in locating and tracking people in indoor environments, however they still have limitations when used by emergency responders and for search and rescue operations due to the challenging situations they confront during emergencies (Fischer & Gellersen 2010). As knowledge of the building’s structure is critical for knowing location of strategic facilities such as fuse boxes or gas cutoffs (Bliss et al. 1997), Bliss et al. (1997) show that fire fighters that received a pictorial navigation aid such as blueprints and virtual reality for training and information perform the rescue tasks quicker compared to those without this prior information. Moreover, knowledge of the landmarks, routes, and spatial configurations is what enables people to learn to navigate in a given environment (Golledge 1991). Most recently serious game platforms with BIM representations and fire simulations have also been proposed for training experts on hazards they may confront on the fire scene (Diez et al. 2016).
Still, searching the interiors of a building could be a complicated task considering the complexity of the structure, unfamiliarity with the areas, visual distractions, slower walking speeds, restricted and limited navigable areas caused by bounded walls or accessibility restrictions (Kwan & Lee 2005). To address the Indoor Search and Rescue Problem, Wu & Chen (2012) introduce a relaxed form of the problem in which a spatio-temporal analysis method is proposed to find a single fire-fighting route for searching the points. Their approach is based on a Traveling Salesman Problem (TSP) which is formulated only for the points that need to be searched inside the building finding a single rescuer route to search all the assigned point in the minimum time. However, the GNM used in their work is not integrated with the outdoor environment and doesn’t consider existence of multiple entering and exiting points as well as multiple responders in the problem. Thus formulating the problem as a TSP, their solution is limited in how it can be used for 3D structures. A scheduling solution for cooperative search of the indoor structures by heterogeneous teams consisting of robots and humans has been presented in (Kulich et al. 2005). The problem is solved in two steps; first finding the guard points by using the Art Gallery Problem and then using the Multiple Travelling Salesman Problem (MTSP) to find the paths for the search team through the indoor area. The approach is solely based on a polygon view of the indoor maps not considering the building information and rescuer limitations.

Although, the above mentioned approaches have targeted the Search and Rescue problem to some extent, they still do not quite fit the requirements of a solution that can be used by first responders mainly because they do not consider the indoor settings and features inside the building such as decisions on types of the egress way such as stairs or elevators that affect decision making. Also, the indoor areas are not viewed as 3D environments that are integrated with the outdoor urban areas. Therefore, the solutions can’t find the most effective points of entry and exit to the structures. Moreover, decisions on crew dispatch should consider the rescuers constraints in terms of maximum time they can spend searching the structure which is not seen in previous work. Furthermore, dynamic changes in the environment are inevitable and the need for updating the currently assigned routes is a crucial part of emergency response and search and rescue routes which is mostly underestimated.
2.5 Chapter Summary

This chapter reviewed the current literature and practice systems in the area of indoor situational awareness for facilitating indoor emergency response. A thorough review of current reports and investigations published by main organization in the domain were given in order to identify challenges faced by emergency responders in current procedures. Based on that, the state of the art research approaches proposed in literature for increasing situational awareness were discussed and the gaps and challenges that remain in terms of providing indoor situational awareness and solving the search and rescue problem were analyzed.

To conclude, reaching the locations and victims and undertaking a thorough search as quickest possible in the indoor environments plays an important role on how the emergency operations are performed. Identifying the best search and rescue routes on-scene is closely related to the underlying spatial and geometric model of the building. Thus, a crucial part of the routing is the presentation of building features to fit indoor emergency response applications. Therefore, this research targets the search and rescue problem by first proposing a 3D indoor spatial model for modelling the interiors of the buildings and how they are related to their outdoor surroundings and then proposing a solution approach to the search and rescue problem.

The next chapter of this thesis will discuss the research approach and methodology undertaken by this research to address these issues to overcome the difficulties mentioned in the domain of indoor situational awareness for emergency response.
Chapter 3

Research Design and Methodology
3.1 Introduction

The previous two chapters discussed the foundation of the research, the background to the problem and state of the art research and solutions to address the problem. Based on this foundation, the research problem in this thesis questions the current indoor spatial models since they are not effective in indoor search and rescue operations and thus indoor decision making is a challenge for first responders. Accordingly, four main research questions are addressed in this thesis: 1) what building information is critical for emergency responders, 2) how should the 3D integrated indoor/outdoor spatial model be developed, 3) can a new solution to the Indoor Search and Rescue Problem be provided, and 4) How well does the proposed model perform compared to current practice systems.

Based on what was discussed in Chapter 1, to be able to propose a solution to the indoor search and rescue problem, first the indoor environment needs to be modelled to reflect indoor emergency requirements and then the underlying model can be leveraged to present the SRP solution. Thus, the research undertaken in this thesis is designed to address both these components throughout the research.

This chapter’s main focus is on the research design, research methodology, and research methods. While the research design aims to state the conceptual structure which the research is conducted (Kothari 2004) and the journey to get from the research problem to proper and correct solutions to the research questions (Bordens & Abbott 2008); the research methodology explains the systematic steps involved in the research; and lastly, research method explains all the techniques and approaches used in the research.

Based on the research description, motivation, and research problem described in Chapter 1, this chapter will discuss the methodology used for undertaking the research, the way the problem is formulated, how the research was designed, the methods used for answering the research questions, and how the research is evaluated and validated. The undertaken research is best fit to the Design Science Research Methodology (Peffers et al. 2008) which guides the research approach and thus will be discussed in further detail in this chapter.

In the rest of this chapter, first an introduction to the way research is undertaken in information systems will be given in Section 3.2. Then the foundation and the framework of the Design Science will be explained in Section 3.3. Section 3.4 will discuss the current disserta-
tion’s research approach and methods used for addressing the research problems and achieving the defined objectives. Finally, Section 3.5 will summarize the chapter.

3.2 Research in Information Systems

Research is defined by Kothari (Kothari 2004) as the art of scientific and systematic investigation for relevant information on a specific topic. The basic types of research consist of Descriptive vs. Analytical, Applied vs. Fundamental, Quantitative vs. Qualitative, Conceptual vs. Empirical, and other types of research which are variations of one or more of these known methods. Based on these types of research, two basic research approaches exist; quantitative approach and qualitative approach. While the quantitative approaches involve generation of data and quantitatively analyzing it, the qualitative methods deal with subjective assessment of attitudes, behaviors and opinions (Kothari 2004).

The quantitative approaches can be categorized into inferential, experimental, and simulation approaches (Kothari 2004). The inferential approaches usually relate to survey researches in which the purpose is to extract relations amongst the data. In experimental approaches, the environment is controlled to analyze the effect of specific parameters on other parameters. And finally, the simulation approaches assess and observe the behavior of the system by creating an artificial environment where data, information, algorithms, etc. can be produced allowing the control of the conditions and the settings of the environment.

Qualitative research on the other hand is involved with a phenomenon that is related to the kind or quality. This kind of research consists of research methods such as motivation research, word association tests, sentence completion tests, story completion tests, attitude or opinion research (Kothari 2004). This kind of research is particularly of interest in behavioral sciences where the researcher is trying to identify the motives of human behavior.

There is also a third approach, namely the mixed qualitative and quantitative method or the third methodological movement (Ridenour & Newman 2008), which is targeted at phenomena that can’t be fully understood by only one of the methods. Although, there has been debates on using mixed methods in both behavioral sciences and information systems, thorough inspection and resolution of these controversial issues enables strong establishment of this third
methodological movement amongst the other two quantitative and qualitative approaches (Teddlie & Tashakkori 2003; Ridenour & Newman 2008; Zachariadis et al. 2013).

Information Systems dominate a vast amount of the research domain. IS is an applied research discipline where theories from other disciplines are frequently used to solve the problems that lie where IT and organizations meet (Peffers et al. 2008).

Most of the research in information systems can be categorized in two paradigms: behavioral science, and design science (Hevner et al. 2004). While behavioral science is focused on human and organizational behavior, design science generates novel and innovative artifacts for expanding the human and organizational capabilities. Furthermore, the artifacts allow creation of innovative ideas, products, or technical capabilities where using the information systems can improve proficiency and efficiency.

Design science research in IS results in an IT artifact that is addressed to solve an organizational problem (Hevner et al. 2004). IT artifacts are defined as constructs, models, methods, and instantiations (Hevner et al. 2004). Constructs consist of vocabulary and symbols; while models are basically abstractions and representations; methods involve algorithms and practices; and instantiations are implemented and prototype systems. These artifacts allow IT researchers and practitioners to comprehend and solve problems in successful implementation of information systems. As Markus et al. states Information system design theories “prescribe effective development practices (methods) and a type of system solution (instantiation) for a particular class of user requirements (models)” (Markus et al. 2002).

Design Science can be used to analyze the feasibility of a proposed approach in IS by creating and evaluating IT artifacts. These artifacts can range from software to complex mathematics, formal logic, and language descriptions. IT artifacts can be quantitatively evaluated by mathematical basis such as optimization proofs, analytical simulation, and quantitative comparison with other designs (Hevner et al. 2004). On the other hand, empirical and qualitative methods can be used to evaluate the way people and the organizations interact with the IT artifact.
Hevner et al. (2004) present a conceptual framework for research in information systems combining both the behavioral science and the design science paradigms (Figure 3-1). Based on their framework shown in Figure 3-1, the environment presents the problem space. People, organizations, and the technologies together define the goals, problems and opportunities to define the business needs or as the researcher sees it: the “problem” in the system. After the researcher develops the theories (in behavioral science) or artifacts (in design science), they need to be justified/evaluated to identify the weaknesses that need to be assessed or refined (usually referred to future directions of the research). Knowledge base is comprised of foundations and methodologies that enable the IS research to be undertaken. Foundations such as the theories, frameworks, constructs, models, methods, and instantiations all assist with the developing phase. While the methodologies in the behavioral science lie mostly in empirical analysis and data collection, computational and mathematical methods are the primary methodologies used to evaluate the efficiency of the artifacts.
3.3 Design Science Research Methodology

To give a more standardized format to the DS research in IS, Peffers et al. (Peffers et al. 2008) develop a Design Science Research Methodology (DSRM) for presenting and evaluating such kind of research. The methodology is based on six major steps shown in Figure 3-2: 1) problem identification and motivation, 2) objective definition for a solution, 3) design and development, 4) demonstration, 5) evaluation, 6) communication.

![Figure 3-2 Design Science Research Methodology (Peffers et al. 2008)](image)

Although the steps are shown in sequential model, the researcher is not limited to move in one way, and can move between steps as seen proper. Each of the steps are described by Peffers et al. (2008) as below:

**Problem Identification**

This is where the research problem is identified and the reason for the solution is justified. The IT artifact will be developed based on this problem description. Thus, a broad knowledge of the state of the problem and the significance of the solution is a main requirement.

**Objective Definition for a Solution**

Based on knowledge of the state of problem and current solutions and their efficiency, the objectives of a solution are defined which could be either quantitative objectives (better performance) or qualitative objectives (descriptive explanation of new artifact effectiveness).

**Design and Development**
This is the step where the artifact being a construct, model, method, or instantiation is created. The research contribution is embedded in the design and includes creating the artifact based on the defined functionalities and architecture of the artifact.

**Demonstration**

This step is undertaken to use the developed artifact to solve one or more instances of the problem. Simulations, experimentations, case studies, proofs, etc. can all be used to achieve this step.

**Evaluation**

This step is where the artifact is observed and measured for performance criteria to evaluate efficiency and feasibility. The evaluation can be done by comparing the artifact’s functionality with those of the earlier defined objectives, using quantitative performance measures such as response time and availability, simulations, use feedbacks, etc. Here, the defined objectives will be compared to the results. At the end of this step, the research decides to either go back and improve the artifact or leave it for future research and projects.

**Communication**

The final stage is then to communicate and present the importance, novelty, and rigor of the developed artifact solution. The outcome of this stage is typically in the format of a report, paper, or thesis.

### 3.4 Thesis Research Methodology

Development of technology has enabled IT solutions in various new applications where designing useful IT artifacts is more complicated because of need for advances in areas that theories are not sufficient (Hevner et al. 2004). Clearly, this thesis is in this domain as the concepts of indoor modelling and navigation are very newly introduced in the field of IT/GIS and thus, the design science can assist in the analysis, design, and implementation of the creation and evaluation of the proposed 3D Indoor Emergency Spatial Model and Search and Rescue Algorithm as our proposed IT artifacts. Thus, in this section, the research methodology will be described based on the Design Science Research Methodology discussed above.
An effective design science research should have new contributions in one or more of the areas of: designing the artifact, designing knowledge (foundation), or designing the evaluation (methodology) (Hevner et al. 2004). In case of proposing a solution to either extend the knowledge base or apply existing knowledge in a creative way that wasn’t used before, the IT artifact itself is the contribution of the research. Creative development of the foundations can also be the contribution of the work; anything from the constructs and the models to the instantiations and methods. Lastly, developing new evaluation methods such as analytics, experiments, observations can also be a direction of the IS research.

The contribution of this research is firstly in the artifact itself (the proposed model) which solves the problem of indoor situational awareness for indoor emergency response. Secondly, the Indoor Emergency Spatial Model and the solution approach proposed for the Search and Rescue Problem are the contributions made in the model and method respectively. And lastly, the implemented and evaluated prototype represent the dissertations contribution in the construct and instantiation.

The research design of the dissertation is shown in Figure 3-3 by outlining the thesis chapters to reflect the methodology undertaken. As discussed in Chapter 1, the indoor situational awareness problem for indoor emergency is addressed in this research by first proposing an indoor emergency spatial model to reflect emergency responders’ requirements, and second using the model to present a solution approach for the indoor Search and Rescue Problem. Thus, the dissertation is formed to present the design, development, and evaluation of each of these two main contributions throughout the chapters as given in Figure 3-3. As seen in Figure 3-3, Chapter 1, Chapter 2, and Chapter 3 identify the problem and define the objectives of the research and the methodology used. The design and the development of the solution approach are given in Chapter 4 and Chapter 5 focusing on both the modelling of the indoor environment and the search and rescue problem. The proposed solution is then evaluated in Chapter 6 and Chapter 7. And lastly, the thesis is concluded in Chapter 8.
3.4.1 Research Problem Identification and Objective Definition

The first step in a Design Science Research is to form the knowledge base for the artifact design. Thus, a thorough systematic investigation of the current literature and current practice systems is undertaken to identify the gaps in the area of indoor emergency response in Chapter 2. The following major areas were investigated in this phase in order to build a
broad knowledge of the state of the problem and highlight the significance of the problem and
the proposed solution. This allows a clear identification of the research problem, aims, and
objectives given in Chapter 1.

3.4.1.1 Challenges of Indoor Emergency Response in Current Procedures

To have a thorough view of the problem in the real world settings and how indoor
operations are undertaken by first responders, a series of literature review of current reports
and investigations published by main organizations in the domain such as The International
Association of Fire Chiefs, National Institute of Standards and Technology (NIST), Federal
Emergency Management Agency (FEMA), etc. are reviewed (Chapter 2, Section 2.2). This con-
sists of learning first responders’ procedures for gaining situational awareness of the indoor
environments and how they proceed with the search and rescue operations.

To confirm the findings and reports with real practitioners and also learn about the procedures
in the Australian context, a series of meetings and face to face interviews are also conducted
with the Dandenong Country Fire Authority (CFA) brigade consisting of 4 fire fighters, a sector
commander, and an incident controller. These interviews were aimed at finding what maps
and information are currently available to emergency brigades, how the utilities are located in
the building, how decisions are made for indoor emergency situations, how the crew is dis-
patched for search and rescue procedures, and how routing decisions are made. Details on
these practical procedures can be found in Chapter 2, Section 2.3 of the thesis.

3.4.1.2 Indoor Situational Awareness in Literature

In the recent years indoor modelling and navigation have been a main focus of a
huge body of research and literature. From improving indoor positioning and localization sys-
tems, to developing new approaches for city representations and proposing improved indoor
spatial models for indoor navigability and evacuation. Although, some of these research target
indoor emergency situations, their applicability to indoor situational awareness and search and
rescue for emergency responders faces various challenges. A thorough review of the research
and literature in this domain and the challenges they confront are discussed in Chapter 2, Sec-
tion 2.4.
3.4.1.3 **Challenges of Search and Rescue Operations**

Searching the incident building for possible victims and location of fire is one of the major tasks undertaken by first responders after an incident occurs. In fact chances of finding live victims in residential buildings under dangerous situations depends on the speed of the primary search done in the building (Bricault 2006). In the current practice, fire fighters use the right hand or left hand technique to keep them oriented and to systematically search the entire area. However, this technique faces various challenges and uncertainties. Chapter 2, Section 2.4.6 looks at current procedures and the approaches literature have taken to target the problem and the difficulties they face.

3.4.2 **Research Design and Development**

The resulting design science research is a purposeful IT artifact (Hevner et al. 2004). Artifacts are aimed at defining an innovative idea where the use of the IS can be effective and thus, they are rarely grown sufficiently to be employed directly in practice.

The Design and Development phase is where the artifact being the constructs, models, methods, and instantiations is created. Thus, in this phase, the proposed solution artifact is designed to address the research problems identified for enabling indoor situational awareness. Based on the body of knowledge gained in the previous phase, this stage designs an Indoor Emergency Spatial Data Model as a construct to the problem after thorough investigation of the first responder requirements. Using the proposed data model, the Search and Rescue Problem is formulated mathematically and a metaheuristic algorithm is designed for solving the problem (method).

The main steps of the design and development stage are described below:

3.4.2.1 **Indoor Emergency Information Requirements Analysis**

To present an efficient indoor spatial data model that enables effective indoor routing and indoor services for emergency situations, both the interior and exterior of the structures need to be modelled to contain detailed 3D geometric and semantic information required during indoor incidents.
Requirements analysis is a major part of the database lifecycle for determining the objects, their relations, and transactions in the system (Teorey et al. 2011). As the effectiveness of the proposed data model relies on the accurate emergency response requirements analysis, Chapter 4, Section 4.2.1 discusses the critical building information requirements of first responders during indoor emergency situations based on interviews, review of relevant previous literature, etc. and will then propose the UML class diagram suggested for the Indoor Emergency Spatial Model (IESM) accordingly.

3.4.2.2 Indoor Emergency Spatial Model Design

The design and development of the 3D Indoor Emergency Spatial Data Model will be presented in Chapter 4, Section 4.2.2. As the current indoor data models have limitations in fulfilling the emergency requirements of indoor incidents, a new UML class model is proposed in this research. The Unified Modelling Language (UML) is a graphical representation for communicating design specifications of object-oriented software (Teorey et al. 2011). The UML class diagrams are used for presenting the database design and capturing the structural aspects of database schemas which are then used for planning and implementing the databases. The UML class diagram design allows representing the objects in the model and their relations.

The proposed model is based on the modified BIM/GIS integration where the IFC class diagram is modified to contain the identified mission critical data requirements and exclude unnecessary constructional complexities. The Outdoor information affecting the indoor emergency decision making is also integrated from CityGML to enable a seamless integration of the indoors and outdoors.

To enable routing and path finding inside the structure and make it a seamless transition from the indoor areas to outdoors, a 3D indoor IESM integrated geometric/semantic network model is then presented in Chapter 4, Section 4.3 which extracts a navigable indoor graph based on the information model from IESM attaching semantic information to the graph elements to allow requirements based routing inside the network for emergency responders. Accordingly, graph weights and route cost computation is explained in Chapter 4 to enable path finding for first responder movements inside the building and designing the solution formulation to the Search and Rescue Problem.
3.4.2.3 Search and Rescue Problem Formulation

Considering the importance of a quick thorough search of inside the buildings by first responders after an incident occurs (Chen et al. 2014), an important research problem is how the first responder crew should be dispatched inside the building in order to search the entire building (or critical points of interest) in the quickest time with minimum number of responders which is referred to “The Search and Rescue Problem (SRP)” in this research. SRP should determine the number of crew required to search the building in order to minimize their overall time and traversed distance inside the buildings.

To be able to present a solution to the Search and Rescue Problem, the problem first needs to be mathematically designed and formulated. Using the indoor GNM presented for IESM, Chapter 5 models SRP as a combinatorial optimization problem and presents an integer programming mathematical formulation of the problem considering the constraints and limitations of the problem. As will be discussed in Chapter 5, SRP is in the category of Travelling Salesman Problem subclasses with NP-hard complexity. Thus, exact algorithms will be unable to find optimal solutions in polynomial time. Therefore, heuristic and metaheuristic approaches should be used to solve the problem.

3.4.2.4 ACO based Algorithm for Solving SRP under Static and Dynamic Conditions

To solve the Search and Rescue Problem, an Ant Colony Based Optimization technique is proposed in Chapter 5 to find the best, near optimum solution in the quickest time. The Ant Colony Optimization approaches are a strong category of metaheuristic algorithms based on the real ants’ behavior to forage food. The ant colony algorithm is based on the idea of parallelizing the search over multiple computational threads using a dynamic memory that saves the effectiveness of the previous results and uses that to improve the behavior of each single agent that mimics the behavior of real ants (Maniezzo & Carbonaro 2002).

The ACO based algorithm is developed for both the initial/static state of the problem where no further information is available on the dynamics of the indoor situation and the dynamic state where routes need to be updated based on timely information received. The algorithm finds the minimum number of rescuers to search all the points of interest in the building in quickest time considering their constraints (mainly maximum time each person can spend inside the building). As the indoor incident progresses and information is received from environmental detectors, the algorithm adapts dynamically by updating the assigned rescuer paths to reflect
changes in the building. Thus, diverting the already assigned paths to avoid navigating through blocked or dangerous areas and re-assigning the unvisited points to on scene rescuers in an efficient way, adding extra rescuers when required to reflect the dynamics of the event. The details of the algorithm will be described further in Chapter 5, Section 5.4.

3.4.3 Research Demonstration

As explained earlier, demonstration is the next step after design in which the developed artifact is used to solve one or more instances of the problem using case studies, simulations, proof of concept, experimentation, etc. To demonstrate the feasibility of the developed artifact proposed in this research, the artifact instantiation is used which for this research is basically a software tool developed for implementing the Indoor Emergency Spatial Model (IESM) and the SRP algorithm aiming to improve the process of information system development. This instantiation provides “proof by construction” (Nunamaker et al. 1991). Furthermore, evaluation of the IESM and SRP will allow efficiency analysis of the proposed model.

For the artifact instantiation of the proposed indoor situational awareness framework, first a case study building is designed to enable a consistent demonstration of the proposed solution. Using the case study building, a proof of concept demonstration of the Indoor Emergency Spatial Model is presented for a case study building in Chapter 6. Once the applicability of IESM is demonstrated, the proposed SRP algorithm is simulated on top of the model and the results of the algorithm under various scenarios and settings are evaluated in Chapter 7. Details of the demonstration steps are given below.

