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Emergency search plan for complex premises

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Abstract

Terrorist attacks, natural disasters are on the rise. Land scarcity has forced cities to grow vertically. As a result buildings are becoming a complex environment, posing remarkable challenge for first-responders in emergency situations. Of the most important operations in emergency management is to conduct a timely search of premises. The question of interest is how many firefighters are needed and what are their search plans? Though it is a crucial question, the literature and industry have yet to address it. To this end, we propose a two-phase methodology to draw up the most efficient and timely search plan, called "search map". In the first phase a minimum number of firefighters is identified. In the second phase, search maps (or routes) for each firefighter are identified. We demonstrate that these two phases have strong resemblances to two famous and quite difficult mathematical problems, namely the "Chinese Postman Problem" and the "Vehicle Routing Problem". We encode the methodology as two optimization problems which are then solved by two leading optimization software package: GAMS and MATLAB. Numerical results of a large sized floor plan is presented and discussed. The two-phase setup results in an efficient methodology which makes it a suitable tool for addressing real-time emergency responses in rapidly changing indoor environments. The results can be integrated in Building Information Management (BIM) systems and city/building 3D models.

1.Introduction

Climate change and global warming as well as terrorist attacks in recent years have resulted in unprecedented human life losses and infrastructure damage. Yearly economic losses have reached a couple of hundred billion US dollars worldwide (Abounacer et al., 2014) which has been a focal point for many disciplines in academia and the industry. In reference to occurrence of disasters, emergency management -a phrase to describe initiatives involved in responding to disasters- consists of actions before (i.e. mitigation and preparedness) and after (response and recovery) the event (Lee and Zlatanova, 2008, Cutter, 2006, Cutter et al., 2003, Abounacer et al., 2014, Altay and Green, 2006, Haddow et al., 2013). Catastrophic events in 9/11, 2001 were a tipping point in emergency management which calls for swift and timely responses. That resulted in a completely new paradigm in response operations based on 3D modelling (Kwan and Lee, 2005, Thill et al., 2011, Pu and Zlatanova, 2005, Lee and Zlatanova, 2008). The 3D modelling synthesized with GIS is perceived to be an effective tool to plan, monitor, manage and execute emergency response operations (Lee and Zlatanova, 2008, Gelenbe and Wu, 2012). A number of these models are reviewed by (Han et al., 2010, Bagloee et al., 2019). In this context, the 3D models are integrated with Building Information Management (BIM) to take details of buildings as well as semantic information into consideration (Chen et al., 2014, Isikdag et al., 2013). Integration of the 3D models of BIM have coincided with the revolution in sensor technologies (Waldrop and Lippel, 2008, Gelenbe and Wu, 2012, Dia et al., 2020).

The building industry is adapting to such emerging technologies in sensors and monitoring devices and it is moving towards intelligent premises. Reduction in costs of sensor technologies renders the prospect of deploying large-scale and robust sensor networks within buildings (Han et al., 2010). This provides precious real-time data (Gelenbe and Wu, 2012) which can be fully integrated in the 3D models and be used in emergency response operations (Isikdag et al., 2013). In the wake of an emergency situation, the first concern is to transport aid response teams to affected areas (Bagloee et al., 2014), which itself could be a daunting task depending on the nature of emergency (fire, natural disaster, terrorist attack) as well as access roads and traffic conditions. This article is concerned with indoor emergency responses assuming that the emergency teams have already arrived at a building. The first action, therefore, is to search the building to spot any casualties and trapped persons. As far as time is concerned, compared to outdoor transport time, the search operation (per se) in buildings, at first sight, does not seem to be of immediate interest. In reality this is not true, especially when encountering large premises with complex floor plans. Empirical data indicate that response delay within the buildings due to the indoor route uncertainty can be much longer than delays incurred in ground transportation (Lee and Zlatanova, 2008). This has been exacerbated by the rapid pace of urbanization as discussed below.

Population growth and land scarcity have pushed cities to become denser and people to move from suburbs to settle in areas closer to city centre seeking job opportunities. As a result, dwelling units are aggregating into residential complex and high-rise buildings. In the other hands, job opportunities are created in city centres where cities provide better infrastructure in terms of transport, utilities, IT communications, security etc. As such, city centres tend to grow vertically -in a confined area- which results in gigantic office towers, shopping mall, multi-use skyscrapers, and residential towers. Consequently, in the new millennium, buildings are becoming larger and more complex which in turn calls for special preparation before encountering an emergency situation (Thill et al., 2011, Pu and Zlatanova, 2005, Tian-yu et al., 2011). Accordingly, indoor emergency management has recently been taken as important as outdoor. In fact, indoor and outdoor operations must be highly coordinated to render timely and speedy services.