3.4.3.1 Case Study Specification

The feasibility of the IESM and SRP algorithm is demonstrated by modelling a test case building (the Infrastructure Engineering building) at the campus of University of Melbourne. The case study will serve as a basis for undertaking different scenarios that first responders usually are faced with to analyze how the system can assist in providing situational awareness to them. Furthermore, the case study environment will analyze the system’s performance in terms of improving visual communication, spatial analysis, decision making, and search paths inside the buildings.
The case study building has four floors, a rooftop and a basement, eight main entrances to the building, two staircases and an elevator. Creating the case study based on a real building allows accurate modelling and evaluation of the system. For this purpose, the 2D indoor CAD floor plans are converted to a 3D building model using the Revit Software\(^6\) (Figure 3-4). Revit is an architectural software that gives the ability to build three dimensional building models enhanced with various types of structural and engineering information for Building Information Modelling (Autodesk 2014). The building is then considered in the GIS context with real world geographical coordinates on the map. The IESM and the SRP algorithm are then applied on the same building to demonstrate the applicability of the proposed IT artifact.

![Figure 3-4 Case study Revit model](image)

### 3.4.3.2 Proof of Concept Demonstration of IESM

The applicability of the proposed Indoor Emergency Spatial Data Model is shown through a proof of concept demonstration of the model for the aforementioned case study. This would allow looking at different scenarios that first responders are usually faced with and analyzing how the system can assist in providing situational awareness to them.

As will be seen in Chapter 6, the proposed IESM is applied on the building case study by adding the emergency utilities and semantic information to the 3D building model. The generated model in this way fits the requirements of the presented IESM class diagram.

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\(^6\) www.autodesk.com
To achieve a fully operational 3D indoor modelling framework, various elements such as the indoor model, route visualization, integration with outdoor environment and road network should work together. The primary focus is to use existing geographical information systems to enable the same mapping, analyzing, sharing and managing capabilities. ArcScene is a well-known ESRI 3D visualization application that allows viewing GIS data in three dimensions and is fully integrated with the geo-processing environment that provides access to many analytical tools and functions. Thus, the IESM model is implemented in ArcGIS’s ArcScene platform creating an integrated indoor/outdoor geo-information model to support indoor emergency response and management. This would allow demonstrating various emergency management functions that will be enabled by the model for different scenarios confronted by emergency responders. Details of the implementation, system design and the capabilities of the system are discussed further in Chapter 6.

3.4.3.3 Simulation of the SRP Algorithm

To evaluate the performance of the solution proposed for SRP, it is implemented for the same aforementioned test case geo-located building based on IESM using Python 2.7.10. The IESM integrated Indoor GNM is extracted from the building using ArcPy and managed using the NetworkX\(^7\) library package. NetworkX is a software package for creating, manipulating, and analyzing complex network structures. To visualize the outcomes of the algorithm, the Mayavi\(^8\) package is used for the 3D scientific data visualization. The implemented algorithm is run for various scenarios and the results and data are collected for evaluation purposes.

To compare the results of the algorithm with that of current procedures, the movement decisions of first responders was simulated with the pedestrian Pathfinder\(^9\) simulator which is an agent based evacuation simulation software. The decisions of indoor movements for searching inside the building was based on interviews and guidance received from interviews with the Country Fire Authority (CFA) brigade. The obtained results are compared with the results from the implemented algorithm to demonstrate the efficiency of the system.

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7 NetworkX can be found here: https://networkx.github.io
8 Mayavi can be found here: http://mayavi.sourceforge.net
9 http://www.thunderheadeng.com/pathfinder/
3.4.4 Research Evaluation

The effectiveness, quality, and the feasibility of the designed IT artifact needs to be thoroughly evaluated and illustrated by using well executed evaluation approaches (Hevner et al. 2004). The IT artifacts can be evaluated based on their performance, usability, functionality, completeness, accuracy, analytical metrics, etc. Hevner et al. (2004) categorize the evaluation methods of IT artifacts as seen in Table 3-1.

<table>
<thead>
<tr>
<th>Evaluation Method</th>
<th>Evaluation Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observational</td>
<td>Case Study: Study artifact in depth in business environment</td>
</tr>
<tr>
<td></td>
<td>Field Study: Monitor use of artifact in multiple projects</td>
</tr>
<tr>
<td>Analytical</td>
<td>Static Analysis: Examine structure of artifact for static qualities (e.g. complexity)</td>
</tr>
<tr>
<td></td>
<td>Architecture Analysis: Study fit of artifact into technical IS architecture</td>
</tr>
<tr>
<td></td>
<td>Optimization: Demonstrate inherent optimal properties of artifact or provide optimality bounds on artifact behavior</td>
</tr>
<tr>
<td></td>
<td>Dynamic Analysis: Study artifact in use for dynamic qualities (e.g. performance)</td>
</tr>
<tr>
<td>Experimental</td>
<td>Controlled Experiment: Study artifact in controlled environment for qualities (e.g. usability)</td>
</tr>
<tr>
<td></td>
<td>Simulation: Execute artifact with artificial data</td>
</tr>
<tr>
<td>Testing</td>
<td>Functional (Black Box) Testing: Execute artifact interfaces to discover failures and identify defects</td>
</tr>
<tr>
<td></td>
<td>Structural (White Box) Testing: Perform coverage testing of some metric (e.g. execution paths) in the artifact implementation</td>
</tr>
<tr>
<td>Descriptive</td>
<td>Informed Argument: Use information from the knowledge base (e.g. relevant research) to build a convincing argument for the artifact’s utility</td>
</tr>
<tr>
<td></td>
<td>Scenarios: Construct detailed scenarios around the artifact to demonstrate utility</td>
</tr>
</tbody>
</table>

The proposed indoor situational awareness system proposed in this dissertation is evaluated based on one or more of these evaluation methods. First the effectiveness of IESM for emer-
ergency response operations is analyzed through the demonstrated model explained above in Section 4.4 of Chapter 4. Once the efficacy of the model is proved, SRP is developed based on IESM and the proposed algorithm is evaluated using the simulation and analytical methods in Chapter 6.

3.4.4.1 IESM Evaluation

As the case study will be used for in depth study of the model and detailed scenarios will be constructed around the model to demonstrate the utilities of the system, based on Table 3-1, the evaluation of IESM is done using the observational case study and descriptive scenario method. The model’s performance is studied by observing how it performs in the case study observation for various scenarios that will be mostly used by emergency responders. This includes how the model improves the 3D visualization of indoor areas, spatial analysis on indoor and semantic information, seamless route finding, indoor decision making and interactions with outdoor environments. The implemented model discusses the effectiveness of the model in both decision making and navigation by demonstrating the model’s indoor spatial analysis capabilities and how it improves destination travel times.

Evaluation of IESM is discussed in detail in Chapter 6 using various scenarios and descriptive/analytical evaluation.

3.4.4.2 SRP Evaluation

As running the system in the real environment exposes risk to people, is very time consuming, and controlling the environmental factors faces various difficulties, the propose solution will be evaluated using artificial data. Therefore based on Table 3-1, SRP is evaluated using experimental simulation to execute the IT artifact with artificial data on one hand; and analytical method using both optimization and dynamic analysis approaches for performance evaluation purposes on the other hand.

The general experimental aim is to evaluate the algorithm’s performance under different scenarios that resemble those of real case situations. We first analyze the capability of the algorithm for finding the Search and Rescue Routes for the minimum number of first responders in order to undertake the search in the minimum time considering the constraints of the problem.
Three main scenarios are considered for evaluating the algorithm. The first scenario will look at finding initial best solutions for searching the building before physically arriving at the building. This will assist incident commanders by identifying number of crew needed to take to the scene and initial view of the structure. The second scenario then evaluates the algorithm under dynamic situations where real time environmental sensors in the building can detect dangerous or blocked areas that should be avoided from that point in time. In such case, the rescuer paths should be updated to reflect these indoor changes considering the progress of the search by rescuers to that point in time. The third scenario is the simulation of decisions made by real fire brigade participants in the agent based simulator.

For each of the scenarios and experiments, performance measures are analyzed. Here, performance is defined in terms of meeting the requirements of the objective function, solution quality, search time, response time and overlap distance. Chapter 7 will analyze and discuss the achieved results.

3.4.5 Research Communication

A design science research must be able to be presented to both a management and technical oriented community (Hevner et al. 2004). The reason being is that, the technical and research community will need enough detail to be capable of recreating the artifact and build upon further extension and evaluation of it. And the managerial community will need such detailed information for assigning resources for constructing the artifact within their organization.

The outputs of this research including findings, models, simulations, and prototype system are archived in this dissertation, publications and presentations from this research.
3.5 Chapter Summary

This chapter detailed the overall research strategy and design method employed in this research. It described the research approach undertaken to address the research questions and the identified objectives during the conceptualization phase. The Design science methodology as a common approach in research in Information Systems was justified to fit this thesis as it is used to analyze the feasibility of a proposed approach in IS by creating and evaluating IT artifacts.

Each of the phases of the Data Science Research Methodology (DSRM) consisting of; research problem identification, research design and development, research demonstration, research evaluation, and research communication were designed and explained in detail in this chapter. To design the proposed solution, a data modelling technique, mathematical modelling and optimization were adopted. To evaluate the proposed solution an observational case study and descriptive scenario method are used for evaluating the efficiency of IESM, while experimental simulation and analytical methods are used for SRP performance evaluation. That is, a proof of concept demonstration of IESM and simulation of the SRP algorithm is undertaken for a case study building under various scenarios and the results are compared for validity reasons with the simulated current movement decisions of first responders.

Having the research path clarified in this chapter, the next chapter identifies indoor emergency information requirements and presents the Indoor Spatial Emergency Model and demonstrates its applicability to indoor incident decision making.
Chapter 4

A new 3D Indoor Emergency Spatial Model
4.1 Introduction

To be able to deliver an indoor search and rescue solution that fits the emergency responders’ requirements, the solution needs to be built upon an accurate and detailed indoor model that consists of the indoor building model (containing the building geometric and semantic elements and utilities) and the indoor network model (containing the navigable model). Such model would facilitate the indoor situational awareness, route planning, and decision making procedures.

As discussed earlier in the foundation of the research, a complete inventory of the information required during emergency response as well as provision of situational awareness based on existing and dynamically created data in the field is a crucial necessity for the success of emergency management and decision making due to various views of different emergency response sectors and also the variety of types of disasters (Dilo & Zlatanova 2011). However, still there is no integrated solution for delivering building systems’ data to emergency responders (Holmberg et al. 2013).

Considering the lack of comprehensive 3D indoor models to enhance situational awareness with regards to both interiors of buildings and their surroundings, this chapter targets the first two research questions of this research introduced in the first chapter; what building information is critical for emergency responders, and how should the 3D integrated indoor/outdoor spatial model be developed? Thus, to answer these questions, the chapter designs and develops a new 3D indoor building and network model that would be leveraged for designing the search and rescue problem in Chapter 5.

For this purpose, in the rest of this chapter, first the requirements of an indoor spatial model used for emergency situations are elaborated in Section 4.2 and a new Indoor Emergency Spatial Model (IESM) is proposed accordingly to overcome the insufficiencies of current indoor modelling methodologies. The proposed model is based on the Industry Foundation Classes (IFC) (Liebich 2009) standard which is a well-known representation of BIM. However, IFC is modified to fit the proposed IESM representation. To enable navigability of the indoor environment and simplification of the building for routing and search and rescue planning, Section 4.3 presents an IESM based indoor network model by integrating both the geometric and semantic information in the route model discussing how route costs are computed in the model to fit emergency response requirements.
4.2 3D Integrated Indoor/Outdoor Spatial Information Model

Rapid development of GIS and ubiquitous computing technologies has taken the space to a further definition where the space is no more limited to outdoor environments and is also extended to indoor spaces (Li 2008). Furthermore, the importance of 3D indoor representations especially for emergency response application were discussed earlier in Chapter 2, Sections 2.4.1 and 2.4.2. Three dimensional representations of the indoor areas provide better perception and conceptualization for humans and can help in more efficient decision making especially in indoor environments (Rakkolainen & Vainio 2001). And, thus, 3D geospatial data are finding crucial applicability in many application such as cadastre information management, city planning, evacuation, emergency response, facilities and utilities management, entertainment, virtual reality, etc. (Biljecki et al. 2015).

Though various research has targeted the indoor environment to enable 3D indoor GIS for indoor services and navigation (refer to Section 2.4.1), still they can’t be applied to indoor emergency applications in their current format as they are not designed for such applications, don’t contain building information that is critical to emergency responders, don’t have network models designed for first responders’ specific navigation needs, and are rarely integrated with outdoor environments. The current models either contain too much architectural complexity (Li 2008), have visualization purposes (Kim & Wilson 2015; Goetz 2013; Kolbe 2009), are targeted for public evacuation (Umit Atila, Karas & Rahman 2013; Rakip et al. 2012; Lee 2007; Meijers et al. 2005) or see buildings as autonomous environments (Isikdag et al. 2013; Chen et al. 2015). Therefore, as discussed in Section 2.4.2, precise information about the buildings, their utilities, etc. is unknown to first responders up until arrival at the scene which increases the risk of life threats to rescuers and complicates decision making.

To have efficient indoor routing and indoor services for emergency situations, both the interior and exterior of the structures need to be modelled to contain detailed 3D geometric and semantic information required during indoor incidents. This section will discuss the critical building information requirements of first responders during indoor emergency situations and will then propose the UML class diagram suggested for the Indoor Emergency Spatial Model (IESM) accordingly. Such comprehensive 3D representation of the indoor environments would provide crucial building information to first responders prior to arriving and entering the incident scenes and would improve their ability to navigate inside the structures in a more informative which will be discussed in detail in Section 6.4.
4.2.1 Information Requirements for Indoor Incident Management

Knowledge of the incident scene and situational awareness of the environment provides the emergency responders with valuable information of available resources, the development of the hazards, as well as real time information of building data which improve first responders’ safety and response capabilities (Holmberg et al. 2013). Having information of the exact location of building data at an earlier stage removes the need of spending valuable time walking inside building floors to find the fire and utilities and will thus increase chances of rescuing civilians while exposing first responders to less severe indoor situations.

There has been a significant focus and understanding of mission critical building information for emergency response in various indoor emergency situations (Walter WW Jones et al. 2005; Yang et al. 2009; Holmberg et al. 2013). Based on these investigations, the building mission critical information required to provide situational awareness to first responders can be categorized into the following three dimensions shown in Figure 4-1.

- **Indoor Building Information**, indoor information that is critical for facilitating emergency response; information such as floor plans, secure gathering points, staircases, elevators, building type, material types, material’s behaviors in various emergency situations, emergency features such as fire panels and utility shutoffs, and existence of hazardous materials in the building.

- **Dynamic and Semantic Building Information**, which could be subject to change in time; such as indoor environmental detectors and sensors, fire sensor signals, HVAC systems, occupancy information of the building, number of people residing during different hours in the building and the accessibility of spaces as well as semantic information regarding ownership and occupancy of the building.

- **Outdoor Emergency Information**, information regarding the direct outdoor surroundings of the disaster site; such as water resources and hazards and also information of the road network and other outdoor features such as accessibility of roads to heavy fire trucks and turning restrictions in junctions.

These identified requirements will form the data model representation of the Indoor Emergency Spatial Model (IESM) presented in the following section.
4.2.2 Indoor Emergency Spatial Model (IESM) Class Diagram

Among the indoor modelling methodologies, BIMs (Underwood et al. 2007) carry comprehensive geometric and semantic information of building elements and are believed to be an important source of managing the building information during its lifecycle (Eastman et al. 2011).

To represent BIMs, IFC (Liebich 2009) is an open, international, and standardized specification which contains advanced semantics and geometries of building elements and spaces inside buildings (BuildingSmart 2008) containing many attributes that other models such as CityGML do not cover (Isikdag et al. 2013). While IFC and CityGML are well known semantic modelling representations for Building Information Modelling (BIM) and Topography Information Modelling (TIM/3DGIS), geometry, topology, and semantic information is presented and managed quite differently throughout the two models. IFC mainly uses volumetric and parametric approaches, whereas, CityGML tends to use boundary representations of building geometries (Khan et al. 2014). To benefit from both representations, researchers have tried to integrate the two representations (El-Mekawy 2010; Laat & Berlo 2011) or transforming between the
A new 3D Indoor Emergency Spatial Model

two models (Isikdag & Zlatanova 2009), and extend the models (Nagel et al. 2009; Tashakkori et al. 2015).

IFCs in their current format contain too much architectural information and are too complex to be used for indoor emergency situations. The Indoor Emergency Spatial Model (IESM) proposed here modifies the IFC classes to contain the mission critical building information and removes the unnecessary complexities of IFC to form a complete indoor data model that can facilitate indoor emergency response and management for emergency responders and decision makers.

IESM is developed to contain all the three categories of mission critical building information mentioned earlier. Figure 4-2 represents the IESM class diagram showing the objects and their relations in the geospatial environment. The spatial relationships will allow the spatial analysis on the objects in the geospatial environment. The solid lines in IESM represent the relations inside the buildings, for example how floors contain spaces and detectors. However, dashed lines form the border between the indoor and outdoor environments and how the indoor objects interact with outdoor city objects. For example, hazards that affect the building and how the indoor GNM is connected to the outdoor road network.
According to the IFC 4 Release Documentation (2013), “each object is the generalization of any semantically treated thing or process”. Key building elements such as floors, space, door, wall, window, and slab are brought into IESM just as they are defined in IFC format and attributes required for emergency management are added. Buildings are composed of multiple storeys.
Each storey contains various elements such as spaces, doors, windows, slabs, etc. with the floorID and material type being of importance for emergency responders. A short description of the main objects of IESM follows in Table 4-1.

<table>
<thead>
<tr>
<th>Object</th>
<th>Definition</th>
<th>Type of relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building</td>
<td>Inherited spatial structures which are aggregated of multiple storeys and provide a closed area for the building’s components</td>
<td>Associates with the indoor features such as staircases; the indoor graph network used for navigating, and outdoor hazards and water resources</td>
</tr>
<tr>
<td>Storey</td>
<td>Consists of building elements on the same floor which are bounded vertically</td>
<td>Is associated with all the spaces and architectural elements of the building</td>
</tr>
<tr>
<td>Space</td>
<td>Virtual elements to represent both physical and theoretical bounded areas</td>
<td>Is associated with owners of the space, occupancy information and existence of hazards in the space</td>
</tr>
<tr>
<td>Environment Detectors</td>
<td>Objects storing the physical quantity measures of indoor parameters</td>
<td>Generalization of any environment detector such as heat and smoke</td>
</tr>
<tr>
<td>Emergency Utilities</td>
<td>Emergency objects of interest inside structures</td>
<td>Generalization of all indoor emergency utilities such as gas pipes and electric shutoffs</td>
</tr>
<tr>
<td>Fire Utilities</td>
<td>Firefighting emergency facilities inside building</td>
<td>Generalization of geo-referenced and semantic information of any fire equipment such as fire hose racks, fire hydrants, and hook-ups</td>
</tr>
<tr>
<td>MaterialInfo</td>
<td>Information regarding type of material utilized in building objects and their behavior in various disasters</td>
<td>It represents a new data type that can be instantiated from any object that needs a material type such as building, wall, door, etc.</td>
</tr>
<tr>
<td>Road Network</td>
<td>Urban road network plus information describing features of road that affect emergency operations</td>
<td>Built upon junction and road type which describe the truck accessibility, width, height tolerance, turn restrictions, and weight restrictions of the roads and junctions</td>
</tr>
</tbody>
</table>

One of the main objects in IESM is the space entity and the attributes and information it carries. In particular, this object’s potential for carrying emergency related information such as occupancy information, ownership, and existence of hazards has not been considered in IFC4. As Figure 4-2 shows, this object has been modified to contain this valuable information. The geometric and semantic information about emergency utilities and detectors that gather real time information inside buildings is modelled using the Environment Detectors, Emergency Utilities, and Fire Utilities’ super classes. MaterialInfo, RoadType and JunctionType are three data type classes that hold more information regarding the material type of building features, road and junction features respectively. Such information could affect the decision plans and
route finding. For example, walking across fire resistant rooms and doors is more favorable, or some roads might not be accessible to heavy trucks due to their narrowness.

4.2.3 3D Visualization of IESM Information for Built Areas

As discussed, IESM provides a 3D framework for the necessary geometric and semantic building information for emergency managers and emergency responders on scene. While the IFC representation of a building gives a 3D view of the structural elements (Figure 4-3), detailed emergency information is missing. Thus, using the 3D model of our case study building (a block of the Engineering Building at The University of Melbourne), the model is modified in Revit; which is an architectural software aimed at assisting with building 3D models containing structural and engineering information to contain the critical emergency elements presented in IESM. Further semantic information of the building such as hazards, occupancy, accessibility, etc. are added to the exported GIS format of the model and integrated with the road network to form a complete indoor/outdoor GIS model reflecting the proposed IESM representation (Figure 4-4). Implementation details are described further in Chapter 6.

Figure 4-3 IFC representation of case study building
A new 3D Indoor Emergency Spatial Model

Figure 4-4 3D view of IESM representation of case study building

As Figure 4-4 shows, each of the objects from the proposed IESM class diagram can be viewed as a separate layer in the Esri platform; giving access to the detailed information of each object and the relations and interactions of the objects with each other. A more detailed view of the inside of the structure reveals the exact location of stairs, elevators, doors, emergency utilities in the building (the highlighted objects in Figure 4-5) which is extremely important for first responders. Moreover, each element contains the semantic information attached to it. Also, each space inside the building now contains the detailed attributes and semantic information of that area as designed in IESM. For example, Figure 4-6 shows the detailed information of a space containing hazardous material in the building. Showing the name of the room, type of hazard, if the space is fire resistant, etc. Quick access to such spatial enabled information can facilitate the decision making process for emergency planners as will be discussed in detail in Chapter 6.
A new 3D Indoor Emergency Spatial Model

Figure 4-5 Detailed indoor view of the building

Figure 4-6 Detailed attributes of a hazard space
4.3 3D Indoor IESM Integrated Geometric/ Semantic Network Model

Routing and evacuation in indoor areas is enabled by creating navigation models that are created for the indoor environments based on the structure’s geometry model which allows visualization and cost computation (based on distance or optimality). The accuracy of an indoor routing algorithm targeted to the emergency operations is reliant on a detailed graph model of the indoor thematic contextual spaces based on the navigation requirements (OGC et al. 2014) of the emergency crew.

The focus of navigation in indoor areas is not only on the architectural components, but also on the spaces that are created by the architectures which should be seen from the cellular space, semantic, geometric, topological, and multi-layered aspects (OGC et al. 2014). The network and topology representation of the cellular space is an essential component for guiding the emergency responders inside the buildings and for finding the search and rescue paths. Although, there are various strategies for building the indoor navigable models (discussed in Section 2.4.3); since IESM is based on the integration of semantic and geometric information with the cellular spaces inside the structures, the indoor network construction will be based on navigable graphs with adjacency and connectivity. The next section will discuss in detail how the navigable graphs are constructed for the indoor environments using IESM.

4.3.1 Indoor Navigable Graph Construction

Various approaches exist for modelling the graph of indoor structures to enable routing computation. In most of these methods, topological structures of buildings are derived using the geometries of buildings. Amongst all these methods, Conventional Dual Graph Approaches (Lee 2001) are the most common method used. The dual graph approaches are based on the Poincare Duality Theory to convert the Room - Door relations to Node - Edge relations for complex spatial relationships between 3D objects (Chen et al. 2012). 3D objects such as rooms in the primal space are mapped to vertices in the dual space. The shared face between the two objects is then mapped into an edge in the dual space (Figure 4-7). Amongst the indoor network models proposed, Lee (2004)’s Geometric Network Model is well known for representing the indoor environments (Figure 4-8). The topological model is derived using the geometrical metrics of a building and the Straight-Medial Axis Transformation (S-MAT) modelling method which can abstract polygons into linear features. The S-MAT representation...
has limitations in finding door-to-door routes for pedestrians (Liu Liu & Zlatanova 2011) and has problems in complex irregular indoor structures. The indoor space could also be decomposed into cells for creating the graph structure (Lorenz et al. 2006). The explicit presentation of the cells in the graph and their connection to the cell centers might result in unnecessary twisted routes. The Multi Layered Space-Event Model (MLSEM) was proposed to enable the representation of different thematic decompositions of indoor spaces (such as topographic space, sensor space) through multiple layers of space (Becker et al. 2009).

![Figure 4-7 Poincare Duality](Wu & Chen 2012)

![Figure 4-8 Node Relation Structure](Lee 2004)
As the majority of indoor data models are based on CAD representations of the buildings, they suffer from common issues such as architectural elements are not seen in the models, the routes constructed for them are not human friendly, dynamic changes and obstacles are ignored, and the granularity of abstraction for the elements in the building are too course. Thus, to have more accurate representations of indoor areas, 3D semantically rich data models such as IFC and CityGML are being used for improving the indoor connectivity graphs (Mortari et al. 2014). The topographic and semantic information provided by such building models can provide the necessary information for various applications. Thus, IndoorGML is introduced as a complementary standard to CityGML, KML, and IFC which consists of geometric and semantic information required for various indoor location based services. To overcome the issue of detailed navigable indoor graph structures for various navigation requirements Khan et al. (2014) present an automatic approach to generate IndoorGML datasets from existing IFC or CityGML datasets by converting the 3D building models presented in IFC to CityGML and then to Indoor GML as shown in Figure 4-9.

Figure 4-9 Generation of IndoorGML datasets from TIM and BIM (Khan et al. 2014)
An important fact is that complex building geometries contain great numbers of vertices and edges in the graph, thus increasing the evacuation and rescue algorithm's running time and complexity significantly. Therefore, complex structures such as grid and triangulated graph constructions are not favorable. Moreover, routing algorithms consisting resource allocation and sequencing of node visits are mainly based on TSP and VRP which makes them NP-hard and dependent on the number of nodes and edges in the graph. Therefore caution needs to be taken regarding the complexity of the indoor network. Consequently, the routing algorithm for routing emergency responders inside the building and assigning the search and rescue paths in this research will be based on Lee’s Node Relation Graph (NRG) which has a sparser graph representation compared to the other representations of the indoor areas.

4.3.2 Indoor/Outdoor Graph Construction for First Responder Route finding and Search and Rescue Operations

Indoor environments need to be modelled precisely to reflect all the navigable locations in the building for an efficient and accurate algorithm that can find best paths for first responders inside structures either for directing them towards specific locations inside the building or for finding the search and rescue paths. Horizontal slabs, vertical access points like stairs and elevators, entrance and exit points, rooms and corridors, hazard points, accessible and non-accessible areas, etc. should all be well represented in the navigable model. Distance based route graphs that only rely on the lengths of edges for finding shortest path algorithms are not sufficient for emergency response requirements in indoor areas. Moreover, 3D geometric and semantic information of the indoor elements such as doors, window heights, and corridor width as well as other semantic information such as accessibility of specific points, door types (entrance or exit), window types (whether they can be used as exit points), hazard status in rooms, etc. play a crucial role in how the route graphs are defined (Lin et al. 2013). Hence, new approaches have been developed for indoors based on the 3D aspects of such structures which contrary to traditional 2D representations contain semantically rich 3D information essential for path finding and navigation (Tashakkori et al. 2015; Isikdag et al. 2013; Chen et al. 2014).

As the time spent by first responders on scene using the models is very short, the information presented to them regarding the building must be chosen carefully (Walter WW Jones et al.
A new 3D Indoor Emergency Spatial Model

2005). The 3D Indoor Emergency Spatial Model (IESM) developed, specifically addresses the emergency responders’ requirements consisting indoor building information, dynamic information, semantic information of components, and outdoor emergency information (Section 4.2.1). IESM modifies IFC to contain mission critical data required by emergency responders on scene and thus can be used to create and enrich the indoor route graphs for emergency response specific applications (Tashakkori et al. 2015).

The integration of the aforementioned IESM information (Section 4.2.2) into the navigable indoor graph allows routing decisions that are specific to first response operations. Also the semantic information in IESM enables finding routes that fit various users and their needs; such as decisions on whether or not to use the elevators or adjusting the graph to find best paths based on time, distance, wheelchair accessibility, heavy equipment accessibility, etc. (which could be achieved by overlay graphs or weight adjustment). In addition, IESM enables the integration of the indoor network with the so called “road network” by identifying the main access points (entrances and exits) of a building and projecting them onto the road network allowing seamless transition between the indoor and outdoor areas.

The IESM representation of the building (Figure 4-10) and the 2D floor plans are used to structure the 3D indoor Geometric Network Model using Lee’s node-relation structure. Using this model as shown in Figure 4-11, rooms, doors, and, windows that can be used as access points, form the nodes of the network; while corridors, staircases and elevators form the edges and enabling connection of floors together (look at Figure 4-11). To enable the seamless connection between the indoors and outdoors, all doors and windows that have the potential to be used as access points to the building are connected directly to the outdoor road network. Figure 4-12 shows how the access points connect the indoor and outdoor networks to create an integrated indoor/outdoor navigable network.

Although, there are various ways to automatically generate the indoor navigable model from 2D CAD plans (L Liu & Zlatanova 2011; Mortari et al. 2014), OpenStreetMap (Goetz 2013), IFC and CityGML (Khan et al. 2014), etc. most of these methods have limitations in how much detail they can generate automatically. Moreover, as the automation process is out of the scope of this thesis, the network model is extracted manually from the IESM representation to reflect all the required attributes.
Figure 4-10 IESM representation of building

Figure 4-11 IESM based GNM extraction for the Infrastructure Engineering building
4.3.3 Semantically Rich Indoor Graph Network

As mentioned above, the integration of IESM information into the navigable indoor graph allows routing decisions that are specific to first response operations. This can be possible by integrating the semantic information of building elements from IESM by labelling the related nodes and edges in the graph. For simplicity, only attributes effective on route optimization in SRP have been considered. Table 4-2 shows how the building attributes are attached to each of the network elements. As could be seen in this table, some attributes are common among all the features, such as floor number which allows categorizing the network based on the floor they belong to. Thus, this attribute is attached as a label to the nodes and edges in the network. However, other attributes are more specific to a particular feature. For instance, nodes that represent doors in the network carry special attributes to identify them as room, door, main exit, main entrance, fire door, or fire resistant. Also, as described in IESM, each space in a building is mapped to a node in the graph which holds critical information regarding that space, such as if it contains hazardous material, type of the hazard, owner information, as well as occupancy information. All of this information can be labelled on the node and stored in the indoor GNM for emergency response path finding in the network. Therefore, for example if it is important for first responders to quickly locate the hazard points in the building and...
search those points first, they can easily identify them and run the SRP for those specific areas first.

### Table 4-2 IESM integration into the indoor GNM

<table>
<thead>
<tr>
<th>GNM Feature</th>
<th>Labels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Node</strong></td>
<td>Segment Type (door, window, roof, slab, stair, elevator, etc.)</td>
</tr>
<tr>
<td></td>
<td>Floor no</td>
</tr>
<tr>
<td></td>
<td>Has Hazard</td>
</tr>
<tr>
<td></td>
<td>Accessibility</td>
</tr>
<tr>
<td></td>
<td>Ownership Information</td>
</tr>
<tr>
<td></td>
<td>Is fire door</td>
</tr>
<tr>
<td><strong>Edge</strong></td>
<td>Segment type (slab, stair, elevator)</td>
</tr>
<tr>
<td></td>
<td>Floor no</td>
</tr>
<tr>
<td></td>
<td>Has Hazard</td>
</tr>
<tr>
<td></td>
<td>Accessibility</td>
</tr>
<tr>
<td></td>
<td>Traversing Time</td>
</tr>
<tr>
<td></td>
<td>Traversing Distance</td>
</tr>
<tr>
<td></td>
<td>Fire Resistance</td>
</tr>
</tbody>
</table>

4.3.4 Route Cost Computation

Route finding algorithms need weighted underlying graphs. To determine the costs on the network links\textsuperscript{10}, it should be noted that traversing speeds of various types of segments in the building differ with one another. Moreover, the time traversed is not in direct relation with distance. While elevators have the quickest movement speed inside a building, walking speed on slabs or horizontal spaces is slower compared to elevators and quicker compared to vertical stair segments. To allow discovery of quickest rescue paths, traversing time of edges are found using Equation 4-1.

\textsuperscript{10} Graph edges, links, segments are used interchangeably
\[ t_{ij} = \frac{d_{ij}}{s_{ij}} \]  \hspace{1cm} \text{Equation 4-1}

Where:

\( t_{ij} \) is the traversing time of edge \((i, j)\)

\( d_{ij} \) is the distance of edge \((i, j)\)

\( s_{ij} \) is the speed of edge \((i, j)\)

Here, similar to previous work, the average travelling speeds on the road are assumed to be 40 km/h, walking speed on horizontal segments is considered 25 meters per minute while the speed for climbing stairs is assumed 15 meters per minute (Kwan & Lee 2005) and office elevators are assumed to move at an average speed between 4 to 9 m/s, which here we have used the average of 6 m/s. Although, the use of elevators is discouraged in emergency situations, some research show that they are a necessity and the usage is unavoidable (Aleksandrov et al. 2015). Storing the type of vertical slabs in the network structure (stairs or elevators), gives the opportunity to swap between decisions of either utilizing the elevators or not in the routing strategies. Accordingly, the cost of each edge is a function of time and its accessibility derived from the equation below:

\[ c_{ij} = t_{ij} \times a_{ij} \]  \hspace{1cm} \text{Equation 4-2}

Where:

\[ a_{ij} = \begin{cases} 
1, & \text{if } (i, j) \text{ is accessible} \\
\infty, & \text{if } (i, j) \text{ is not accessible}
\end{cases} \]
Here $c_{ij}$ is the cost of each edge from node $i$ to $j$, $t_{ij}$ is the speed and $a_{ij}$ shows the accessibility of the edge. If the edge is not accessible in the graph meaning the location is blocked or inaccessible in the building, it is impossible to use that edge, so the cost of traversing it will be set to infinity; avoiding any passage from that link.

Any route found in the network will have a total traversing time that is a combination of the three types of segments that are used to traverse the path calculated using Equation 4-3.

\[
\sum_{i,j \in E} x_{ij} \frac{d_{ij}}{s_{\text{horizontal}}} + y_{ij} \frac{d_{ij}}{s_{\text{stair}}} + z_{ij} \frac{d_{ij}}{s_{\text{elevator}}} + r_{ij} \frac{d_{ij}}{s_{\text{road}}}
\]

Equation 4-3

Where:

$D_{\text{horizontal}}$ distance walked horizontally indoors

$D_{\text{vertical}}$ distance walked vertically indoors (like stairs)

$D_{\text{road}}$ distance traversed on road

$s_{\text{horizontal}}$ horizontal indoor walking speed

$s_{\text{stair}}$ stair walking speed

$s_{\text{elevator}}$ elevator speed

$s_{\text{road}}$ road speed

And:

\[
x_{ij} = \begin{cases} 1, & \text{if } (i,j) \text{ is used on tour and type = horizontal slab} \\ 0, & \text{otherwise} \end{cases}
\]
The graph network with the above cost assignments based on the semantic information, now allows finding shortest paths seamlessly for first responders and allows the proper formulation and solution development for the Search and Rescue Problem which will be given in Chapter 5.
4.4 Chapter Summary

Considering the lack of comprehensive 3D indoor data models developed specifically for enhancing situational awareness about both interiors of buildings and their surroundings in case of indoor disasters, this chapter proposed the new 3D Indoor Emergency Spatial Model (IESM) to assist rescuers in planning for emergency response in a timelier manner. IESM is based on the IFC representation of BIM which contains advanced semantics and geometries of building elements and spaces inside buildings. The data model presented for IESM takes out the unnecessary complexities of IFC and integrates it with mission critical data required by emergency responders in case of indoor disasters. The model is integrated with the outdoor spatial information to form a complete 3D indoor/outdoor GIS.

To enable route planning for first responder movement and developing the search and rescue algorithm, IESM was utilized to extract a 3D indoor GIS integrated geometric/semantic network model. Lee’s node relation structure was used for constructing the topology of the network and the emergency critical information was retrieved from IESM to semantically enrich the network. Accordingly, the edge costs were computed on the network to create a complete representation of the integrated network.

The presented IESM model and the 3D IESM integrated geometric/semantic network model can now be utilized to formulate and solve the Search and Rescue Problem for finding the optimum searching paths in an incident building, identifying the number of crew and the designated route for each person to minimize total response time. The formulation and solution approach for the Search and Rescue Problem will be discussed based on the building elements and semantic information modelled in IESM, in the next chapter.
Chapter 5
Spatially Enabled 3D Indoor Search and Rescue
5.1 Chapter Introduction

Continuing from the 3D Indoor Emergency Spatial Model (IESM) and the integrated semantically enriched network model presented for indoor situational awareness in Chapter 4, this chapter focuses on the third research question of this thesis: “Can a new solution to the Indoor Search and Rescue Problem be provided?” The aim is to present a solution approach that finds the minimum number of first responders required and the way they should be dispatched inside the building in order to minimize the overall time spent traversing inside the building.

Having the 3D indoor IESM targeted at first responders, the model can be leveraged for presenting a solution approach to the Search and Rescue Problem (SRP). To answer the third research question and find a solution to the Search and Rescue Problem, this chapter models SRP as a combinatorial optimization problem and presents an integer programming mathematical formulation to it. The navigable network is based on the 3D Indoor/outdoor Geometric Network Model (GNM) proposed in Chapter 4 in order to integrate both geometric and semantic information of the building in the route finding algorithm. As discussed later in this chapter, formulation of SRP proves it to be in the category of Travelling Salesman Problem subclasses and is classified in the NP-hard problems. Thus, exact algorithms will be unable to find optimal solutions in polynomial time. Therefore, heuristic and metaheuristic approaches should be used to solve the problem. Thus, an Ant Colony Based Optimization Technique is proposed in this chapter to solve SRP and find near optimum solutions to the problem in reasonably short time for both the static and dynamic case.

5.2 Search and Rescue Problem in Complex Indoor Environments

Although vast amounts of research have focused on improving evacuation of public through buildings and assisting them in finding quicker, shorter paths for exiting the buildings, the matter has not gained much attention from the opposite point of view for emergency responders. First responders need plans for entering the buildings to search for something which could be the location of the fire, potential victims, interior fire conditions, power utilities, etc. Above that, they are required to remove victims physically from the dangerous areas to a safe location (Bricault 2006). The two actions are widely used among fire services as “Search and Rescue”.

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As discussed earlier in Section 2.2.1, the indoor search and rescue operations face a big deal of complications and uncertainties due to unavailability of indoor information and optimized search paths prior to entrance to the premises. Such complications include but are not limited to: visual distractions caused by smoke, blockage of certain areas, limitation of navigable spaces caused by walls and barriers, wandering inside the building due to uncertainty of routes, probability of getting lost or repeated traversal of same areas. All of which exposes rescuers’ lives to more danger and risk.

Firefighting strategies for indoor structures have been analyzed by many researchers by field work with fire brigade teams (Denef et al. 2008; Dyrks et al. 2009; Wilson et al. 2005). To understand these tactics and procedures used by firefighters on the scene, the Fire Information and Rescue Equipment (FIRE) team at The University of California Berkeley conducted interviews with 50 firefighters and three fire chiefs. Their findings show that firefighters need to make guesses of the ignition point of the fire and its movement in the building based on the sequence of the alarms activated or by occupants or smoke coming out of the windows (Wilson et al. 2005). Moreover, they don’t carry a map of the building with them due to difficulties of reading when on the mission in the building. To be able to locate themselves and find routes out in smoke and dark situations during the search operations, they unreel ropes called lifelines or fire hoses along the way. Knots are tied along the way to mark the important locations and doors are marked with crayons. Moreover, they are trained to use the right or left hand technique to orient and navigate through a room when visual quality is low. Furthermore, thermal imaging cameras are used to find people and visualize the walls, doorways and windows in poor vision conditions (Safety Health and Survival Section International Association of Fire Chiefs 2012). However, there are various incidents which these techniques haven’t worked and have resulted in loss of fire fighters in the environment and suffocation to death (The National Institute for Occupational Health and Safety (NIOSH) 2016). Moreover, getting lost in a building, disorientation, miscommunication of locations and spaces, and not knowing the paths cause huge amounts of casualties in indoor structures (Safety Health and Survival Section International Association of Fire Chiefs 2012). And in fact, getting lost inside the buildings, disorientation and inability to locate the victims have been identified by NFPA (The US National Fire Protection Association) and NIOSH (The US National Institute for Occupational Safety and Health) as main factors of firefighter fatalities (Fahy 2002; The National Institute for Occupational Health and Safety (NIOSH) 2016).
To decrease the risks of fatalities caused by getting lost in buildings, the incident commander should know the location and status of all firefighters and be aware who is inside or outside the building. However, it is difficult to keep track of indoor locations of crew members. Thus, a rapid intervention team is always placed as backup rescue firefighters that unexpectedly get trapped or lost in the building. The rapid intervention is risky and time consuming. Research done by Phoenix Fire Department found that it will take several members to rescue a downed firefighter and there is a high probability of these rescuers becoming disoriented during the search process (Phoenix Fire Department 2009) and thus it is preferable to avoid such incident up comings by provision of indoor situational awareness and path guidance inside the building prior to entrance.

The size-up information assists the incident commander in predicting the conditions for planning. This pre-fire planning is extremely important for the success of the structural fire attacks (FEMA 2012). Two way communications should be maintained with the firefighters and change in the conditions should be reported to interior crew quickly. The action plan should be revised based on progress reports and the location and status of all firefighters should be insured at all times.

Still, searching the interiors of a building is a quite challenging task considering the complexity of the structure and the various entrances, exits, stair cases, elevators, doors, and windows that can be used as exit points as well as unfamiliarity with the areas and visual distractions. Moreover, slower walking speed, uncertainty of paths, navigation restrictions caused by bounded walls and navigable spaces cause higher indoor travel times compared to outdoors (Kwan & Lee 2005). While many research address routing and navigating inside buildings (Fallah et al. 2013; Afyouni et al. 2012), most of such research focus on how to traverse between two specific points for evacuation and optimal route finding for moving people from affected areas to safer locations (Tang et al. 2014) and thus can’t be utilized for the indoor search and rescue operations.

From the point of an emergency response, the incident commander is required to know about the building layout (such as the stairs, exits, occupant number, etc.), location of the crew members in the incident and the parts of the building that have already been searched to avoid multiple visits of the same room and failing to visit another. Valuable time could be wasted for searching the same room twice or failing to search another. The rescue team should be able to locate a firefighter if he/she signals a distress call and the incident com-
manders are required to have information of the building elements. There are various incidents of firefighter deaths due to disorientation and running out of air. Thus, several reports highlight the importance of tracking and navigation systems for buildings as well as sharing building information with fire departments and using Computer Aided Dispatch Systems (CAD) for pre-incident planning.\(^{11,12}\)

There has been some effort to address the search and rescue problem in literature using spatio-temporal analysis for a single rescuer TSP route (Wu & Chen 2012) or using a time-dependent vehicle routing approach for finding rescue routes from victim to victim on 2D floor plans (Chen et al. 2015). However, these methods lack integration with building semantic information, don’t see the indoor environments in their 3D context as an integrated part of the outdoor GIS. Moreover, the dynamic case of the problem which is subject to changes in the environment is left unconsidered.

Therefore, considering the limitations and challenges of current practice and research systems, this chapter introduces and solves SRP to take out the guessing and risk factor of path decisions and crew dispatch strategies in indoor environments.

### 5.3 Search and Rescue Problem Formulation

As discussed in Section 4.3, path finding and movement of occupants and first responders relies on the availability of an accurate underlying navigable model that represents the topological, geometric, and semantic aspects of the environment and thus, the 3D IESM integrated geometric/semantic model was presented to fit the navigation requirements of first responders in indoor incidents. Using this underlying graph network, this section will define and formulate the Search and Rescue Problem mathematically.

The problem of indoor search and rescue can be defined as follows: Given a network dataset of a building on a graph \( G = (V, A) \), where \( V \) is the set of \( N \) nodes (vertices) and \( A \) is the set of arcs (edges) and \( C = (c_{ij}) \) is the cost associated with traversing each edge, where \((i, j) \in A\), let there be \( k \in \{1, 2, \ldots, K\} \) responders that are located on the street closest to the build-

\(^{11}\)http://www.cdc.gov/niosh/fire/pdfs/face200718.pdf
\(^{12}\)http://www.cdc.gov/niosh/fire/pdfs/face201314.pdf
ing. There are M points of entry to the building that can be either used for entrance or exit which we generally refer to as access nodes. The remaining nodes (rooms, corridors, etc.) that are to be visited are referred to as intermediate nodes (Figure 5-1). The Search and Rescue Problem (SRP) then consists of finding tours for K responders, who all start from an access node and finish at an access node, such that each intermediate node is visited exactly once, and the total number of responders and total cost of visiting all nodes are minimized.