In such emergency situations, the very first basic necessity is to get firefighters, paramedic personnel, security forces (in short “first-responders”) to premises searching every corner for victims when even seconds count (Diehl et al., 2006, Kwan and Lee, 2005, Wu and Chen, 2012, Bricault, 2006). Although a large body of research is dedicated to indoor location/navigation support and 3D path planning, little has been done on search planning. More precisely, the question of interest is: when first-responders arrive at an affected premise, who (i.e. how many firefighters) needs to search and how/where? In other words, first-responders need to be supplied with search plans or maps in which everyone knows his/her search route and what to search for, such that the entire premise is fully searched at minimum possible time and with minimum possible squads. It is important to deploy as minimum possible search teams, since the environment could be very volatile and risky and first-responders’ lives could be at stake (Abounacer et al., 2014). This also greatly helps to keep order in hand and better manage the situation in such a chaotic environment. Studies as well as empirical evidences show that number of people involved in the rescue operations can easily amount to hundreds (Diehl et al., 2006).

To the best of our knowledge, literature in this realm is sparse. Some scholars have reported that, although emergency management problems fit perfectly into the discipline of operations research and management science (OR/MS), the research conducted by the OR/MS community on the subject is still limited especially in the response phase (Altay and Green, 2006, Abounacer et al., 2014). Perhaps, it could be due to the fact that emergency environment is a very fluid and dynamic in which everything is changing rapidly (Fischer and Gellersen, 2010) including the search area. In such cases, one may accept there is no point to look for any preplanned search map. Although the assumption of this argument sounds valid, search planning can and should be an indispensable part of any emergency management scheme. The buildings are becoming more intelligent, equipped with a variety of detectors, sensors, and cameras, as so do the first-responders. Therefore real-time information of the environment can be used to draw up a dynamic map of the area (Gelenbe and Wu, 2012) which in turn is communicated to the first responders helping them in their navigation and search operation. In such cases, one still needs to transmit the most efficient and effective search route to the search operatives, though, it could be changing over time.

Furthermore, no matter how communication devices and sensors are smart, robust and sophisticated, there is still a high probability of failure in their operations (Fischer and Gellersen, 2010, Fallah et al., 2013). There is no silver bullet for location and navigation support for emergency response (Fischer and Gellersen, 2010). In such cases, a search plan is still better than nothing. To this end, US National Institute for Occupational Safety and Health (NIOSH) strongly advise that “Working in large structures (high rise buildings, warehouses, and supermarkets) requires that fire fighters be cognizant of the distance travelled and the time required to reach the point of suppression activity from the point of entry. In fact there is a bold trade-off between systems that provide high-quality location information and those that are easy to deploy (Fischer and Gellersen, 2010), and “search map” is of the latter.

Nowadays, safety standards across the world enforce a number of easy and highly effective measures such as posting an evacuation map (or sometimes called an “access map” (Isikdag et al., 2013)) on the boards of every floor of buildings in which topography of buildings, such as location of exit doors and corridors as well as exit routes are shown. By the same token, it is also easy to supply buildings with search maps tailored to architectural specifications of each floor. Based on a minimum number of first-responders, a search map clearly indicates search route of each firefighter such that the entire floor is fully checked and searched. This study addresses the “search map” problem. We divide the problem into two sub-problems: given topography of a floor (called floor plan) we first identify the minimum number of firefighters to conduct the search in which the total search times is minimized. Given the minimum number of firefighters and the floor plan, in the second sub-problem, a search map of every firefighter is drawn up.

The rest of the paper is organized as follows: section 2 presents mathematical model in detailed, section 3 is dedicated to two pilot studies, Section 4 concludes the article and sheds light on future research directions.

2. Mathematical Model

For the purpose of modelling (a virtual representation of reality), buildings and spaces are discretised and are represented by simple elements (Lin et al., 2013, Wu and Chen, 2012). Examples are small polygons denoting a planar object like floor space, or line segments (also called links or arcs) displaying corridors, or points (or nodes) depicting cross points, entry/exit points and so on. Since the circulation of first-responders is of interest, we comply with graph theory terminology and represents corridors, passages, elevators, escalators, scape stairs and doors as a network G(V,A) where V, A are sets of nodes (or vertices) and links (or arcs) respectively. The question now is how to represent a floor plan using node and links which is discussed in the next section.

2.1. Representing a floor plan as a network graph

As noted before, a search must be conducted in a way that the entire network is searched and checked. This can be formulated as a mathematical programing problem (or simply called optimization problem) in which some of the constraints enforce visiting all elements on the network at least once. Knowing that a network consists of two types of elements (nodes and links), one typical way is to represent every corner of a building including all rooms, their doors and other details with nodes and make sure that in the search plan every node is visited at least once (Wu and Chen, 2012, Lin et al., 2013). This has typically shown for a floor plan in Figure 1. As can be seen, Figure 1(c) depicts a fully detailed floor. With respect to computational intensity (which is a significant concern when dealing with large sized and complex buildings) we prefer to have fewer of nodes and links. An intuitive method is to ensure that every link of the network is visited once. It is like a firefighter passing along corridors and searching all rooms along his/her passage. In such cases, each link may represent a passage (such as a corridor) as well as all rooms and other details on side passages. Therefore, there is no need to code every single element of the building, rather, one only needs to code corridors, hallways, elevators, stairs, escalators for which nodes are their cross points. This coding has shown in Figure 1(d), such that number of links and nodes from 32 in Figure 1(c) drastically reduces to 1 and 2 respectively. According to Figure 1, a firefighter passing through link (1, 32), by default, searches all rooms and doors in between. Hence nodes 2 to 31 (of Figure 1(c)) as well as corresponding link segments become redundant, that is they add no insight to the model, otherwise, they adversely become a hefty burden on computational times. Note that, we denote each link or arc of the network using tail and head nodes id.