Let’s consider the set of nodes in the network to be \( V = \{0, 1, 2, ..., M, ..., N\} \), \( |V| = n \). The problem should be formulated in a way that also suggests best access nodes both to enter and exit the building in order to maximize routing efficiency. Therefore, we propose adding an extra virtual node mapped outside the building that connects all the exit nodes (Figure 5-1). We refer to this node as a depot node where all responders start and finish their traversing path. All the edges connecting the depot node to the exit nodes will have the same cost of zero which forces all responders to enter the building from an access node and finish their route by exiting through an access node. Node 0 is regarded as the depot node, and nodes \( \{1, 2, ..., M\} \) are the access nodes. The rest of the nodes \( \{M + 1, ..., N - 1, N\} \) are the nodes that should be visited in the graph. As seen in Figure 5-1, all doors in the building that could be used for entering or exiting the building are connected to a virtual node (the red node) which will set the start and finishing of all routes found in the building. This kind of initiation of the problem would force all routes to start from an access point and finish their route exiting from an access node. As the costs of the edges between the depot node and each access point is zero, all entrance points have the same probability of being chosen in the routes and in fact the overall route cost in the building will determine which access points are assigned to which routes.
Such formation of the indoor network dataset will allow the following integer programming formulation of the SRP. We first define the following binary variable:

\[ x^k_{ij} = \begin{cases} 
1 & \text{if arc } (i,j) \text{ is used by responder } k \\
0 & \text{otherwise} 
\end{cases} \]

A general scheme assignment-based directed integer linear programming formulation of the SRP can then be given as follows:

\[
\text{minimize } F_k + \sum_{k \in K} \sum_{\substack{i,j \in V, i \neq j}} c_{ij}x^k_{ij} \\
\text{Equation 5-1}
\]
Such that:

\[ \sum_{i<j, i \in V, j \in V} c_{ij} x_{ij}^k \leq T_k \]  
Equation 5-2

\[ \sum_{k \in K} \sum_{j \in V} x_{0j}^k \leq K \]  
Equation 5-3

\[ \sum_{k \in K} \sum_{j \in V} x_{j0}^k \leq K \]  
Equation 5-4

\[ \sum_{j \in V} x_{0j}^k = 1 \]  
Equation 5-5

\[ \sum_{j \in V} x_{j0}^k = 1 \]  
Equation 5-6

\[ \sum_{i=1}^{M} \sum_{j=M+1}^{N} x_{ij}^k = 1 \]  
Equation 5-7

\[ \sum_{i=1}^{M} \sum_{j=M+1}^{N} x_{ji}^k = 1 \]  
Equation 5-8

\[ \sum_{k=1}^{K} \sum_{i \neq j, i \in \{M+1, ..., N\}} x_{ij}^k = 1 \]  
Equation 5-9

\[ \sum_{k=1}^{K} \sum_{i \neq j, i \in \{M+1, ..., N\}} x_{ji}^k = 1 \]  
Equation 5-10
\[ u_i - u_j + px_{ij} \leq p - 1 \text{ for } 2 \leq i \neq j \leq n \]  

Equation 5-11

In the equations above, the objective function given in Equation 5-1 minimizes the total cost of travel of all the responders in completing their tours to search the building. An extra cost is incurred for assigning each extra responder to the problem \( F_k \). Thus, this would enable finding minimum number of responders required to search the area. Each route is assigned to one responder and the cost of the route corresponds to the sum of the arcs forming the route plus the fixed cost of associating a rescuer to that route. The rest of the equations (Equation 5-2-Equation 5-11) set the constraints of the problem to ensure the conditions are met.

The first constraint in Equation 5-2 ensures that the maximum time spent by each rescuer on the tour is less than the time limitation that person has (which is the maximum time the oxygen tank allows the person to traverse the indoor area without exposing him/her to danger). The constraints in Equation 5-3 and Equation 5-4 guarantee that the number of tours are K by selecting at most K outgoing and K ingoing arcs from the depot \((i=0)\). Equation 5-5 ensures that for each responder, exactly one outgoing arc from the depot is selected. Similarly, Equation 5-6 ensures that for each responder, there is exactly one arc entering into the depot node \((i=0)\). Therefore, Equation 5-5 and Equation 5-6 make sure that there is a complete tour for each responder in the network.

Equation 5-7 makes sure that each responder enters through an exit node exactly once to enter the building. And Equation 5-8 makes sure he/she leaves through an access point towards the depot to finish the tour. These two constraints ensure each route traversed by a responder starts from a depot node, continues through exactly one access node and finishes at an access node which could either be the same node it entered from or it could be a different access node. This type of formulation allows responders to be routed through the best entrance and exit doors and will not force every responder to enter from the same point; allowing optimized indoor/outdoor route integration. The important thing is to ensure that the total number of entrances and exits used each way are equal to K. That is, an access node might get used several times by various responders or might not be used at all.

The constraint of Equation 5-9 makes sure that from each node other than the depot and exit nodes, only one arc emanates from that node for all responders in the solution. Equation 5-10
also ensures that for each node \( j \) other than the depot and access nodes, only one arc enters into it between all responders in the solution. These two constraints together guarantee that for all nodes except \( \{0, 1, \ldots, M\} \) each node is only visited by one responder in the solution. Thus, distributing the available resources in the network in an efficient manner.

The final constraint given in Equation 5-11 aims at sub tour elimination in the problem based on (Miller et al. 1960). In this constrain \( p \) denotes the maximum number of nodes visited by a person and the node potential \( u_i \) shows the order of visiting the node in the tour.

All these constraints together make sure the conditions of the problem are met and the solution approach will find the best fit for solving it.

The formulation of the problem shows that it could be regarded as a modified multiple Traveling Salesman Problem (mTSP), which finds the routes for \( m \) salesman located at a single depot who aim to visit the rest of the nodes (places) in the network such that each place is visited exactly once and the total cost of visiting all the nodes is minimized (Bektas 2006).

There are many variations to mTSP such as single vs. multiple depots, bounded or fixed a priori number of salesman, fixed charges for adding each salesman, time windows consideration, other bounds limiting the number of nodes or distance each person visits. The mTSP and its extensions such as the Vehicle Routing Problem (VRP) are Integer Linear Programming problems and thus are NP-hard (Bektas 2006). Thus, heuristic and metaheuristic approaches are required to solve the SRP. Here we propose an ant colony based approach for solving the SRP explained in detail in the next section.

5.4 Ant Colony Based Algorithm for Solving SRP

The formulation of the Search and Rescue Problem given in the previous section shows that it is an integer linear programming problem, which can also be regarded as a modified multiple travelling salesman problem, putting it in the category of np-hard problems where a solution can’t be found in polynomial time. Moreover, solving such problems using exact optimization methods is very difficult in acceptable CPU times especially for real world large data sets such as buildings which have hundreds to thousands of nodes. Thus, heuristic and metaheuristic algorithms are more favorable in such problems.
To solve similar categories of problems, Ant Colony Optimization (Dorigo et al. 2010), Genetic Algorithms, Greedy Randomized Adaptive Search Procedure (Feo & Resende 1995), Simulated Annealing, Tabu Search (Osman 1993), Variable Neighborhood Search (Mladenović & Hansen 1997), and hybrid metaheuristics (Gendreau & Potvin 2010) are all strong metaheuristics with outstanding performance. Each of these methods differs based on the applications they best fit and the time they take to converge to the optimum solution as well as the quality of the solution. The indoor graph is a sparse network where the solutions are limited. Also, SRP doesn’t have as many limiting constraints as there are in problems such as the Vehicle Routing Problem (VRP). Amongst the various metaheuristic approaches used, Ant Colony Optimization techniques have shown promising results (Dorigo et al. 2010; Ghafurian & Javadian 2011; Montemanni et al. 2005) and thus a solution based on the ant colony system is proposed for solving SRP in this thesis. This section will give a brief overview of the ant colony optimization algorithm and will propose the ant colony inspired algorithm for solving the search and rescue problem for the initial static state of the problem when no building environmental information is available as well as the solution approach under dynamic changes to the environment.

5.4.1 Ant Colony Optimization

Ant Colony Optimization (ACO) is a strong category of metaheuristic algorithms based on the real ants behavior to forage food (Maniezzo & Carbonaro 2002). ACO algorithms have promising results for TSP (Dorigo et al. 2010) and its generalized form the Vehicle Routing Problem (VRP) (Gambardella et al. 1999) and thus is being applied to more recent applications such as optimizing evacuation routes inside buildings (Amalina et al. 2016).

The basic ant colony algorithm is based on the idea of parallelizing the search over multiple computational threads using a dynamic memory that saves the effectiveness of the previous results and uses that to improve the behavior of each single agent mimicking that of the behavior of real ants (Maniezzo & Carbonaro 2002). Each ant constructs a solution for the problem iteratively by choosing the next state in each iteration according to a probability distribution based on the attractiveness of the move and the desirability or trail level of that move by past ants. In each iteration, the trail levels, also called pheromone, are increased for more attractive solutions making them more desirable for the rest of the agents. Meanwhile, a tabu list keeps track of the infeasible moves during the iterations to avoid infeasible solutions. After
all ants have completed their solution in the iteration, the trails are updated with attractiveness and the colony moves to the next iteration. The general structure of an Ant Colony Optimization algorithm is as follows (Maniezzo & Carbonaro 2002):

Step 1. (Initialization)
   Initialize $\tau_{ij}, \forall (i,j)$

Step 2. (Construction)
   For each ant $k$ do
   repeat
   compute $\eta_{ij}, \forall (i,j)$
   append the chosen move to the $k$-th ants set $\text{tabu}_k$
   until ant $k$ has completed its solution
   carry the solution to its local optimum
enddo

Step 3. (Trail update)
   For each ant move $(ij)$ do
   compute $\Delta \tau_{ij}$
   update the trail matrix
endo

Step 4. (Terminating condition)
   If not (end condition) go to step 2

Figure 5-2 ACO general structure psuedo code (Maniezzo & Carbonaro 2002)

In the above algorithm, the partial problem solutions are seen as states; each ant moves from a state $i$ to state $j$ towards completing the solution. The attractiveness of the move is shown with $\eta$ while $\tau$ represents the trail level, and $\Delta \tau_{ij}$ is the sum of contributions of all ants that used move $(i,j)$. As the algorithm starts, the trail levels are initialized on the network. Then the algorithm starts building solutions for all ants where each ant decides the next move from one state to the next towards completing the solution using a probability function based on the attractiveness and level of trail. Once all ants have built their solutions, their solutions are compared and trails are updated by emphasizing the trail level on favorable solutions that contributed to better solutions. The algorithm repeats the iterations from there until the terminating condition is met which. The termination condition is mostly the point when no further improvement is seen in the solution for a certain number of iterations.
The ant colony algorithm has been modified in different variations such as the Max-Min Ant System, rank-based Ant System, Ant System with elitist strategy (AS_{elite}), Ant-Q, etc to fit the different application’s requirements (Dorigo et al. 2010). The main difference between these approaches is the decision strategies for choosing next moves and updating the trail levels (Maniezzo & Carbonaro 2002).

5.4.2 ACO for SRP

To address and solve the Search and Rescue Problem based on the conditions of the problem, an ant colony based algorithm is presented in this dissertation. As described earlier in Section 5.2, the Search and Rescue Problem aims at finding the minimum crew required to search an entire building or points of interest inside the structure in the minimum time.

The ACO heuristic developed for SRP plants a colony of agents/ants at the depot node right outside the building to explore the network for best solutions. Each ant in the colony represents a complete tour of all rescuer paths inside the building. That is, each ant holds the paths of all first responders in the indoor network. Therefore, a complete tour found by an ant represents all rescuer paths and is constructed incrementally selecting rooms and points of interest in the building until all these points have been visited. This tour will determine the number of first responders required and will show their individual paths starting from the depot node, going through a door, traversing unvisited nodes in the network and exiting through the closest door towards the depot considering their constraints.

To minimize the number of rescuers while controlling the maximum time one responder spends inside the dangerous areas as well as balancing the traversal times amongst the rescuers, a similar concept to that of Distance Constrained Vehicle Routing Problems from (Laporte et al. 1987) is used in which next best nodes are gradually added resulting in more time efficient routes which do not violate the upper bound time threshold. Therefore, a constraint of maximum threshold time a rescuer can spend inside the building before exiting it is considered to control the number of rescuers and balance the routes amongst them. Here, the oxygen masks’ limitations are assumed for assigning this threshold time; i.e. a typical 2261 psi oxygen tank of a Self-Contained Breathing Apparatus (SCBA) can usually last about 30 minutes based on the ordinary respiration rate of 24 breaths per minute. However, this time is based on an average mail breathing speed under normal activities and the same cylinder can only last be-
tween 6 to 21 minutes for heavy firefighting activities (Marino 2006) and the time threshold should be adjusted accordingly.

Although all points are required to be visited only once by a responder, decreasing the travelled time and distance by using the shortest path between nodes can be beneficial. In such situations, some points may be crossed more than once to save time and thus the cost between node \(i\) and \(j\) will be replaced with the cost of the shortest path between the two nodes (Laporte et al. 1987). This is especially important for indoor environments where stairs and elevators as well as corridors might be passed several times to visit rooms, etc. For this reason, a weighted adjacency matrix is used to hold shortest paths between each two points in the network. Therefore, the probability of visiting the next node on the path is dependent on the cost of shortest time between the two nodes. The nodes visited on the shortest path towards the next chosen state will be placed in the visited list and the algorithm will avoid visiting such nodes unless they fall on the route to visit another node and avoiding them is absolutely impossible.

In each iteration of the algorithm, each ant builds a complete solution of search routes in that iteration based on attraction and pheromone levels of moves. Once all ants have found their solutions, the pheromone levels are updated proportional to the inverse of the total cost of the solution (i.e. time). Thus, leaving more pheromone on better/quicker routes making them more favorable compared to slower paths for the next iteration of ants. Once the iteration is finished, all ant tours are compared and the best solution found so far is updated. Before moving to the next iteration, pheromone evaporation happens on the entire network to increase the exploration capability of ants and to forget weaker solutions. Then the algorithm moves on to the next iteration with a fresh colony of ants and repeats the algorithm until the termination condition is met, here meaning until a certain number of iterations without improvement have been passed.

During the running of the algorithm, each ant selects the next unvisited point according to the transition rules which are based on a combination of the closeness of each arc and the amount of pheromone that lies on it. During the iterations, a tabu list holds the set of already visited points that should be avoided by the ant in the current iteration. A Pseudo-Random-Proportional rule is used for choosing the next point to visit in the network in which a combination of random selection and best option is used. For exploitation of the best solutions, the probability of visiting the next point \(j\) from point \(i\) is calculated using the following equation:
\[
    p_{ij} = \frac{(\tau_{ij})^\alpha(\eta_{ij})^\beta}{\sum_{u \in M_k}(\tau_{ij})^\alpha(\eta_{ij})^\beta} \tag{Equation 5-12}
\]

In this equation \( \tau_{ij} \) is the amount of pheromone on arc \((ij)\), \( \tau_{ij} \) represents the pheromone level on the arch, \( \eta_{ij} \) is inverse of time, and \( \alpha \) and \( \beta \) reinforce each of these parameters. The probability \( p_{ij} \) is calculated for each of the points that have not yet been visited by the ant stored in the tabu list memory \( M_k \). In this case the ant selects the arc with the highest value from Equation 5-12 favoring quickest paths with high levels of pheromone.

To avoid getting stuck in local optimums and to enable exploration of the solution area, a random number \( 0 \leq q_0 \leq 1 \) is generated and the next point \( j \) is chosen only if \( q_0 \leq p_{ij} \). If the addition of the new point will violate the capacity constraint, the ant will then return to the depot by using the closest exit door. And from there it will start a new path (which represents addition of a new first responder to the tour). The new path will then start from the depot moving towards the next unvisited point in the building. The decisions of following pheromone trails are based on the previous iteration and independent of the current movements of ants since the pheromone levels will be updated at the end of each iteration once all ants have finished making a solution to the problem. The setting of the ant colony based algorithm in this way imposes the constraints of the problem given in Equation 5-2 - Equation 5-11 making sure each responder starts and finishes their route at the depot, going through an access point, and exiting through an access node. Also, every point in the building is visited only once unless it falls on the shortest path to another point (as discussed above) or is a passing connection such as stairs. The solution built by each ant shows the number of first responders required for searching the building and individual paths for each one of them. Figure 5-3 gives a view of what an ant’s solution looks like. In this figure, the blue dot represents the depot node, while the red dots show the entrance/exit points and the rest are points that need to be visited in the network. As can be seen in Figure 5-3, three responders will be needed to cover the search area. As can be seen, a solution doesn’t necessarily need to use all the doors in the network.
Figure 5-3 Solution built by each ant in the network (the red dots are the entrances/exits of the building)

Once the iteration is finished and the tours are constructed for all the ants in that iteration, the best solution among the ants is chosen using the objective function below which is based on Equation 5-13 and the global optimum is updated accordingly.

$$F_k = \sum_{i \in V} \sum_{j \in V, i \neq j} c_{ij} x_{ij}^k$$  \hspace{1cm} \text{Equation 5-13}$$

The pheromone trails are updated after each iteration using Equation 5-14:

$$\tau_{ij} = (1 - \rho)\tau_{ij} + \rho(T)^{-1}$$  \hspace{1cm} \text{Equation 5-14}$$

The first part of the equation is for pheromone evaporation on all routes and the second part is for updating the pheromone on trails based on the quality of each tour found. This process will encourage the use of quicker routes and increases the probability that future routes will use the arcs contained in the best solutions.

From here, the colony moves on to the next iteration and this process is repeated until either no further improvement is made to the solution or a maximum number of iterations has been reached. The best solution found in all iterations of the algorithm at this point would present a
good approximation of the optimal solution to the problem. All the steps of the algorithm can be seen in the flowchart given below.

![Flowchart](image)

**Figure 5-4** The SRP Ant colony based algorithm
def RunACO(gr, capacity, start_point, antNo, alpha, beta, rho, iteration):
    # Ant Colony Parameters:
    iter = 0
    initPheromone = 1.0
    antRun = AntSystem.AntSystem(gr, capacity, start_point, antNo, alpha, beta, rho, initPheromone)
    antRun.init_ants()

    # can be run for a maximum number of iterations
    while (True):
        if iter > iteration:
            return antRun.get_best_tour()   # return the best
tour unvisited
            return antRun.get_detailed_tour()   # return detailed
paths

        while (antRun.simulate_ants() != 0 ):
            antRun.simulate_ants()

        antRun.update_trails()
        antRun.restart_ant_system()
        iter += 1

Figure 5-5 ACO based SRP solution code

5.4.3 Dynamic SRP

Building intelligent systems and access to real-time data collected from sensors and
detectors inside buildings hold the potential to improve fire service safety and response capa-
bilities. Rather than spending valuable time walking the floors of the building to find the fire,
victims, or dangerous areas and then calling in reinforcements, the incident commander (IC)
can start implementing a plan for mitigation even before the additional units arrive (Holmberg
et al. 2013) and can update the plans that are in action to reflect the real-time changes in the
environment.

The ant based algorithm developed for SRP above returns the best solutions to the problem in
the initial static stage of the event. This solution will assist emergency managers for initial
planning of the search and rescue operations; the number of crew required, how they need to
be dispatched in the building considering the access points and ingress/egress ways in the
building, and overall response time for searching the entire building (will be discussed in the
results of Chapter 6). However, this solution is valid only until the conditions and state of the building are unchanged.

When there is a change in the environment such as blockage of certain areas or inaccessibility to navigable areas, the algorithm needs to adjust itself; pushing the first responder crew away from dangerous areas and updating their current assigned routes. Various events such as increased smoke or heat level, area blockage, victim detection, etc. can all impact searching decisions, where specific points that were part of the search path can become dangerous and should be avoided at all times not even allowed for passing unless there is no other way in the network.

If the detection of danger in a specific point/area in the building happens before entrance to the building, the algorithm can be re-run to find the new best paths. However, this detection might happen during the course of searching the indoor environments where the crew have been assigned their paths and have already started searching the building. In this situation, one strategy could be to re-run the algorithm for unvisited points in the building, pull back the crew, and assign the newly found routes to a new crew. However, this strategy would be a waste of time and resources especially since the rescuer might be able to search some other areas before being pulled back.

The other strategy is to update the current assigned paths in a way to consider the already visited points in the building, re-assign the unvisited points to the rescuers that are already in the scene, and adding new ones if required which makes more efficient use of available resources and time.

The algorithm proposed here is based on the second strategy. Once the dangerous points are known at time $t_i$, those points are labelled as inaccessible. The points already visited by all responders are moved to a visited list, the conditions of the initial stage of the algorithm are modified and the algorithm is run for the rest of the unvisited points.

The dynamic version of the algorithm has the same steps of the static algorithm: Initialization, Construction, Trail Update, and Terminating Condition. The main difference though is the initialization step. The static version of the algorithm has no prior knowledge of routes and movements and thus a flock of clear ants start the exploration of the environment and an initial pheromone level is placed on all edges in the network. While the dynamic version of the algorithm starts running from points of time where the network faced alterations e.g. blockage
of a certain area. If this point of time is after the initial entrance of rescuers takes place, then the rescuers have already started their routes and visited some areas in the building. Figure 5-6 shows the initial routes assigned to rescuers $R_1, R_2, \ldots, R_K$ and their traversed routes up to time $t_i$. Thus, the dynamic algorithm can’t start with empty ant routes and in fact each ant should have the already traversed paths from the static solution stored in its initial stage. Figure 5-7 shows how the initial ant paths are extracted from traversed paths using the initial static solution. The nodes in the traversed paths will be listed in the tabu list as visited to avoid being re-visiting.

The other aspect that needs consideration in the dynamic algorithm is the pheromone distribution on the connections. While the static algorithm sets the same initial pheromone level on all connections in order to allow exploration of the environment, when running the dynamic algorithm, the aim is to quickly update the routes considering the alterations in the network. Thus, re-initializing the pheromone matrix which holds the trail levels of all connections in the network is not efficient as it will force the colony to explore the environment again especially
since the indoor graph is sparse, route options are limited, and the area around the inaccessible point will be the most affected area leaving the rest of the routes less likely to change. Thus, in the dynamic algorithm proposed here, instead of changing the pheromone levels, the costs of connections entering or emanating the inaccessible points in the graph are increased significantly. This way after running a few iterations of the algorithm (dependent on network size), the ants will avoid entering or exiting the inaccessible nodes to avoid increasing the overall cost of the objective function. Thus, making routes with effected edges less favorable and therefore decreasing their pheromone trails during the iterations and finally converging to routes that avoid passing through the inaccessible nodes. Increasing the edge costs is chosen over removing the blocked/inaccessible edges to allow the affected links to be chosen in case no alternative way exists. Whereas, removing the broken link from the graph will cut the possibility of that link being chosen completely and the algorithm might get stuck. This could be the case for a rescuer that is already in that area and needs to be routed out. This is especially important as the indoor route graphs are sparse and not complete, thus have limitations in the number of alternative ways that can be found to reach a specific point.
5.5 Chapter Summary

This chapter presented the main challenges faced by first responders for indoor search and rescue operations in complex indoor environments and highlighted the importance of tracking and navigation systems for buildings as well as sharing building information with fire departments and using Computer Aided Dispatch Systems for pre-incident planning. Accordingly, the Search and Rescue Problem was designed and formulated mathematically to meet emergency responders’ requirements using the IESM integrated geometric/semantic network model. Using the model, an ant colony based algorithm was proposed for solving the problem in the initial static state of the problem and how the algorithm should perform to recover from dynamic changes in the environment.

The conditions of the problem set the conditions of movement for each rescuer in the building, forcing each person to enter from an access point, cover the search area not violating the maximum time he/she can spend inside the building, and then exiting from another access point in a way that the entire building is covered by all rescuers in the minimum time possible.

As the formulation proved the problem to be in the category of integer linear programming problems, the solution approach was based on an ant colony metaheuristic algorithm. The algorithm was designed for both the initial state of the algorithm considering the building settings are intact and then the dynamic state of the algorithm has the ability to adapt the assigned routes to conform to the new conditions of the problem where the search area is changed due to real time updated information.

Having developed the 3D Indoor Emergency Spatial Model and Indoor Search and Rescue algorithm, Chapter 6 and Chapter 7 will evaluate the proposed solution approach.
Chapter 6
Implementation and Evaluation Analysis of IESM
6.1 Introduction

Based on the body of knowledge in the previous chapters and the highlighted importance of existence of situational awareness for indoor environments, a new indoor emergency spatial data model containing both the interior and exterior of the structures with detailed 3D geometric and semantic information was presented in Chapter 4 to address the first responders’ information requirements on the incident scene. Accordingly, the search and rescue problem (SRP) was formulated based on the model and an ant colony based solution approach was proposed in Chapter 5 to solve the on-scene search and rescue problem. Having presented the design and development stages of the thesis, this chapter and Chapter 7 focus on the research demonstration and evaluation to address the final research question of the thesis which is: “how well does the model perform compared to current systems”.

To evaluate the performance of the proposed model, first IESM’s feasibility and applicability is evaluated in this chapter using an observational case study and descriptive scenario method. This allows looking at different scenarios that first responders are usually faced with to analyze how the system can assist in providing situational awareness to them. Using this method, this chapter will discuss in detail how the model improves seamless 3D visualization of indoor areas, seamless spatial analysis on indoor/outdoor geometric and semantic information, seamless route finding, indoor decision making and interactions with outdoor environments.

The proven feasibility and performance of IESM in providing situational awareness will then allow evaluating the SRP solution which is based on the geometric and semantic information presented by IESM for modelling the indoor route network which will be given in Chapter 7.

The rest of this chapter will first present the implementation properties and system design for evaluating IESM in Section 6.2 and Section 6.3 respectively. Then the emergency management capabilities of IESM in terms of visualization, routing, spatial analysis, and decision making will be analyzed in Section 6.4. Section 6.5 will highlight the importance of integration of the indoor model with outdoor GIS and Section 6.6 will discuss the necessity of web based presentation of the model. Lastly, Section 6.7 will conclude this chapter.
6.2 IESM Implementation Properties

The Indoor Emergency Spatial Model (IESM) was proposed in Chapter 5 to address the key information and visual requirements of first responders in an indoor incident case to provide on-scene situational awareness before physical arrival. This information was classified by the class diagram model in the following dimensions: indoor building information, surrounding outdoor information, dynamic and semantic information of the building. Using the IESM class diagram, the indoor network model was extracted to contain both geometric and semantic information of the built area while connecting the indoor model directly with the outdoor environment to allow seamless routing.

To evaluate the effectiveness of the proposed IESM model for enhancing indoor situational awareness, this chapter uses a scenario based method on a case study building in the campus of The University of Melbourne. A prototype system is developed for testing the scenarios on the given building. Typically, GIS applications are used to manage emergency response operations. In this study, building information is also added to the geo-information model to support indoor emergency response and management.

To achieve a fully operational 3D indoor modelling framework, various elements such as indoor model, route visualization, integration with outdoor environment and road network should work together. The primary focus is to use existing geographical information systems to have the same mapping, analyzing, sharing and managing capabilities. ArcScene as a 3D visualization application allows viewing GIS data in three dimensions and as it is fully integrated with the geo-processing environment, it provides access to many analytical tools and functions. A snapshot of the developed platform using ArcScene can be seen in Figure 6-1. As can be seen in Figure 6-1, this prototype has integrated the Melbourne University campus building footprints on top of the outdoor road network and modelled the interior of the case study building based on IESM. The system’s design features and the work tasks performed in this study as well as the spatial analyzing and emergency management capabilities provided by IESM will be explained further in the rest of the chapter.
6.3 IESM System Design

To implement the prototype platform for evaluating IESM, the system was designed using the framework illustrated in Figure 6-2. As can be seen in this framework, 2D indoor CAD files are first converted to 3D building models using Revit\textsuperscript{13}. Revit is an architectural software that gives the ability to build three dimensional building models enhanced with various types of structural and engineering information for Building Information Modelling (Autodesk 2014). At this stage, Information regarding emergency utilities and semantic information in the IESM data model discussed earlier in Chapter 4, Section 4.2.2 are added to the 3D building model. The resulting model can be exported to the IFC (Industry Foundation Classes) format which is an open, international, and standardized specification for Building Information Modelling (BuildingSmart 2008). Revit allows addition of furnishing elements, architectural features, indoor space definition, staircases, etc. which help in detailed modelling of inside of the build-

\textsuperscript{13} Autodesk.com
ings. The 3D Revit model was designed to fit the requirements of the IESM class diagram presented.

The 3D building elements are then exported to the Esri geodatabase format (represented as multipatch surfaces) by using the Data Interoperability extension in ArcGIS. The output model is then modified to meet the IESM requirements in terms of addition of the semantic information to the elements. Each IESM entity is represented as a layer holding that entities’ attributes in its attribute table. Thereafter, the 3D indoor geometric/semantic network model (GNM) is created for the building (as explained in Section 4.3) and together with the indoor building model, a 3D indoor navigable model is provided. At this stage, the road network, building footprints containing 3D elevation information, 3D city objects, and real-time information gathered are all integrated with the IESM platform which uses the Esri environment (the real-time information was not considered in the implementations due to lack of resources). The indoor GNM and road network are connected to each other to enable the use of the Network Analyst extension to find routes seamlessly between each two locations indoors and outdoors, thus enabling integrated navigation strategies. This is done by using the Esri ModelBuilder for building the geoprocessing workflow (Figure 6-3). As seen in Figure 6-3, the ModelBuilder allows chaining together a sequence of processes and geoprocessing tools for finding seamless routes on the integrated network based on the routing algorithm and cost features defined on the edges of the network.

IESM offers more detailed building information compared to the Level of Detail (LOD) 4 representation of CityGML which adds interior structure information. Custom ArcObject plugins can be developed and added to the geo-information environment to enable specific purpose spatial analysis functions for emergency situations. The proposed IESM framework will enable various emergency management functions shown in Figure 6-2 (system’s functions) which is explained further in the following sections.
Implementation and Evaluation Analysis of IESM

Figure 6-2 IESM implementation framework

Figure 6-3 Geoprocessing model for integrated route finding using ModelBuilder
6.4 IESM Emergency Management Capabilities

To analyze the feasibility and applicability of the proposed IESM model to first responders in case of indoor emergency situations, this section will look at the various capabilities of the system under related scenarios which were undertaken for the case study environment. The effectiveness of the model will be discussed in terms of providing improved 3D visualization of the incident scene, spatial analysis on the indoor environment and semantic information, seamless indoor/outdoor routing, and provision of situational awareness for facilitating decision making.

6.4.1 3D Visualization and Various Indoor Views

One of the main advantages of the IESM is its integration with IFC entities which allows representing the data classes as separate layers in the GIS platform (Figure 6-4 (a)). This enables having 3D views of the indoor environment with different levels of detail adjusted to fit the first responder’s requirements just by turning on and off the visibility of various layers and adjusting their transparency and zoom extend. First responders and decision makers can either have an overall view of the building and how it interacts with its surrounding (Figure 6-4 (b)); a general idea of the storeys, floor plans, and egress points such as staircases (Figure 6-4(c)); a detailed indoor view of all the elements inside the structure (Figure 6-4 (d)), or a closed up view of the indoor rooms, corridors, doors, etc. (Figure 6-4 (e)). Such views will enhance the emergency responders’ perception and situational awareness of the indoor areas before physically entering the building.
Figure 6-4 Various building views for first responders (a) building elements viewed as various layers (b) general overview of the building and surroundings, (c) floors and egress points view (d) detailed building elements view (e) indoor close up view
6.4.2 Spatial Analysis on Indoor and Semantic Information

Loading the Indoor Emergency Spatial Model (IESM) into ArcScene enables all the spatial analysis abilities of a GI System which would help in identifying building information and representing it spatially to emergency responders by enabling user interaction with the building and allowing a large number of space and semantic related queries. The first responders’ information requirements can be revealed using queries on the building elements. To make it clearer, a few examples are given below.

To find all spaces containing hazardous materials in the building, the following query can be used:

SELECT * FROM Space WHERE “Has_Hazard” = 1 (Figure 6-5)

To identify all fire and exit doors, the below query is used:

SELECT * FROM Doors WHERE (IsFireDoor = “TRUE” OR IsExit = “TRUE”) 

As shown in Figure 6-5, all spaces containing hazards in the building are highlighted and each feature’s semantic information can be retrieved by identifying that feature according to IESM. As seen in the Figure 6-5, the semantic information regarding the hazard space reveals that the space is located on level 1, it is privately used as a laboratory, the hazard type is chemical, and it contains 3 occupants throughout office hours.
One of the other main things first responders would like to know when arriving at the scene is an estimate of the number of people in the building and ownership information of each space which could help in accessing the building spaces and planning for evacuation. IESM allows retrieving such information regarding building spaces. In addition, the statistics information can show the total occupancy of the building which will help in evacuation planning.

Retrieving Occupancy Information:

SELECT * FROM Space WHERE Occupancy > y; SELECT Owner_ID FROM Space WHERE SID = x

In case of indoor emergencies where quick evacuation is required, it is important to notice which windows could be possibly used as exiting points. Windows that are close to the floor or roof of the building or might even have short jumping distance to the adjacent buildings can all be used as points of exit for occupants as well as points of entry for first responders. The IESM enables detecting such windows. As seen in Figure 6-6, windows that have less than 1 meter distance with either the ground or roof or have adjacency with roof tops from other buildings could be highlighted to first responders for emergency planning decisions.
6.4.3 3D Network Modelling and Integrated Indoor/Outdoor Route Finding

Evacuation and 3D indoor routing is an important component of emergency management, which seeks to find optimal routes for moving people from an affected area to safe locations. What matters most is to enable a seamless transition from the indoor to outdoor environment and vice versa.

As was explained in Chapter 4, Section 4.3, to enable 3D integrated indoor/outdoor routing for IESM, the 3D indoor network dataset for the sample building was constructed based on the geometric network model where rooms and spaces are connected to corridors and stair-cases and elevators connect the floors (Figure 6-7). The indoor network dataset is integrated with the road network to form a complete 3D indoor/outdoor navigable routing network.

As was discussed in Chapter 4, Section 4.3.4, the traversing speed of various segments on the network is different and thus the problem of finding the optimum route could not be bounded to finding the shortest path. That is, considering walking speed on horizontal indoor floors, vertical speed on stairs and elevators, and road speed which is traversed by cars, the problem of finding the best route in the context of emergency would be to find the fastest route towards the destinations. Thus, the cost of each edge is based on the time it takes to traverse that edge which can be derived from the following equation:

\[ t_e = \frac{D_e}{S_e} \]  

Equation 6-1

where
Implement and Evaluation Analysis of IESM

$t_e$ time to traverse edge

$D_e$ distance of edge

$S_e$ speed of traversing the edge

Using previous literature (Kwan & Lee 2005), travelling speeds in the network are assumed to be 40 km/h for road speed, 75 feet per minute for horizontal indoor walking speed, and 40 feet per minute for climbing stairs. The quickest path between any two points is calculated using the Dijkstra algorithm (Dijkstra 1959) with the aforementioned edge costs. Accordingly, the fastest route between two points is the path with the minimum total traversing time based on the following formula:

$$T = \min \sum_{i \in 1}^{n} [(D_{horizontal}/S_{walking}) + (D_{vertical}/S_{vertical}) + (D_{road}/S_{road})]_{\text{path } i}$$  \hspace{1cm} \text{Equation 6-2}

Where:

$T$ total traversing time

$i$ is each path found

$D_{horizontal}$ distance walked horizontally indoors

$D_{vertical}$ distance walked vertically indoors (like stairs)

$D_{road}$ distance traversed on road

$S_{walking}$ horizontal indoor walking speed

$S_{stair}$ vertical indoor walking speed

$S_{road}$ road speed
The overall distance of the optimal route would be the sum of the distances traversed on the indoor and outdoor network:

\[ L = D_{horizontal} + D_{vertical} + D_{road} \]  

Equation 6-3

Where:

\( L \) is total traversed distance

After building the indoor network dataset with the relevant edge costs and connecting the indoor network to the road network, the Network Analyst Module can be used to find optimal (fastest) paths between each two points either inside or outside the building (Figure 6-8). This would allow first responders to have an estimate of the time and distance required to reach the desired point inside the building.

Figure 6-7 3D indoor network dataset and connectivity with outdoor road network

Figure 6-8 Integrated indoor and outdoor route finding
6.4.4 Indoor Situational Awareness for Emergency Management and Decision Making

One of the main advantages of IESM is provision of indoor situational awareness to first responders by 3D visualization of indoor and outdoor geometric and semantic information and in particular locating emergency utilities’ information in the model and retrieving their semantic information which can be seen in Figure 6-9. Such information can remarkably impact the routing and navigation strategies inside buildings and decrease the uncertainty routing and wandering inside structures. This is especially crucial in indoor situations where time can be easily lost due to severe air and blockage issues. It is also extremely important to optimize the route selection to reduce the distance and physical exposure to dangerous situations which associates with carrying heavy equipment.

![Figure 6-9 Locating indoor emergency utilities and retrieving their semantic information](image)

To evaluate the effectiveness of IESM in decision making and optimizing indoor routing times, we have considered three common scenarios faced regularly in terms of emergency situations. The first scenario assumes that emergency responders want to reach a designated location inside the building and evaluates how IESM can impact their navigation decisions (Figure 6-10). In the second scenario, the emergency team is willing to locate and reach the main electric panel which is an important emergency utility inside the building (Figure 6-11). And in the third scenario, a blocked area inside the building prevents reaching a specific location (Figure 6-12). The focus building is a 4 storey building with a basement and two stair cases, one located inside the building and the other outside the building. In each scenario, we will analyze how
IESM can increase situational awareness, assist in decision making and outperform the time and travelled distance compared to not using it.

As Figure 6-10 depicts, in the first scenario, emergency responders reach the main entrance of the emergency scene willing to reach a gathering point on the third floor. In the traditional case, they will not have any information regarding the building plan prior to entrance, thus, assuming they use the outside stair which is quite visible to them and seems to be the quickest way, they will spend 463 seconds and 148.5 m to carry the equipment (Figure 6-10 (a)). However, using IESM, they could visually locate all egress points in the building and use the network analysis routing function (as described in section 4.3.4) to find the quickest path even before arriving at the scene (Figure 6-10(b)). The optimized path suggested by IESM will then save them half the time and walking distance (Table 6-1).

In the second scenario (Figure 6-11), we assume first responders use the traditional 2D access maps of the building to locate the electric panel shutoff inside the building and make a mistake in locating the utility due to a misaligned map or lack of sufficient information. Assuming the rescuers go to the left wing of the third floor instead of the right wing of the second floor, they would need to reroute back to the second floor to the right location again (Figure 6-11 (a)). In the best case if they take the quickest path to reach that point based on indoor distances and traversing speeds explained earlier, it will take them 690 seconds and 220 meter walking distance to get them to that location (Table 6-1). On the other hand, assuming first responders are equipped with IESM, they could locate the electric panel inside the building using the 3D visualization model quickly just by turning on its layer and retrieving the semantic information for each feature as was shown in Figure 6-9. Furthermore, IESM will find the quickest entrance and route towards that point and visualize it on the map (Figure 6-11(b)). Thus, they could have located the right location of the utility and direction towards it in first place and only 90 seconds would have been spent to reach that point and near 28 meters traversed resulting in 10 minutes less delay which is a considerably large amount of time in terms of emergency response as well as 192 meter less wasted wandering distance and heavy equipment carriage inside the building.

The last scenario, analysis the case when a part of the building gets blocked due to collapse, heavy smoke, congestion, etc. In the traditional practice, emergency responders will be unaware to such event unless they are confronted with the blocked location. As Figure 6-12(a) shows, emergency responders will have to detour from the original path once the blocked...
point is identified and this might take quite long if not aware with the structure of the building and accessible areas. However, IESM’s routing component allows the placement of various barriers in the model which will find alternative best routes as soon as the blocked areas are detected (Figure 6-12(b)). The availability of real time information gathered from building detectors can enable visualization of such updated information in real time on the model which would enhance wiser decision making.

Figure 6-10 Scenario 1 - navigation assistance

Figure 6-11 Scenario 2 - situation awareness

Figure 6-12 Scenario 3 - indoor route blockage

Table 6-1 Travel times and distances with and without IESM in various scenarios
As a result of this evaluation, a simple mistake or unavailability of information could cause a huge delay in reaching various locations inside buildings as well as increased travelled distances and exposure to dangerous areas. The test case assessed in this chapter is a simple 4 storey building for the sake of better comparison and visualization, however real cases can be much more complicated and the effect of IESM would be even more noticeable due to its improved situational awareness and optimized routing.

Another important fact for first responders, especially fire fighters, is identifying which areas of the building can be accessed by using a fire hose with a certain length and in particular identifying the originating point. In other words, which parts of a building could be accessed within a certain length from a defined point. This would decrease the need for carrying heavy fire hoses and equipment and adding length to the hoses after setting in place or either repositioning the trucks for originating points. A simple origin destination cost matrix or closest facility analysis can help in finding positions that are within a certain distance from the originating point. It is important to note that this is the walking distance based on the route graph. IESM can help identify all points that can be reached within 10 meters walking distance from the originating point even considering the stairs travel distances (Figure 6-13).
6.5 Integration and Interactions with Outdoor Environment

In order to better plan for 3D urban infrastructures, knowledge is required on both the building structures and their environments in the city (El-Mekawy et al. 2012). Researches mostly tend to view structures as independent components and don’t consider their relations with the surrounding objects (Li 2011; Lin et al. 2013; Rueppel & Stuebbe 2008; Rakip et al. 2012). Rich data from indoor and outdoor structures could be beneficial in urban planning, emergency planning and response, insurance and real estate management and construction management. Having a disaster in a nearby building might result in blocked entrances and exits on other buildings which will change the navigation strategies. The existence of hazardous materials in the surrounding outdoor environment such as gas lines, propane tanks, chemical materials, gas stations, etc. can impact upon the emergency planning decisions. First responders require situational awareness regarding the features around the disaster site. Information such as volume and location of hydrants, triage areas, access areas via driveways, parking areas, etc. can assist them in effective decision making. Therefore, IESM integrates the 3D indoor model with current 2D outdoor GIS to enable such integrated situational awareness.

Figure 6-14 shows a snapshot of the campus of the University of Melbourne including two buildings with detailed indoor models surrounded by 3D elevated footprints of nearby buildings. As shown in Figure 6-14 a simple cross indoor/outdoor spatial analysis on the IESM model reveals the locations of all hazard points (marked in red) and water resources (marked in blue) around the building.
6.6 Web Based Visualization of IESM

One of the main aspects of an urban decision making system should be its quick availability and accessibility to the information. This is especially important in case of using the information for dealing with emergencies. As the same concept applies to the developed Indoor Emergency Spatial Model proposed here, the model is exported to a web based representation allowing it to be presented on the ArcGIS online platform as seen in Figure 6-15. The platform enables online access to the model featuring a bird’s eye view with rotating and spanning view of the area, capability to switch between layers and turning them on and off, searching for elements/ utilities/ features inside the model, retrieving their detailed semantic information that was modelled based on IESM, as well as changing some viewing features of the maps such as shadowing and sunlight (Figure 6-16).
Such web based representation of IESM enables prompt access to critical emergency information regarding the incident scene, the indoor settings of the building, indoor features, and utilities. For example, quick identification of the ingress/egress points such as stairs and elevators which are seen in Figure 6-17, locating extinguishers or hose cabinets in the building and quickly retrieving semantic information on their type (Figure 6-18), as well as identifying any hazards/chemical labs etc. around or inside the building.
Although the web based platform enables some visual spatial cognition and information retrieval, it is still very limited in its spatial analysis capabilities and needs further improvement. As this is outside the scope of the objectives of this research, further development in the area will be left to the commercial community.

Figure 6-17 Locating ingress/egress ways in the building

Figure 6-18 Locating and retrieving semantic information of fire cabinets
6.7 Chapter Summary

As part of addressing the final research question of this thesis in terms of how well the proposed model perform; this chapter evaluated the feasibility and effectiveness of the proposed Indoor Emergency Spatial Model (IESM). A system design framework was presented for implementing the model in the Esri platform by integrating the IESM based building representation integrated with the elevated building footprints, and 3D city objects while integrating the indoor geometric/semantic network model with the road network to enable routing.

The implemented prototype evaluated the model using an observational case study on a building in the campus of The University of Melbourne and used the descriptive scenario method to analyze how the model performs under common practice situations confronted to first responders. The model’s efficiency in facilitating indoor emergency response was proved through the following: 1) Enabling 3D seamless indoor/outdoor visualization; providing a detailed geometric/semantic view of the indoor environments and adjustable levels of detail to fit emergency responders’ on-scene requirements. 2) 3D seamless indoor/outdoor routing; assisting first responders to find fastest routes towards points of interest using the proposed indoor geometric network model. 3) Seamless spatial analysis on indoor geometric and semantic information; by modelling the indoors spatially, user interaction with the building is improved and space and semantic information could be queried easily. 4) 3D seamless indoor/outdoor situational awareness, which facilitates decision making and was proven to reduce simple mistakes that can cause huge delays as big as 10 minutes even for a very simple building.

Having proven the efficiency of IESM, the next chapter evaluates the proposed SRP solution approach which is based on the indoor network model extracted from IESM.
Chapter 7
Implementation, Evaluation, and Validation of the SRP Algorithm
7.1 Introduction

Following the proposed solution approach for solving the Search and Rescue Problem in Chapter 5 and the proved efficiency of the IESM underlying building model in Chapter 6, this chapter addresses the final research question of this thesis: “How well does the proposed SRP model perform?” by evaluating the effectiveness of the proposed solution approach in terms of the algorithm itself as well as comparing it with current practice systems. The chapter describes the algorithm’s implementation details, the case study used for the evaluation, undertaken scenarios, and performance measures analyzed to evaluate the performance of the algorithm. Furthermore, to evaluate the feasibility and efficiency of the algorithm, the solution approach is also validated against the current procedures and strategies used by first responders.

In the rest of this chapter, first the implementation properties consisting of how the experiments were designed, the topology of the test case route graph derived from the building, and the ant colony properties are described in Section 7.2. Section 7.3 then evaluates the algorithm’s efficiency based on the performance measures such as number of rescuers, response time, travelled distance, and route overlaps. The dynamic adjustment of the algorithm based on real time received data is then analyzed in Section 7.4. How IESM and semantic information can impact the found solution and be adjusted to fit first response requirements is then given in Section 7.5. Finally, Section 7.6 validates the algorithm by comparing it with the current real indoor movement strategies of first response teams which is done by simulating both strategies in an agent based simulator. The validation clearly highlights the limitations of current procedures and emphasizes the advantages of the proposed SRP algorithm over the current methods.

7.2 Implementation Properties

The solution approach proposed for SRP in Chapter 5 finds the minimum number of rescuers required and the individual paths assigned to them for searching a building in minimum time considering the constraints of the problem for the static and dynamic situations. To evaluate the performance of the solution proposed for SRP, the algorithm is implemented in Python 2.7.10 for the same geo-located test case building used for IESM in Chapter 4 and Chapter 6. The case study building has four floors, a rooftop, basement, eight main entrances
Implementation, Evaluation, and Validation of the SRP Algorithm

to the building, two staircases, and an elevator. The IESM integrated Indoor GNM is extracted from the polyline shapefile of the building using ArcPy and is managed using the NetworkX\textsuperscript{14} library package. NetworkX is a software package for creating, manipulating, and analyzing complex network structures. To visualize the outcomes of the algorithm, the Mayavi\textsuperscript{15} package is used which allows the 3D scientific data visualization. More detailed implementation properties are given below.

7.2.1 Experimental Design

The solution approach proposed for SRP in Chapter 5 is evaluated using experimental simulation to execute the model with artificial data on one hand, and analytical method using both optimization and dynamic analysis approaches for performance evaluation purposes on the other hand. The empirical evaluation detailed here studies the performance of the SRP algorithm for finding near optimum solutions, which is due to the fact that optimum solutions for SRP are not possible as the problem definition puts it in the np-hard category of problems making it a complex problem that can’t be solved in polynomial time. Therefore, while the ACO based algorithm proposed cannot guarantee optimal solutions, it can find efficient solutions with acceptable quality that can be found within a reasonable time.

The general experimental aim is to evaluate the algorithm’s performance under different scenarios that resemble those of real case situations. We first analyze the capability of the algorithm for finding the Search and Rescue Routes for the minimum number of first responders in order to undertake the search in the minimum time considering the constraints of the problem given in Chapter 5, Section 5.3. These constraints push all responders to enter through an entrance door, go through their assigned routes, and exit through an exit door. All points of interest in the building should be visited by one of the responders on scene, and the combined route paths should cover the entire search area. To control the number of assigned first responders to the problem and balance the time and distance each responder spends searching the building; each responder is limited to a maximum time he/she can spend inside the build-

\textsuperscript{14} NetworkX can be found here: https://networkx.github.io
\textsuperscript{15} Mayavi can be found here: http://mayavi.sourceforge.net
ing before it is dangerous and he/she is required to leave the building. This maximum capacity time that can be spent inside the building is based on the maximum apparatus breathing time.

It is important to note that disaster environments are complex areas that are highly subject to dramatic changes in short times and various variables and structural parameters can affect the decisions made on the scene. However, the objective of our proposed approach is to facilitate route finding and increase movability for first responders in the short time right after an indoor incident occurs in an effort to reduce response time by increasing indoor situational awareness. Therefore, the aim is to provide decision makers with route awareness and knowledge of indoor areas while travelling towards the scene in their trucks to minimize the time wasted due to uncertainty routing inside buildings.

To evaluate the performance of the algorithm proposed, three main scenarios are considered. The first scenario looks at finding initial best solutions for searching the building before physically arriving at the scene, which will assist incident commanders by identifying the number of crew members needed to take to the scene and will give an initial view of the structure and the assigned routes. The second scenario then evaluates the algorithm under dynamic situations where real time environmental sensors in the building can detect dangerous or blocked areas that should be avoided by rescuers from the occurrence time. Under such circumstances, the rescuers’ paths should be updated to reflect these changes considering the progress of the search by rescuers up until that point in time. The third and final scenario validates the SRP algorithm by comparing it with current strategies used by first responders. For this scenario, the test case was presented to our interviewees from the Dandenong Fire Brigade team and both their strategies and the output of the SRP algorithm were simulated in an agent based simulator for accurate comparison and analysis.

For each of the scenarios and experiments, performance measures are analyzed. Here, performance is defined in terms of meeting the requirements of the objective function, solution quality, number of rescuers, search time, and overlap distance.

7.2.2 Graph Topology

As explained earlier in Chapter 4, Section 4.3, the indoor GNM route network is extracted from IESM, which is based on Lee’s Node Relation Structure while integrating semantic
information of the indoor utilities that affect the indoor route finding decisions (Chapter 4, Section 4.3.3). Using this method, the indoor route graph extracted from the test case building of Infrastructure Engineering results in a graph consisting of 350 vertices and 377 weighted edges. In the graph, all doors and windows that can be used as entrance/exit points are referred to as access points and are directly connected to the outdoor environment. Furthermore, all points of interest in the building consisting of rooms, hazard points, power utility access points, etc. are represented as accessible points in the building. In addition, nodes carry semantic information describing their type (door, room, utility, ...), floor number, and accessibility. On the other hand, edges carry information regarding their slab type (horizontal or vertical), floor number, length, and obviously the weight, which is based on the segment’s traversal time and is calculated using the edge parameters as described in Section 4.3.4.

The NetworkX library stores the network data structure featuring functions to efficiently calculate adjacency matrices and all-pair shortest paths routes between each two nodes in the network that are used later by ants for next neighbor selection in their route finding strategies. To demonstrate the indoor network and the solutions found by the algorithm, the Mayavi package is used for 3D interactive visualization of the data. The implemented platform allows the visualization of the indoor route graph and visualization of the connection segments based on the semantic data withdrawn from IESM attributes. Thus, enabling the incident managers to locate and visualize the information crucial to them such as access doors, stairs, elevators, hazard points and other semantic information described by IESM. Figure 7-1 shows the mapped network model in the implemented platform, where the semantic information separates the various features in the building. For example as shown in Figure 7-1, the access points are shown with blue dots while stairs and elevators are color coded differently. Other features of the building can also be extracted and shown on the model or used for various analysis reasons.
7.2.3 SRP Algorithm Properties

To implement the proposed Ant Colony Optimization (ACO) based approach presented in Chapter 5 for solving the Search and Rescue Problem, the ACO metaheuristic developed here for SRP consists of a number of artificial ants that are all placed at the virtual depot node at the beginning of the algorithm. Each ant in the colony represents a complete tour of all rescuer paths inside the building and is constructed incrementally selecting rooms and points of interest in the building according to a probabilistic transition rule. In each iteration of the algorithm, each ant searches the network to find the best routes for minimum number of rescuers to minimize the total traversal time considering the constraints of the problem as well as rescuers’ capacity, which is considered here as the maximum time they can spend inside the building.

The algorithm consists of various parameters that affect the speed and performance of the algorithm for finding best solutions. These parameters include the number of artificial ants assigned to searching the network, $\alpha$, and $\beta$ which reinforce the pheromone and traversal time respectively in the probability transition rule, $\rho$ which identifies pheromone evaporation, maximum number of iterations without improvement, and the initial amount of pheromone set on edges. Fine-tuning and calibrating these parameters can result in quicker path finding. However, as this would not contribute to this research’s objectives and is out of the scope of
the current thesis, parameter calibration will not be covered here. The values chosen for these parameters are given in Table 7-1.

### Table 7-1 Ant Colony Properties

<table>
<thead>
<tr>
<th>Ant No.</th>
<th>Initial pheromone</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\rho$</th>
<th>Max iteration without improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>0.9</td>
<td>10</td>
</tr>
</tbody>
</table>

#### 7.3 SRP Algorithm in Static Conditions

The first scenario evaluates the algorithm’s performance in finding the best search paths in the test case building considering the building under stable conditions, when the building is intact and all areas are accessible and safe to visit. Under such circumstances, the algorithm returns the minimum number of crew required to take to the incident scene for the emergency procedures.

SRP could be customized to run under different circumstances and parameters. By setting the maximum time a rescuer is allowed to spend indoors, running the algorithm for the case study building will return the number of first responders required, their individual traversal paths, time and distance of each person’s path as well as the collective traversed length and spent time by all rescuers in the building to search the entire building in minimum time as the output of the algorithm (Figure 7-2). The returned routes, all start from an access node (entrance point to the building), go through their assigned designated points in the structure and exit through an access node.

![Figure 7-2 Algorithm’s output](image-url)
In the first test case, the indoor capacity time is assumed 900 seconds or 15 minutes which is based on the oxygen tank of a Self-Contained Breathing Apparatus (SCBA) that can usually last up to 30 minutes. Albeit, this 30 minutes time is based on an average male breathing speed and under the heavy activities of a firefighter this can only last between 6 to 21 minutes (Marino 2006). Under these conditions, the proposed algorithm finds the best search paths in the building resulting in a minimum of 6 rescuers to search the entire building in 17.65 minutes. Figure 7-3 shows these six assigned routes to rescuers. The green links in each of the six routes show the path that a single rescuer should traverse while the red dots show the access nodes to the building. As can be seen in the figure, an individual path is assigned to each one of the six rescuers for searching inside the building. The starting access point (entrance door) and the point of exit (exit point) are selected through the algorithm to optimize the total traversal time, which is dependent on the search areas assigned to the rescuer. Looking more carefully at Figure 7-3, one can see that the algorithm tends to visit the nodes in a floor based clustered approach. As shown in Figure 7-3, while Route #1 searches the basement and the first floor, Route #3 searches the left set of staircases and the rooftop, and Route #5 searches the fourth floor of the building. Meanwhile, Routes #2, Route #4, and Route #6 cooperatively complete searching the third floor and the right set of staircases. As the ACO based algorithm enforces the solutions to obey the conditions and constraints of the problem (refer to Section 5.3), the found routes are all feasible solutions to the Search and Rescue Problem.
Implementation, Evaluation, and Validation of the SRP Algorithm

Figure 7-3 SRP assigned paths for searching the entire building with maximum 15 minutes on-route time as constraint for each rescuer
7.3.1 Evolution of the Algorithm towards Optimum Solutions

To have a deeper understanding of how the algorithm performs in terms of creating the SRP solutions, this section analyzes the evolution procedure of the algorithm. A main property of a metaheuristic evolutionary algorithm is its learning process during the evolution of the algorithm to converge to the global optimum solution and the strategies it takes to avoid getting stuck in local optimums. Figure 7-4 shows a detailed view of the optimization behavior of the algorithm during the iteration improvements. As Figure 7-4 illustrates, the SRP solution converges to a lower number of rescuers and less aggregated search time (the summation of time spent by all individual rescuers) as the algorithm evolves for the test case described above. As the results in Figure 7-4 depict, the number of rescuers required to cover the entire search area decreases from 9 to 6 people while at the same time the aggregated time spent by all rescuers during the search process decreases from 8466 seconds to 5310 seconds. At the same time, the overall distance traversed by all first responders in the building is also reduced from 2960 to 1871 meters as the solution’s quality improves towards optimality, which can be seen clearly in Figure 7-5.

![Figure 7-4 Quality of best found solution with respect to number of iteration resulting in improved aggregated search time and number of rescuers during the evolution of the algorithm](image-url)
7.3.2 Optimizing Rescuer Number and Response Time for SRP

The main aim of the SRP algorithm is to minimize the overall response time while also minimizing the number of responders required for undertaking the search operations for indoor structures. The developed algorithm is capable of finding near optimum solutions for various settings of the problem. Typically, an inverse dependency would be expected between the number of rescuers and the total search time; that is, increasing the number of first responders should result in a quicker search time in the building. However, the results of the evaluations imply a different outcome.

To have a better view of how the algorithm performs, the limiting factor; which is the maximum time a rescuer can spend inside the building, is alternated in the range of 5 to 80 minutes and the returned results in terms of total response time, number of rescuers required, and distance travelled are recorded for each condition setting given in Figure 7-6 to Figure 7-8. Firstly, Figure 7-6 depicts how increasing the number of rescuers affects the total response time for searching all affected areas in the building. In Figure 7-6 there is a clear trend of decreasing search time by increasing the number of first responders, which is due to the parallelization of the search process in breaking the workload among a greater number of rescuers. As
shown in Figure 7-6, this means if one person is responsible for searching the entire area, it will take him/her 78 minutes to complete the task, while adding a second person to the task can reduce this time significantly to 41 minutes. Continuing from this point, adding a third person will decrease the response time to 34 minutes and further addition of rescuers will decrease the search time smoothly up to the point where the entire building can be searched by 8 rescuers in 13 minutes. From this point onward as shown in Figure 7-6, adding more rescuers would not improve the search speed any further.

But why does the algorithm stop improving after reaching a certain threshold point? To explain what is happening, the number of rescuers used for searching the building is plotted against the aggregated search time in Figure 7-7. As illustrated in this figure, increasing the number of rescuers leads to increased aggregated search time (i.e. the summation of all rescuers’ search times) in the building. Similarly, increasing the number of rescuers for searching the indoor areas causes an increase in the total aggregated travelled distances (i.e. the summation of all rescuers’ travelled distances) as can be seen in Figure 7-8. As the data in Figure 7-6 to Figure 7-8 implies, when 8 rescuers are assigned to searching the building, the search will be undertaken in 13 minutes while a total tour time of 5584 seconds is required and overall they will traverse 2048 meters inside the building. When the number of rescuers is increased to 14, the search will be undertaken in 11.9 minutes, while the total tour time is 7035 seconds and a total length of 2621 meters is traversed. This means adding 6 more resources to the building would only result in one minute improvement in the total search and response time.

The reason behind what is happening is mainly because increasing the rescuers would mean more overlap in the routes since the number of egress points (stairs, elevators) and the number of paths that can be used in a single building setting are limited. Thus, every new rescuer assigned has to use the same staircase or elevator being used by others as the number of egress points may not be the same as the number of rescuers. As illustrated in Figure 7-7 and Figure 7-8, although the increase in time and distance are smooth for the first 6 rescuers, these parameters increase hugely after a threshold of 8 rescuers is hit. And while there is an abrupt increase in the aggregated travelled distance and time for adding these extra resources, the overall search time for the entire building is not improved much compared to using 8 rescuers; mainly because of increased overlap of the routes which will be discussed further in Section 7.3.3.
The results discussed here highlight the fact that knowing the optimum amount of rescuers required to efficiently undertake the search and rescue procedures are extremely important for emergency responders and incident commanders both for minimizing the response time and effective use of available rescue resources. In addition, as every minute counts in disaster management, an improvement from 78 minutes to 13 minutes is a huge difference and can mean saving more lives and less exposure of rescuer lives to danger. This is especially important in fire incidents where there is generally a noticeable amount of time between the start of the incident and the point where smoke and fire overtake the building and warn the start of a collapse. And thus, being able to perform the search in $1/6^{th}$ of the time just by assigning more responders is a huge improvement in this case.

![Figure 7-6 Total search time with respect to number of rescuers assigned to the building](image-url)
Another aspect of the proposed algorithm is its ability to balance the assigned routes amongst the rescuers as the algorithm evolves. To have a better understanding, the on-route times assigned to each rescuer for different settings of the problem are shown in Figure 7-9. As Figure 7-9 shows, the on-route time assigned to each rescuer tend to be in a close range with the rest of the rescuers for each setting of the problem. For example, as illustrated in Figure 7-9,
when 8 rescuers are assigned to the problem, they all have a search time in the range of 648 to 770 while in the case of assigning 3 rescuers they will have an on-route time of 1064, 1802, and 2040 seconds. Looking at the distance travelled by each rescuer, the same could be inferred for each of the settings (Figure 7-10). This confirms the capability of the algorithm to make the routes more balanced; in other words similar in terms of the on-route time and travelled distance/workload assigned to each first responder. Thus, as the routes are less dispersed, the first responders would have a more balanced workload distribution, which is quite important for effective resource management.

Figure 7-9 Balancing the travelled time amongst rescuers
7.3.3 Optimizing Overlap for SRP

As discussed in the previous section, a common issue with adding rescuers is the fact that although it decreases the overall search time in the building, it also increases the possibility of repeated crossings on similar segments of the indoor areas especially the ingress/egress ways such as stairs, elevators, and corridors, which are inevitable for entering and exiting the structures; making overlap an unavoidable issue. Although, the conditions of SRP limit the problem to visit all intermediate points in the network only once by one responder, this cannot be satisfied at all times due to the sparse essence of indoor graphs and limited number of traversing alternatives. Also, the shortest paths are used for decreasing the travelled time and distance between nodes; resulting in some points being crossed more than once in order to save time. Under such circumstances the cost between node i and j will be replaced with the cost of the shortest path between the 2 nodes (Laporte et al. 1987). Therefore, overlap exists no matter what strategy is undertaken. Thus, an efficient solution would minimize this overlap by effective resource assignment strategies.

The overlap phenomenon explains why increasing the number of rescuers causes repetitive use of some areas in the building and thus ceasing any further improvement after reaching a
certain threshold. To have a better grasp of how overlap affects the solutions to the given problem, the overlap overhead was analyzed in the results by plotting the number of times each point in the building is crossed by rescuers for the assignment of 1, 3, and 8 rescuers to the problem. The results are compared in the 3D plot given in Figure 7-11. As shown in the plot, the blue bars represent the number of times a node has been passed when only one rescuer is assigned for searching the entire building while the green bars show the same parameters for using 3 rescuers and finally the red bars show the case of assigning 8 rescuers to undertake the search. As it can be seen, increasing the number of rescuers results in increased overlap. While the increase is slight between 1 and 3 rescuers, the value grows hugely for 8 rescuers.

![Figure 7-11 Comparison of overlap on points](image)

As can be seen from Figure 7-11, the solution for a single rescuer to visit the entire building is supposedly the solution with the minimum overlap since there is no repeated usage of ingress/egress ways or passage nodes for reaching the designated areas. However, even in this situation, the indoor network conditions such as existence of peninsula nodes (Figure 7-12) forces the rescuer to cross a node more than once.
On the other hand, additional rescuers mean another passage of all the nodes that are placed on the chosen ingress way to enter the structure as well as all the nodes placed on the selected egress way to exit the building. To prove this statement and analyze exactly which nodes are being passed more than once, the histogram of the frequency of node visits is given in Figure 7-13, and the total number of overlap visits on nodes is presented in Table 7-2. As can be seen in Table 7-2, for a single rescuer to search the building, although there are 350 nodes in the network, the total node visits including the overlap visits will be a total of 632 times including overlaps. Now this overlap is due to existence of dead end nodes or what we call peninsula nodes (Figure 7-12), entrance/exit nodes, and stairs and elevators. Looking deeper at the histogram of frequency of node visits in Figure 7-13, it is revealing that around half of the nodes in the network are only visited once, while another third is only visited twice which by delving deeper into the trajectories was apparent that most of these points were corridor nodes where the rescuer needs to pass once to search inside a room and pass a second time to come back. The rest of the nodes are either on the stair cases or elevators or access nodes which need to be visited by all rescuers. That is why, adding the number of rescuers to 3 will increase the number of visits to 663 while increasing the rescuers to 8 will result in 783 visits on the nodes where the depot node is visited 18 times (minimum two times by each rescuer for entering and exiting) as it is the point that all rescuers will need to start and finish their route (refer to Figure 7-11). During the search process, some rescuers might have to exit an
access point and enter through another access point to continue the search, thus resulting in visiting the depot node twice. This is because although the mathematical formulation of the problem forces each responder to only go through a door once in its path, this matter has not been forced here as long as the same rescuer can search the area within his/her breathing apparatus reaching capacity and time.

![Figure 7-13 Histogram of frequency of visits on nodes](image)

**Figure 7-13 Histogram of frequency of visits on nodes**

<table>
<thead>
<tr>
<th>Total no. of Nodes</th>
<th>Total node visits for 1 rescuer</th>
<th>Total node visits for 3 rescuer</th>
<th>Total node visits for 8 rescuer</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>632</td>
<td>663</td>
<td>783</td>
</tr>
</tbody>
</table>

Deeper analysis on the trajectory of routes and results depicted that nodes with more than one visit had one of the following states in the network; they were either the depot or access nodes, entrance points to staircases or elevators, connected directly to an egress/ingress...
point, dead ends, or nodes that connect peninsula nodes. The rest of the nodes in the indoor graph were guaranteed to be visited only once even when increasing the number of rescuers.

To see how much distance overlap occurs in the search procedure, Table 7-3 shows the total distance that has been traversed repetitively in the network as the algorithm evolves. As shown in the table over the iterations, the overlap decreases due to finding better paths in the network. It can be seen that in the best solution found for a single rescuer, there is a total of 312 meter that is counted as duplicate traversal. From there, increasing the rescuers will apparently increase this duplicate traversal time.

Analysis of the repetitive passage of segments in the network and how increasing the number of rescuers increases this even when using the best paths in the network for distributing them, highlights the importance of the fact of proper resource allocation and management. Also, it highlights the significance of the SRP algorithm for minimizing the time and resource allocation reducing room for error and wasted time, energy, as well as exposure to risk.

Table 7-3 Overlap distance on edges over the iterations

<table>
<thead>
<tr>
<th>No of Rescuers</th>
<th>8</th>
<th>6</th>
<th>4</th>
<th>3</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overlap Distance</td>
<td>5344</td>
<td>3929</td>
<td>3854</td>
<td>2857</td>
<td>2981</td>
</tr>
<tr>
<td></td>
<td>4494</td>
<td>3625</td>
<td>2946</td>
<td>2920</td>
<td>2596</td>
</tr>
<tr>
<td></td>
<td>2497</td>
<td>2130</td>
<td>1744</td>
<td>1679</td>
<td>1499</td>
</tr>
<tr>
<td></td>
<td>1521</td>
<td>1197</td>
<td>726</td>
<td>809</td>
<td>632</td>
</tr>
</tbody>
</table>

7.4 SRP Under Dynamic Changes and Real Time Information Updates

Provision of search and rescue paths even in the static state where no further information of real time changes in the building is available, was shown in Section 7.3 to be highly effective in decision making and planning for emergency responders by giving an estimate of the number of crew required to take to the scene and the way they should be dispatched. However, the importance of dynamicity of indoor incidents and rapid changes in danger levels of indoor areas that could potentially result in inaccessibility should not be underestimated.
Real time information from buildings can either be readily available to rescuers after the start of the search procedures from their fellow firefighters who are inside the incident building; or more recently through intelligent building systems, which collect a wide range of real time HVAC information including air quality, humidity, temperature, current, and occupancy information. Either way, the SRP algorithm is incomplete unless it considers the dynamic changes in the environment. Thus, this section analyzes the performance of the algorithm in the event of blockage or inaccessibility of certain areas in the building based on the dynamic SRP algorithm presented in Section 5.4.3.

As was explained in Section 5.4.3, once a blockage or danger is detected in a certain area of the building, the dynamic ACO based SRP algorithm will consider the rescue paths and points that have already been visited and will adjust the ant colony properties to run amongst the unvisited points in order to re-assign these areas. This reassignment considers the already traversed paths, avoids going through dangerous areas, and keeps in memory the maximum time each rescuer can spend on the route. However, As the constraints and conditions of the problem such as maximum travel time must be met at all times, updating the paths for full coverage of the unaffected areas might require assigning additional rescuers to compensate for the changes forced to the network.

To understand how the algorithm performs under these dynamic situations, the second experimental scenario presented here focuses on evaluating the algorithm as the environment changes during time and analyzes how it reacts to these changes in terms of route re-assignment. The assumption in this scenario is the existence of real time environmental sensors that can detect unstable and dangerous conditions and send warning of areas that should be avoided.

The assumption in this scenario is a maximum capacity time of 15 minutes inside the building. The initial SRP algorithm finds a best solution of 6 rescuer paths with an aggregated search time of 5630 seconds with a total of 17.65 minutes of response time (note that the result might be slightly different after each run due to the essence of the algorithm being evolutionary and having a random search parameter). These six assigned paths for covering the search area inside the building are shown in Figure 7-14. Within five minutes after starting the initial search, the environmental sensors detect an office area on fire as well as blockage on the stairs of the fourth floor (highlighted in yellow in Figure 7-14). As can be seen in Figure 7-14, the second and fourth rescuer pass through these areas in the current assigned routes expos-
ing them to danger. The algorithm then needs to quickly adjust itself to fit the new requirements of the problem. That is, noticing which areas have already been visited and how the crew is moving in the building in this moment. Figure 7-15 shows the search areas that have already been covered by the six rescuers up to this point. As shown in Figure 7-15, the second rescuer is about to enter the danger zone based on his/her initial route assignment. However, the other rescuers are clear from that area in this moment. The algorithm then places the blocked points and areas into the tabu list to avoid passing through them. Then the network is adjusted to increase the cost of all edges that enter or exit those points to prevent any routing towards those areas as well as preventing passing through them, unless it is absolutely necessary (for example, to get a person currently in danger area out of that zone). Finally, the algorithm is re-run to assign the points that haven’t been visited so far to the rescuers that are already in the scene, and if that means crossing the capacity rule, new rescuers are added automatically to cover the rest of the areas.

Figure 7-14 Best assigned routes for covering the search in the building before the dynamic event
Looking deeper into this scenario, the new updated paths are given in Figure 7-16. As can be seen, all the adjusted paths stay clear from the danger area. As “Rescuer 2” is the most exposed to the danger zone and could probably not cover any other areas within his/her reach and capacity, he/she is routed towards the exit. Also, the path for “Rescuer 4” is rerouted to avoid going through that danger area. As shown in Figure 7-16, paths for “Rescuer 1”, “Rescuer 3”, “Rescuer 5”, and “Rescuer 6” are adjusted to the new conditions, and another fresh rescuer is added to cover the rest of the search area cooperatively with the other six rescuers. All of this is done in the most efficient way to avoid sudden increases in response time.
Implementation, Evaluation, and Validation of the SRP Algorithm

Rescuer 1’s updated route

Rescuer 2’s updated route

Rescuer 3’s updated route

Rescuer 4’s updated route

Rescuer 5’s updated route

Rescuer 6’s updated route
The efficiency of the proposed dynamic algorithm is apparent from the results of this scenario given in Table 7-4. While the initial state of the problem requires 6 rescuers, an aggregated traversal time of 5630 seconds and a total of 17.65 minutes to finish the entire search, the new adjusted routes result in 7 rescuers with a total aggregated search time of 5840 seconds and response time of 16.4 seconds. As Table 7-4 shows, using the proposed algorithm doesn’t allow the response time and maximum time each person spends inside the building to breach the maximum time. What stands out is the fact that the response time has even improved which is because of adding another rescuer to the problem causing less workload to the other rescuers. However, as expected the total aggregated time is increased because of this addition. Without the proposed SRP solution, this process would have been subject to trial and error where rescuers would have walked towards the blocked or dangerous areas and from there had to work out a new way to route back to searching the rest of the areas.

The results of this scenario prove the importance of the algorithm in quickly adjusting itself while keeping the total response time fixed by planning for the on-scene resources. Using the algorithm ensures that the total operation time is kept controlled while at the same time no rescuer is ought to spend more than the 15 minutes time that was set in the prior conditions of the system. If such indoor situational awareness wouldn’t exist, rescuers can easily be headed towards the danger zones, facing blocked areas, getting lost, and as the big picture is not available to them rerouting and managing the resources could become extremely difficult and
based on human limitations and errors; in which rescuers might be forced to spend more than 15 minutes to walk inside the building and still there would be no way to ensure every point of interest is covered in the search process.

Note that one strategy after detection of blockage is to reset the entire pheromone matrix to its original state and run the algorithm for the unvisited points. However, most of the routes and navigation decisions other than in the area of blockage would be the same. Thus, resetting the pheromone matrix would just increase repetitive computation overhead. Thus, the strategy here is to apply a significant increase of cost to edges entering/exiting the blocked areas and allowing the ant simulation and the next running iterations to adjust the paths and the pheromone matrix. The results in Table 7-4 confirm this strategy. As it can be seen, when using the same pheromone matrix compared to resetting it, a far less number of iterations (5 compared to 15) are required before the algorithm converges and also, better solutions are achieved at the same time due to using the past learning memory. As Table 7-4 indicates, the total response time using the updated pheromone matrix is 16.4 minutes, while resetting it will find a solution with 20 minutes of response time.

<table>
<thead>
<tr>
<th>Table 7-4 Results for dynamic SRP (max capacity time= 900 seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of iteration to convergence</td>
</tr>
<tr>
<td>---------------------------------</td>
</tr>
<tr>
<td>Before event</td>
</tr>
<tr>
<td>Dynamic changes相同 pheromone matrix</td>
</tr>
<tr>
<td>Dynamic changes重置 pheromone matrix</td>
</tr>
</tbody>
</table>

7.5 Adjusting Routing Decisions Based on Building Semantics

As the underlying indoor graph is created based on the proposed IESM, it carries semantic information of building elements and spaces. Thus, this would allow more proprietary solutions that are adjusted to fit individual requirements by first responders. For example, search and rescue routes that are customized to only pass through doors with a certain height, or fire resistant areas, etc. One of the important factors for fire fighters is their decisions on
whether they would use the elevators or not. The proposed IESM based graph model and the SRP algorithm developed allow configuration of the network to adjust with first responder needs. Thus, the algorithm can easily find the best search and rescue paths that only use the stairs as illustrated in Figure 7-17. Figure 7-17 shows the detailed six search paths found by the algorithm to cover searching inside the building. As can be seen in these paths, they all only use the stairs during their search. While using the elevator would result in a solution with 6 rescuers and 17.7 minutes of response time, using the same number of rescuers the search will take 24.2 minutes. Using the underlying semantic information, other conditions can be applied to meet specific requirements of the routing strategy.
Implementation, Evaluation, and Validation of the SRP Algorithm

Figure 7-17 Solution for search and rescue paths based on semantic knowledge of building, resulting in paths that avoid elevators at all times
7.6 Validation of the SRP Algorithm with Practitioners Strategies

Validating the efficiency of the proposed model and the obtained results with practitioners from their point of view is essentially important for proving the solution’s feasibility. Moreover, the results of the proposed search and rescue algorithm need to be compared with the real movement of practitioners to prove how well the algorithm performs in comparison with real practice systems. For this reason, a series of face-to-face interviews were conducted with experts from the Country Fire Authority (CFA) at Dandenong Station to understand their strategies and search and rescue procedures (reviewed in detail in Chapter 2). After comprehending their oral explanation of on-scene preferred strategies, an outdoor view of the case building was presented to the incident commander and firefighters at the station to record their decisions on how the crew would be distributed in the building and how they would find their way through it. It is important to note here that although some other research such as (Chen et al. 2015; Wu & Chen 2012) have proposed some efforts to address the indoor search and rescue problem, as they don’t meet the complete set of conditions of the problem presented in this research such as existence of more than one rescuer, 3D essence of the problem, and integration with outdoor (which helps in identifying various entrance/exit doors and ingress/egress ways); it is impossible to compare them with the results of this thesis’ solution approach.

For simplicity and to have same comparable conditions, all other factors that impact the decisions such as smoke, blockage, etc. are eliminated from both strategies. Any change in the environment would affect both solutions and cause increased delays.

The last scenario presented here will thus simulate the movement of first responders in the building according to their real practice strategies from what was learned from our participants and will compare it with the proposed algorithm’s output. To have an accurate comparison, both strategies are simulated in Pathfinder\textsuperscript{16} which is an agent based pedestrian simulator specifically designed for structural movement simulations which is able to give accurate 3D animated results (Figure 7-18).

\textsuperscript{16} http://www.thunderheadeng.com/pathfinder/
The interviews with CFA highlighted the fact that since detailed building and routing information is not available from the incident building, the way the search and rescue procedures are undertaken are dependent on various factors. Firstly, in the case of availability of fire alarms that identify the fire ignition point, the search procedure will be started from that specific point in the building rather than starting from an arbitrary point and moving from end to end. Rescuing people would not necessarily mean moving them outside the building in these situations, in fact it could just involve moving them from the danger zone to a fire isolated area within the building and continuing with the search until there is enough resources to move everyone. If the incident commander estimates a low chance of saving lives in the incident structure or if the indoor areas are in extreme danger situation, an interior attack is completely avoided.

For search and rescue operations, decisions on crew number and dispatch strategies inside the building are mostly reliant on the incident commander’s experience and available resources. From what was learned from the interviews, a fire station with 10 crew members and 2 trucks has more flexibility compared to a station with only one truck and 4 crew members. The incident commander at CFA Dandenong however explained the basic strategy is to send two firefighters to quickly observe the situation and detect the number of people needing rescue,
what situation they are in, and how they need to be rescued. Thereafter, another two firefighters will be sent for rapid intervention and to back up the previous two members.

The crew members usually work in pairs rather than side to side to back up each other. That is, they will navigate to the same floor, searching different rooms separately and meeting back at the corridor. Staying together is a safety measure, however is inefficient in terms of time and effective use of resources. Therefore, crew members tend to move in line of sight of each other as the preferred method, especially when the visibility and passability are under normal situations. In more severe conditions such as when a room is filled with smoke, more crew members are needed to attend to.

For the case study building used in our evaluation, the search strategy that would be utilized by the incident commander interviewed is shown in Figure 7-19. Assuming there is a rough estimate of the location of the fire in the building (either through the fire alarms or occupants’ information) two crew members are first sent inside the building to attend to the fire. While they will be dealing with the fire, the search will be undertaken by other crew members in an emanating strategy; meaning the floors will be searched in an outward direction from the fire point.

In this scenario case it was assumed that the fire starts on the third floor, thus two of the firefighters find the fire point in the building and start the extinguishing process (as can be seen in Figure 7-19, on the third floor), two other firefighters start searching the same floor in order to vacate it and rescue the occupants. At the same time another two firefighters will start searching the floor below the fire and the fire fighters will work their way above or below the danger floor until the entire building is covered. This means searching the building floor by floor working the way up or down the fire point. After the third floor is searched the two firefighters will work their way up to search the fourth and fifth floor. At the same time the other two firefighters continue their search on the second floor and then move towards searching the first floor. On searching the second floor, they realize there is no access to the other side of the second floor unless to go back out of the building and enter from the other side (look at the two firefighters on the stair cases on the left side of the building in Figure 7-19 ). So, two other members are informed to perform the search on the other side (the two firefighters on the stair cases on the right side of the building in Figure 7-19). Meanwhile, another two firefighters are sent to search the basement of the building only to understand the backside of the basement is not accessible from that side. Thus, they need to return to the ground floor and go visit
the other side of the basement. Using this strategy, overall 10 firefighters will be required to search the entire building. Simulating this strategy, the overall search time is 1952 seconds equal to 32.5 minutes (Table 7-5).

Figure 7-19 Firefighters’ strategy of movement in the building

To have a realistic comparison, the output of the SRP algorithm has also been simulated in the pedestrian agent simulator. In this case we have used the result for when the maximum indoor capacity time is limited to 15 minutes. Using the solution from the SRP algorithm, this resulted in 6 rescuers for covering the entire building. Each of the rescuers and their search paths are simulated into the Pathfinder software and the results are stored. The implemented algorithm in the developed Python code returned a solution of 6 rescuers with an overall search time of 17.7 minutes. Pathfinder has a few limitations, such as automatically adjusting the vertical movement speeds based on the assigned horizontal speed and congestion. Also, as the basic application of the software is for evacuation, elevators can’t be used for taking the agents to upper levels. Thus, elevators were not used in the simulations. As the building is not a very tall, complicated structure, the difference made by such small changes doesn’t have much effect on the solution and thus simulating the agents with the same speeds set in the algorithm, the simulated paths in Pathfinder result in a total of 1049 seconds equal to 17.5 minutes of total
search time as given in Table 7-5. Note that the walking speeds used by firefighters in both the practical and algorithm solution approach are set to the same speed.

<table>
<thead>
<tr>
<th></th>
<th>No. of rescuers required</th>
<th>Total search time (min)</th>
<th>Min On-route Time (min)</th>
<th>Max On-route Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Firefighter practice strategy</strong></td>
<td>10</td>
<td>32.5</td>
<td>4.1</td>
<td>28.95</td>
</tr>
<tr>
<td><strong>SRP Algorithm</strong></td>
<td>6</td>
<td>17.5</td>
<td>10.7</td>
<td>17.48</td>
</tr>
</tbody>
</table>

Pathfinder allows deep and detailed analysis of agent movement and their trajectories generating various results and reports on occupants’ behaviors. Closer inspection of the results highlights the importance and effectiveness of existence of an indoor situational awareness model and SRP routes. From the results given in Table 7-5 it is apparent that undertaking the search using the SRP algorithm reduces the number of required first responders from 10 to 6 while also reducing the overall search time from 32.5 minutes to only 17.5 minutes making the response time 46.1% faster while using less resources. As every minute counts in emergency response, 15 minutes improvement in the response time is quite significant. Considering the small size of this test case building, one can see how using this system for larger buildings can make huge differences. This is especially important for indoor areas to quickly wrap up all the emergency operations before the collapse of the building.

The results obtained from the simulation analysis signifies the work load and travel time distribution amongst the rescuers. Not having prior information of the building and distributing the fire fighters in an arbitrary approach, results in uneven rescuer paths where rescuers have very different indoor travel times and workload (travelled distance). Figure 7-20 compares the travel times of each rescuer in both scenarios (firefighters’ strategies and SRP algorithm) by analyzing the movement trajectories of each agent retrieved from Pathfinder. The chart clearly indicates that using the firefighters’ strategies leads to imbalanced travel times where one responder has a total on-route travel time of 29 minutes (excluding waiting time) while another responder will be taking a route that will only take him/her 4 minutes (again excluding the waiting time) and the rest of the eight responders’ travel times sits anywhere between this wide range of 25 minutes.
Figure 7-20 Comparison of travel times assigned to each rescuer

Figure 7-21 Comparison of assigned workloads for each rescuer
At the same time, analyzing the travelled distance by each of the responders, confirms the same finding. As Figure 7-21 shows, there is a significant difference between the travelled distances of the responders in the range of 86 meters to 617 meters using firefighters’ practical strategies. Thus, in this strategy the workload is distributed unevenly amongst the responders and this makes it complicated to control and manage the time spent indoors which is extremely important for keeping track of the breathing apparatus capacities. Furthermore, lack of indoor information and routes makes it impossible to estimate how long each responder will spend inside the structure in advance of starting the operations.

While, in the current firefighter first response tactics, there is no way to guarantee the maximum time spent inside the building and the workload distribution amongst the rescuers, the SRP algorithm presents a much more robust solution where the evolution of the algorithm improves the solution to have more balanced routes both time wise (Figure 7-20) and length wise (Figure 7-21). As Figure 7-20 and Figure 7-21 show, the SRP algorithm solution improves the routes to only 6 paths which tend to be similar in terms of travel time and distance. The travel time of the paths found in SRP lies within a minimum and maximum of 11 and 17.5 minutes. Thus reducing the wide range of 25 minutes in the firefighters’ tactics to only 6.5 minutes. At the same time, the travelled distance is also balanced leaving the rescuers to search a range of 230 to 379 meters. Table 7-6 compares the standard deviation of the found routes. As shown in Table 7-6, it is evident that the SRP algorithm provides much lower dispersion of travel time and distance in the SRP routes compared to the firefighter paths.

<table>
<thead>
<tr>
<th></th>
<th>Travel time dispersion (min)</th>
<th>Travel distance dispersion (meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firefighter tactics</td>
<td>9.4</td>
<td>177.3</td>
</tr>
<tr>
<td>SRP algorithm</td>
<td>2.2</td>
<td>47.1</td>
</tr>
</tbody>
</table>

7.7 Discussion

Unavailability of building and routing information makes the emergency responders’ decision making process extremely complicated and based on experience. As we learned from
our interviewees from the fire brigade, all decisions particularly decisions on dispatch of rescuers is made on-scene after the 360-degree size-up of the scene. The simulated fire fighter tactics reveals the limitations and uncertainties involved with this kind of strategy; there is no clear way of distributing the responders in the building, no way to control or predict how long one will spend inside the building and will be exposed to risk, how long the overall response time will be, and how many responders will be needed. Even after these decisions are made, there are various unexpected situations that can be encountered while the search is taking place such as inaccessibility of certain areas in the building, unknown areas or blockage which will lead to rerouting and wasted time caused by it. Most importantly, there is no clear estimate of the time and number of responders required before starting and planning for the emergency response.

Overall, based on the obtained results from the evaluation and validation of the proposed SRP solution approach presented in this chapter, it can be inferred that while the current firefighters’ practice systems carry a lot of uncertainties, utilizing the SRP routes can present a much more certain, robust, and reliable solution. That is, by finding the best search paths for each rescuer, the SRP algorithm identifies the maximum time each rescuer will spend for the search and thus presents the total on-scene response time. This would assist highly with decision making and management of resources and plans by emergency responders. Moreover, SRP routes give confidence of movement to responders, where they are fully aware of the areas inside the building and the routes will guide them through, adjusting to any dynamic changes in the building. This is especially important as knowing the structure of the building can help to emanate from the danger area, however it will become extremely difficult to do so if this information is not available which is the current case in the way indoor emergency response in undertaken.

It is important to note that searching every point in the building is not rationale, however comprehensive search was undertaken in all scenarios to analyze how the algorithm works. Otherwise the algorithm can be set to only run between priority points in the structure. In addition, various unpredicted situations may occur while on scene such as smoke, need to break through objects in the building, etc. This is why the best case scenario were considered and compared for both strategies where everything is in its ideal condition. Thus, any change in the environment will affect both cases and cause same delays or changes in both strategies.
However, SRP will be able to handle it dynamically as it supports real time changes in the environment.

As every minute counts in disaster management, an improvement from 78 minutes to 13 minutes is a huge difference and can mean saving more lives and less exposure of rescuers’ lives to danger. This is specifically important in fire incidents where there is usually a noticeable amount of time between the start of the incident and the point where smoke and fire overtake the building and warn the start of a collapse. Being able to perform the search in 1/6th the time just by assigning more responders is a huge improvement in this case.
7.8 Chapter Summary

This chapter addressed the final research question of this thesis, which was “How well does the proposed SRP model perform?” To answer this question, the proposed SRP algorithm was implemented, evaluated and validated in this chapter and the effectiveness of the proposed solution approach was analyzed and discussed. The solution approach was tested under various scenarios to analyze the capability of the Search and Rescue Algorithm for finding the best routes to minimize the number of rescuers and search time on scene. The scenarios included initial stage of the problem, adoption with dynamic changes in the building, and comparison with real case fire fighter strategies collected from our CFA Dandenong Fire Brigade partners.

The obtained results and simulations of the algorithm prove its high efficiency in solving the Indoor Search and Rescue Problem compared to current methods. Moreover, it highlights how the response time can drastically change by adding or removing rescuers to the problem and how it affects the overlap of routes. In addition, the proposed SRP algorithm balances the found routes where rescuers are assigned paths that are close in terms of maximum on-route time and distance travelled.

The proposed algorithm’s efficiency was also validated against real case firefighter strategies in terms of analyzing how it performs and compares with current practice systems by simulating decision strategies of our fire brigade partners as well as the outcome of the SRP algorithm in an agent based pedestrian simulator. The simulations highlighted both the limitations of current practice strategies due to unavailability of indoor information and the advantages of the SRP algorithm proposed.

The developed model can be utilized by emergency planners to identify the minimum number of crew needed to be taken to the incident scene, their individual assigned routes, and the overall search time. This could highly improve the efficiency of first response operations.
Chapter 8

Conclusion and Future Work
8.1 Introduction

From the research problem given in Chapter 1 it was understood that: “despite the considerable amount of research done in the area of indoor spatial modelling, the current data models are not effective in indoor search and rescue operations and thus indoor decision making is a challenge for first responders”. This thesis addressed the problem by presenting a new indoor emergency spatial model (IESM) and an ant colony based solution approach for solving the search and rescue problem. Moreover, throughout the past seven chapters the background of the research, proposed solutions, models, their development, and evaluation were presented, discussed, and analyzed. To conclude the thesis, this chapter summarizes the methods, approaches, outcomes, achievements, and lessons learned from this research. Moreover, the contributions of the research to the area of indoor situational awareness for emergency response are discussed and future improvements and directions of research are presented.

8.2 Addressing the Research Aim, Objectives and Main Outcomes of the Research

At the outset of this thesis, the research problem was discussed; issuing that the current data models are not effective in indoor search and rescue operations and thus indoor decision making is a challenge for first responders.

Lack of a consistent 3D indoor spatial model that contains all the geometric and semantic information required for emergency response causes incomplete situational awareness of the indoor disaster scene and the surrounding environment. Also, lack of such a model complicates the Search and Rescue procedures which are a major task undertaken by first responders after an incident occurs. Taking this as motivation, the main aim of the thesis was set out to:

“Develop a new 3D indoor spatial model that contains geometric and semantic information of building utilities and outdoor environment aimed at emergency response operations and leverage it for formulating and solving the indoor search and rescue problem”
To address the stated research problem and achieve the research goals; the Design Science Research Methodology was used as a common scientific approach for research in information systems which is based on six major steps: 1) problem identification and motivation, 2) objective definition for a solution, 3) design and development, 4) system demonstration and data collection, 5) research analysis and evaluation, 6) interpretation and communication. Accordingly, and with the above aim, the following objectives were defined for the research:

- Objective 1: Assess current indoor disaster management models to identify the gaps and limitations of current indoor models and search and rescue procedures to establish a theoretical framework for the research
- Objective 2: Design and development of the 3D indoor disaster management data model based on mission critical information for indoor emergency response
- Objective 3: Formulate the Search and Rescue Problem based on the 3D indoor spatial model for indoors and solving the problem by using a heuristic approach
- Objective 4: Develop of the 3D indoor situational awareness prototype system based on the designed indoor data model and SRP solution approach, consisting of indoor emergency spatial services and path finding
- Objective 5: Test the system and evaluate its efficiency based on quantitative methods

To address the objectives of the research, a comprehensive study of related work in the field of indoor situational awareness, indoor modelling, and indoor search and rescue was undertaken both from the research and first responders’ practical point of view. Relevant approaches were evaluated against the identified challenges to indoor situational awareness and their strengths and weaknesses in answering these challenges were argued. Moreover, interviews were conducted with fire fighter practitioners to understand their procedures and strategies for indoor emergency response operations. From these findings, mandatory requirements of an indoor spatial model aimed for emergency response applications were deduced that served as basis for the design of a conceptual data model for the spatio-semantic description of indoor space.
Conclusion and Future Work

Using the critical indoor mission data identified through research and practitioner’s reports, a new conceptual 3D indoor spatial model was designed in Chapter 4 that modelled emergency critical geometric and semantic information for the indoor environments and integrated it with the outdoor spatial information to present a full 3D indoor/outdoor GIS representation of the incident scene. The model was based on the IFC representation of BIM which contains advanced semantics and geometries of building elements and spaces inside the building. However, the IFC representation was modified to reflect the emergency responders’ requirements for decision making, situational awareness, and navigation through the built environment.

IESM was then used to extract a geometric/semantic aware indoor route graph which allowed routing decisions based on emergency responders’ requirements. The geometric and semantic information are what allow the various layouts, settings, and information of buildings to be integrated within the route model. This information includes entrances/exits to the building along their accessibility, types of ingress/egress paths, indoor spaces and their accessibility, corridor widths and door heights which help identify passability for crew members. This was done by using the labelling system of the graph elements explained in the thesis.

The Search and Rescue Problem (SRP) was modelled as a combinatorial optimization problem in Chapter 5 based on the 3D indoor/outdoor geometric network model derived from IESM in Chapter 4 and an integer programming mathematical formulation for the problem was presented considering the constraints and conditions of the problem. These conditions included forcing crew members to enter the building through a door, searching the unvisited areas, and exiting through an exit door; guaranteeing all points have been visited only once in the building. The solution approach proposed for SRP identifies the minimum number of first responders required to search an incident building in the minimum time considering their constraints and limitations. As SRP was proven to be an NP-hard problem, a metaheuristic ant colony based algorithm was proposed to solve the problem. The algorithm solves the problem in both the initial static phase of the problem, where the building conditions are intact, and in the dynamic phase where the accessibility and danger levels of the spaces are changed and the already assigned routes need to be adapted to the new conditions.

To evaluate the efficiency of the proposed indoor situational awareness system, both IESM and the SRP solution were implemented and evaluated. IESM was evaluated using an observational case study and descriptive scenario method in Chapter 6. And the SRP solution was
evaluated and validated using experimental simulation on artificial data using optimization and
dynamic approaches for performance analysis.

The feasibility and efficacy of the 3D Indoor Emergency Spatial Model (IESM) was evaluated by
implementing it for a test case building in the University of Melbourne using the Esri platform
in Chapter 6. The implemented model illustrated the effectiveness of the proposed solution in
enhancing the emergency responders’ perception of the indoor areas by enabling seamless 3D
visualization of the disaster site, seamless indoor/outdoor spatial analysis, and seamless deci-
sion making and routing between the indoor and outdoor environments.

On the other hand, the performance of the proposed SRP algorithm was implemented, evalu-
ated and validated by using the appropriate computer based implementation strategies and
agent based simulations, and the effectiveness of the proposed solution approach was ana-
alyzed and discussed in Chapter 7. The solution approach was tested under three main scenari-
os to analyze the capability of the Search and Rescue Algorithm for finding the best search
paths inside the building in order to minimize the number of rescuers and search time on sce-
ne. The first scenario considered the initial state of the problem for finding the minimum num-
ber of rescuers required and assigning them to the building, the second scenario analyzed the
performance of the algorithm under dynamic changes in the indoor environment, and lastly,
as the solution approaches proposed in literature do not comply with the requirements of the
indoor search and rescue problem defined here, the last scenario compared the results with
real practitioners’ movement strategies based on close collaboration with the Dandenong
Country Fire Authority (CFA) of Victoria.

The obtained results and simulations of the algorithm prove its high efficiency in solving the
indoor search and rescue problem compared to current methods. Moreover, it highlights how
the response time can be drastically affected by assigning different number of rescuers to the
problem and how having knowledge of the indoor environment and following the assigned
routes could save tens of minutes in overall search time even in the small case building consid-
ered in our simulation scenarios.

The developed Indoor Emergency Spatial Model integrated with the Search and Rescue Algo-
rithm can be effectively used by emergency planners to provide them with indoor situational
awareness, number of responders required for searching the area, and their individual design-
nated paths. All of which can be provided to them in their trucks or handheld or head mounted
devices to help for quicker and more efficient emergency planning prior to entering the scene removing the need for physical entrance for gaining information.

The key outcomes and conclusions of each of the above objectives are highlighted below.

8.2.1 Objective 1: Assess Current Indoor Disaster Management Models, Identify Gaps, and Establish the Theoretical Framework

Chapter 2 drew on literature from a range of sources to provide the context for meeting this research objective. It was necessary to provide an overview regarding the increasing speed of urbanization and development of complex structures that have caused various complications for indoor emergency management. Moreover, it drove attention to challenges faced in current practice systems and limitations and gaps of the indoor spatial and city models proposed in the literature.

To have a thorough view of the problem in the real world settings and how indoor operations are undertaken by first responders, a series of literature review of current reports and investigations published by main organization in the domain were reviewed. Moreover, a series of face to face interviews with the Dandenong Country Fire Brigade (CFA) were conducted to confirm what information is available to them in the current setting regarding the maps and indoor information.

Thereafter, Chapter 2 gave an overview of solutions, models, approaches, and state of the art research and technology developed in literature to overcome the difficulties faced in indoor emergency management in terms of indoor situational awareness and search and rescue operations. 3D city models and 3D GIS solutions as a chief area for indoor situational awareness for built areas and how they are used to handle indoor incidents were discussed. Then, various aspects of indoor situational awareness such as indoor spatial awareness, indoor localization, and indoor routing and evacuation were analyzed in the literature and the search and rescue models proposed thus far were discussed.

The review of the current literature provided the basis for understanding the strengths and weaknesses of the current practice indoor incident strategies. Highlighting the fact that in the current practice system, no additional information is known about the disaster building and the environment around it before physically arriving at the scene. It was discussed that alt-
hough, some building owners provide the fire brigades with their 2D CAD maps, such maps are difficult to interpret quickly, lack detailed emergency information and are not available for all structures and residential areas.

Review of the state of the art literature proved that although there are various approaches for modelling the indoor environments such as CityGML, IndoorGML, BIM, terrestrial laser scanning, etc. for improving the indoor situation awareness; most of these indoor models are not applicable to indoor emergency applications in their current format. This is mainly because these models are not specifically targeted to first responders’ requirements and have limitations in modelling the semantic features of building elements. Thus, more advanced indoor geometric/spatial models should be developed to meet emergency response applications requirements.

Thereafter, the way search and rescue operations are undertaken by first responders for indoor environments was reviewed. It was seen that in the current practice the search and rescue is planned after a rapid 360-degree size-up of the incident and an assessment of the structure and blueprints of the buildings and physical spaces is conducted which happens after arrival of the emergency crew and accordingly an action plan is developed on the site. All of which is time consuming and could have been done on the way towards the scene if the information was available beforehand. While, availability and access to existent and timely information regarding the incident scene in a reasonably short time vastly impacts the efficiency and decision making of the emergency situation and lack of this information reduces first responders’ preparedness ability to act rapidly when confronted with an incident.

Chapter 2 also discussed how unavailability of this information complicates the search and rescue decisions and why the solution approaches proposed thus far for this problem do not fit the requirements of first responders completely. The reasons mainly being the fact that they do not consider the indoor settings and features inside the building such as types of ingress/egress (e.g. stairs or elevators) that affect decision making. Also, the indoor areas are not viewed as an integrated object with the outdoor environment. Thus, having limitations in choosing the right point of entrance and exit to the building. Moreover, first responder constraints and limitations in term of maximum time they can spend searching the inside areas were not seen in previous work. Furthermore, dynamic changes in the environment and need for route updating which is an inevitable part of the emergency response were mostly underestimated.
8.2.2 Objective 2: Design the 3D Indoor Emergency Spatial Model

Identifying the knowledge gap in the area of indoor spatial models that can be applied to emergency response applications, this research proposed a new 3D indoor spatial data model based on indoor mission critical data required for emergency operations. Both the interior and exterior of the structures were modelled to contain detailed 3D geometric and semantic information required during indoor incidents in the proposed UML class diagram. The information is comprised of three categories:

1. **Indoor building information** such as floor plans, stairs, elevators, points of entry, building type, and more specific information needed in a fire incident such as location of fire hydrants, hoses, switchboards, gas isolations, water isolations, main utility shutoffs, etc.

2. **Dynamic and semantic building information** which are received by environmental detectors such as, smoke detectors, HVAC systems, occupancy and ownership information and have become more available recently through intelligent building systems and IoT

3. **Outdoor emergency information**, which is information regarding the outdoor surroundings such as water resources, hazards, road networks, etc. that can impact the emergency decision making.

The Indoor Emergency Spatial Model (IESM) proposed in Chapter 4 modified the IFC classes to contain this mission critical building information and removed the unnecessary complexities of IFC to form a complete 3D indoor data model that facilitated indoor emergency response and management for emergency responders and decision makers.

To enable route finding for first responder movement and develop the search and rescue algorithm, IESM was then used to extract a 3D indoor IESM integrated geometric/semantic network model. Contrary to previous literature the indoor graph extracted from IESM labeled the graph elements (nodes and edges) in the graph to be relied on the indoor thematic contextual spaces based on emergency responders’ crew, thus, allowing route planning specifically for emergency planners’ needs. Indoor graph construction should be mindful of the fact that com-
plex building geometries contain great numbers of vertices and edges which could lead to significant increases in evacuation and rescue algorithm’s running time and complexity. Therefore, it was discussed that complex structures such as grid and triangulated graph constructions are not favorable. Moreover, routing algorithms using resource allocation and sequencing of node visits are mainly based on TSP and VRP which have the essence of an NP-hard problem and are dependent on the number of nodes and edges in the graph. Thus, there needs to be caution on the complexity of the indoor graphs. Therefore, the search and rescue routing problem in this research based its graph construction strategy on Lee’s Node Relation Graph (NRG) which has a sparser graph representation compared to the other representations of the indoor areas. The retrieved indoor network was connected to the outdoor road network to form a seamless indoor/outdoor route network. The network then allowed route computation for further path finding in the building which was used for formulating the indoor SRP.

8.2.3 Objective 3: Formulation of Search and Rescue Problem and Developing a Solution Approach

Considering the challenges of current search and rescue procedures and limitations of proposed solutions in literature mainly due to the fact that buildings were not considered as 3D environments and geometric/semantic information was not considered; Chapter 5 met this objective by using the 3D IESM integrated geometric/semantic network model to formulate the Search and Rescue Problem mathematically and propose an ant colony based algorithm for solving the problem in both the initial static and dynamic state of the problem.

To have an efficient SRP algorithm which can accurately find best paths for responders inside structures; indoor environments need to be modelled precisely to reflect all the navigable locations in the building. Horizontal slabs, vertical access points like stairs and elevators, entrance and exit points, rooms, corridors, hazard points, accessible and non-accessible areas, etc. should all be well represented in the navigable model. Distance based route graphs that only rely on the lengths of edges for finding shortest path algorithms are not sufficient for emergency response requirements in indoor areas. Moreover, 3D geometric information of the indoor elements such as door and window heights, corridor wideness, etc. as well as semantic information such as accessibility of specific points, type of doors (entrance or exit), type
of windows (whether they can be used as exit points), hazard status in rooms, etc. play a crucial role in how the route graphs are defined.

It was shown in Chapter 5 that integration of the above information into the navigable indoor graphs allows routing decisions that are specific to first response operations. Also it enables finding routes to fit various users and their needs such as decision on whether or not to use the elevators, adjusting the edge weights to meet specific requirements (time, distance, accessibility, wheelchair accessibility, heavy equipment accessibility, etc.).

Based on the developed IESM based GNM and its proven efficiency, SRP was modelled and the problem was mathematically formulated in Chapter 5. A virtual depot node was used to link the indoor and outdoor areas to enable best entrance and exit selection for each rescuer on scene. The conditions of the problem set the conditions of movement of each rescuer in the building, forcing each person to enter from an access point, covering the search area without violating the maximum time he/she can spend inside the building, and then exiting from another access point in a way that the entire building is covered by all rescuers in the minimum time possible.

As the formulation proved the problem to be in the category of integer linear programming problems, an ant colony based approach was proposed for solving it in Chapter 5. The algorithm was designed for both the initial state of the algorithm considering the building settings are intact; and also the dynamic state when the algorithm needs to adapt the assigned routes to conform to the new conditions of the problem where the search area is changed due to real time update information.

The initial static algorithm is extremely important to assist emergency managers for initial planning of the search and rescuer operations, the number of crew required, how they need to be dispatched in the building considering the access points and egress/ egress ways in the building, and overall response time for searching the entire building. On the other hand, the dynamic part of the algorithm, assists them after reaching the scene to adapt timely to new indoor situations. This could be a sudden blockage of an area or becoming inaccessible or addition of new victims that need rescuing, etc.
8.2.4 Objective 4 & 5: Implementation, Evaluation, and Validation of the Proposed 3D Indoor Situational Awareness Model (IESM and SRP Solution Approach)

Having designed the 3D indoor situational awareness model based on IESM and SRP in Chapter 4 and Chapter 5, the development and evaluation of the model were presented in Chapter 6 and Chapter 7.

First, IESM’s feasibility and applicability was evaluated in Chapter 6 using an observational case study and descriptive scenario method which allowed analyzing the system under different scenarios that first responders are usually faced with. The prototype system implemented in the Esri environment proved the effectiveness of the proposed 3D IESM and the following conclusions were proved:

1. To fit each application’s needs, proprietary indoor spatial models should be developed based on the users’ needs.

2. IESM enhances emergency responders’ perception of the indoor areas by enabling 3D visualization of the disaster site and indoor environments in which the view can be adjusted to various levels of detail based on preference.

3. IESM provides detailed geometric, semantic, and geographical information of the incident building which enables spatial analysis and information retrieval about indoor environments.

4. IESM enables integrated and seamless indoor/outdoor routing and the availability of semantic information such as space accessibilities, decreases the uncertainty routing and wandering inside structures.

5. IESM enables seamless indoor/outdoor spatial analysis in the disaster site such as identifying all windows within a certain height of a city furniture.

6. IESM decreases indoor reaching times due to improved situational awareness and optimized route finding.

7. IESM improves situational awareness of indoor areas and offers more detailed building information compared to the Level of Detail (LOD) 4 representation of CityGML.
8. Web based IESM simplifies first responder and decision makers’ access to the system as it makes it accessible via web browsers and mobile devices increasing the usability of the model.

9. The developed IESM was presented to the CFA fire brigade whom we had close collaboration and was found to be very useful and helpful to them particularly for big structures such as universities and schools.

The proven feasibility and performance of IESM in providing situational awareness then allowed evaluating the SRP solution approach which is based on the geometric/semantic information presented by IESM for modelling the indoor route network given in Chapter 7.

Chapter 7 evaluated the efficiency of the proposed SRP algorithm and validated it with current practice strategies. The SRP algorithm was implemented in Python 2.7.10 using ArcPy for IESM based GNM extraction of the test case. The visualization platform and the obtained results gave a clear view of how the algorithm finds the minimum number of first responders needed and assigns the routes to them based on their constraints and conditions.

The algorithm was evaluated under three main scenarios: initial solution state which is before physical entrance to the building, adaption of routes based on dynamic environmental changes, and finally as none of the previous SRP solutions meet the conditions required for modelling the problem (such as solving it as a TSP single rescuer mode or considering the building as single floored, neglecting the doors, and other semantic information), and to have a more realistic comparison and evaluation of the algorithm, the last scenario validated the output of the proposed SRP solution with the current practice movement and decision strategies of first responders which was simulated after rigorous interviews with the CFA fire brigade. As it was not possible to evaluate the approach under all circumstances in the scope of this thesis and also searching every point in the building is not rationale and various unpredicted things might occur while on scene such as smoke, need to break through objects in the building. That is why the best case scenario for both strategies were considered and compared in which everything was assumed to be in its ideal condition. This way, any change in the environment affects both cases and causes same delays in both strategies. Albeit, SRP will still be able to handle the new conditions dynamically as it supports real time changes in the environment. For each of the
scenarios, the performance measures were analyzed for the obtained results and were presented in Chapter 7.

The evaluations, simulations, and results highlighted both the limitations of current practice strategies and the advantages of using the proposed SRP algorithm.

The following main outcomes and conclusions were drawn:

1. It is obvious that disasters are complex environments that are highly subject to dramatic changes in short time and various variables and structural parameters can affect the decisions made on scene. However, as shown in Chapter 7, lack of knowledge of the incident scene and indoor paths makes decision making and routing more difficult and time consuming. Therefore, the proposed SRP solution targeted these difficulties and facilitated path finding and confident movability inside the building in the short time right after an indoor incident occurs which was shown to highly reduce the overall response time.

2. This study has shown that in the current practice, decisions on crew number and dispatch strategies inside the building are made on-scene and are mostly reliant on the incident commanders’ experience and available resources; making it impossible to estimate the overall response time of the operations, the maximum time each first responder will spend inside the building, and number of resources required.

3. The research proved that availability of IESM based model of the structure consisting of detailed geometric and semantic information required by emergency responders allows the SRP approach to identify the number of crew and the designated 3D routes for each person (including which entrance/exit and ingress/egress path to use) to minimize total response time; saving critical on-scene investigation and planning time. Overall, based on the obtained results it can be inferred that while the current firefighters’ practice systems carry a lot of uncertainties, utilizing the SRP routes can present a much more certain, robust, and reliable solution.

4. The SRP approach returns the total response time for the given building settings considering the conditions. The empirical analysis proved that the total response time and number of rescuers can be significantly improved using the SRP approach compared to
the usual fire responders’ strategies. Having this response time is extremely important for the proper decision making, resource allocation and management.

5. As shown, contrary to the practice strategies, the SRP solution returns paths that are balanced in terms of on-route travel time and distance, thus distributes the workload evenly amongst the rescuers which is very helpful for effective resource management.

6. The empirical results and the findings of the thesis highlighted how important the decisions of crew assignment is for searching the interiors of a building where changing from 1 first responder to 8 can improve the response time from 78 minutes to 13 minutes; which is a huge improvement especially when every minute counts in disaster management and can mean saving more lives and less exposure of rescuers’ lives to danger. This is especially important in fire incidents where there is usually a noticeable amount of time between the start of the incident and the point where smoke and fire overtake the building and warn the start of a collapse. Being able to perform the search in 1/6th the time just by assigning more responders is a huge improvement in this case.

7. The findings have shown that, increasing first responders decreases the overall response time. However, after a certain threshold has reached, adding more rescuers will only increase the overlap of the paths and will not improve the response time any further which is due to the fact that there is a limited number of egress points (stairs, elevators) and paths that can be taken in an indoor environment. Knowing this threshold is quite important for incident commanders for proper resource allocation and to avoid wasting extra resources.

8. The Dynamic SRP approach was shown extremely efficient as it adapts the assigned routes to the new situation and as the conditions of the problem force the rescuers not to violate their breathing apparatus capacity, the dynamic algorithm adjusts to the changes of the problem by adjusting the routes or assigning new rescuers. Thus, as was shown in the results, the dynamic SRP approach keeps the overall response time the same and controls the conditions of the problem to make sure they are met at all times. Under the current practice strategies, rescuers could easily be led towards the danger zones, facing blocked areas, getting lost, and as the big picture is not available to them rerouting and management of resources could become extremely difficult and
based on human limitations and errors; in which rescuers might be forced to spend more time than their maximum breathing apparatus capacity to navigate inside the building and still there is no way to make sure all points of interest have been covered (shown in the validation simulations).

8.3 Contributions to Knowledge

This research represents one of the first in-depth investigations and developments of indoor modelling and route finding from the aspect of first responders and emergency managers. It provides a contribution to this identified gap in the current indoor modelling area and provides the basis for establishing a new research direction for agenda that to date has been dominated by a focus on civilians and their applications for indoor environments.

In summary, this research has achieved five key contributions to knowledge:

1. The research investigated the strengths and weaknesses of current indoor first response procedures and the related literature in the area and discussed the importance of provision of indoor situational awareness to first responders prior to physical entrance.

2. The research proposed a framework for 3D modelling of the indoor environments based on first responders’ emergency response requirements discussing the importance of detailed geometric and semantic information for indoor spatial modelling resulting in the 3D IESM

3. The 3D IESM enabled seamless indoor/outdoor various levels of detail, as well as seamless spatial analysis and routing for emergency responders

4. Presented and formulated the Search and Rescue Problem and developed the application of an ant colony solution approach for the problem based on the geometric/semantic indoor graph extraction from IESM, for finding the optimum number of rescuers to undertake the search procedures in the minimum time.

5. Leveraged indoor information to solve the Search and Rescue Problem for 3D indoor environments both statically and dynamically which facilitates resource allocation
management and improves response time drastically compared to current fire fighter practice strategies.

8.4 Outlook and Future Research Recommendations

As an exploratory study in the area of indoor situational awareness for emergency response, this research will serve as base for future research opportunities. Some of these are associated with the limitations of the research and the research design/development; others aim to extend the work that has been achieved here.

8.4.1 Automatic Indoor Graph Construction Based on IESM

The IESM based indoor geometric network model was extracted manually in this research to ensure complete extraction of semantic/geometric information from the model and since the automation procedure was out of the scope of this research. Further research should be carried out to establish a solid framework to enable extraction of route graphs that could be customized to each application; from evacuation, to civilian path finding and first responder routing. The main point for the indoor GNM is to contain all the building information so other graph variations can be extracted to fit the specific application.

8.4.2 Real-time Indoor Graph Reconstruction

The accuracy and reliability of the navigation routes depends on the accuracy of the underlying route network. Availability of IoT systems for buildings allows finding paths that match the real time conditions of the building more realistically. Thus, it is recommended future studies focus on approaches for dynamic update of the indoor graph network elements based on building conditions. For example, what is the optimized way of making the blocked areas inaccessible, or how obstacles change the corridor passability, or smoke movement, etc.
8.4.3 Quick and simple building information update

One of the main challenges of creating indoor spatial models is the difficulty and time consumption of creating them in the modelling softwares such as Revit and manual entry of semantic information. Moreover, keeping the models updated with their latest changes in the building is quite difficult and thus, using them in a larger scale is impossible at the moment. A very useful area of future research would be how to simplify the creation process with minimum human involvement such as ability to extract the geometry and semantic information from indoor LiDAR scans. Also, updating the created models to adjust with building changes should be easy enough to be undertaken by civilians.

8.4.4 Improving the Efficiency of the SRP Algorithm

The main aim of this research was to introduce the 3D Search and Rescue Problem for the indoor environments and develop a solution algorithm to showcase the significant improvement it can make to indoor emergency response time and resource management compared to the current practice strategies. Although the proposed algorithm delivers the expected solution and improves response time drastically, there is opportunity for further research to improve the algorithm’s efficiency by improving the ant colony’s strategies or by developing other stronger algorithms such as tabu search, etc. Also, addition of other conditions such as giving priority to searching the hazard or victim prone areas first, or using time and priority constraints to force somewhat important points to be visited in a specific time frame, or the dynamic graph weight adjustment based on the building condition; can be useful in having more practical results.

In addition, the all-pair shortest path is used for next neighbor selection in the ant colony algorithm proposed. As this would have a high computation time for big structures, it is recommended that further research be undertaken to use less time consuming strategies.

8.4.5 Resource Based Route Assignment

There are many situations where the maximum number of first responders, trucks, or other resources are limited and thus, the search and rescue routes should be adjusted to fit these conditions. It is suggested that future research develop algorithms that can meet these
conditions. In addition, in the case of availability of victim locations in the building, the search and rescue problem could be configured to only search these points rather than a thorough search of the building.

8.4.6 Immersive Technology for Better Understanding and Presentation of the Indoor Search and Rescue Approach

Due to the essence of the problem, evaluation of the system couldn’t be undertaken on the field. Thus, here a computer based implementation and an agent based simulation were used for the evaluation and validation. It is recommended to undertake to evaluation with a virtual reality system for a more realistic and accurate testing of the system and to record user experience and how effective emergency planners find the proposed approach.

The full potential of the solution approach could be released if it is provided to first responders on a wearable device. Thus, future research should attempt to develop the IESM and SRP approach on augmented reality, head mounted systems, or hand held devices.

8.4.7 Integration with positioning systems

Finally, although provision of routes on detailed 3D models gives very good comprehension of the environment, still any indoor routing approach is reliable on an accurate localization system. Future research directions should focus on how the positioning systems could be integrated with the proposed indoor spatial model and searching algorithm.
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