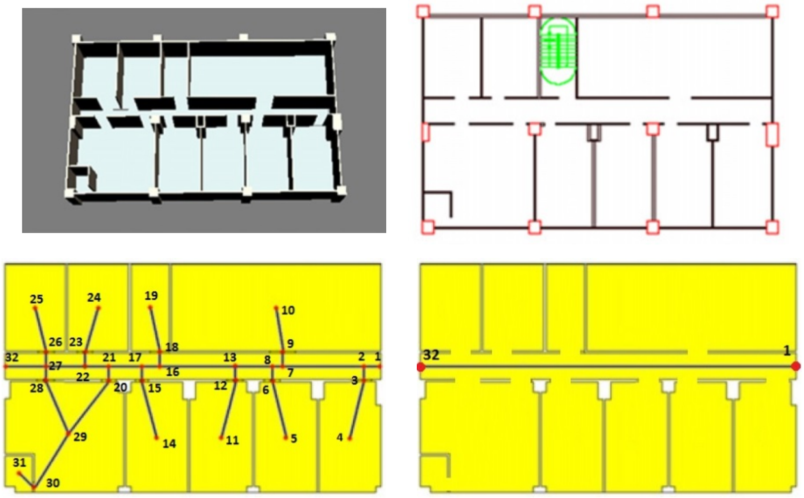

Figure 1, Floor plan: from 3D representation to 2D as well as two network representations

2.2. Phase 1: finding minimum number of firefighters based on CPP

Since the movement network is ready, we can code the search of firefighters as a network flow problem which has benefitted from extensive research and a rich literature. To this end we need to comply with their terminology. Let us consider the deployment point of firefighters as an origin (or source) and the exit door as the destination (or sink). Note, it is easy to consider multiple deployment points using dummy links connected to a dummy source. The same can be said for multi exit doors.

Now the problem is modelled as a network flow with a pair of origin-destination or O-D. Hence, the first challenge is to find out –at a minimum- how many firefighters are needed to get each link of the network visited at least once. If we assume there exists only one firefighter, the problems leads to a very interesting and famous problem called Arc Routing Problem or Chinese Postman Problem (Eiselt et al., 1995) (CPP). Inspired by the formulation of the CPP (proposed in the literature), the above problem -to identify minimum number of firefighters-can be written as an integer programing given below (all terms are non-negative unless otherwise stated):

SM-CPP (It is acronym for Search Map Chinese Postman Problem):

$$\min \sum_{(i,j)\in A} t_{ij}.x_{ij} + q \quad (1)$$

$$\text{s.t.:} \quad x_{ij} + x_{ji} \geq 1, \qquad \forall (i,j) \in A \quad (2)$$

$$\sum_{(v,j)\in A} x_{vj} - \sum_{(i,v)\in A} x_{iv} = \begin{cases} -q & v \in D \\ +q & v \in O \\ 0 & o.w. \end{cases} \qquad v \in V \quad (3)$$

$$x_{ij} \leq c_{ij} \qquad (i,j) \in A \quad (5)$$

$$x_{ij} \text{ integer} \quad (6)$$

where x_{ij} is the number of firefighters traversing link $(i, j) \in A$ [1], t_{ij} is search time along link $(i, j) \in A$. Therefore the objective function (1) simultaneously minimizes two terms: (i) total time spent by all firefighters in the building and (ii) total number of firefighters denoted by q. The search time can be generalized as a (nonlinear) function of the total number of firefighters passing through the respective link to reflect additional delay due to being overcrowded. It is a well-known concept in transportation science known as traffic congestion. Constraint (2) ensures that each link is visited at least once. Note that, a link $(i, j) \in A$ has two directions i→j and j→i so it can be searched from either direction[2]. Constraint (3) ensures total flow entering a node is equal to total outgoing flow which is formally called a conservative flow constraint. For two origin and destination nodes, the net difference between incoming and outgoing flow equates the total number of firefighters q. In other words, the unit of flow in the network is firefighter. Constraint (5) keeps the flow on links under their respective capacities (c_{ij} is capacity of link $(i, j) \in A$). Last constraint (6) is the integrality condition. The above problem SM-CPP is encoded in GAMS -a leading optimization software- as a mixed integer nonlinear programing (MINLP)[3] problem.

For a clear and concrete illustration let us consider a small network as shown in Figure 2. All links are identical, that is they are associated with equal search times and infinite capacities. After solving problem SM-CPP, links' flows are identified as shown on each link in Figure 2(a) and value of q is found to be $q = 1$. Inclusion of a second term in the objective function (1) bears an interesting interpretation. It is equivalent to solving a network flow problem where the destination node is connected to the origin node (using a dummy and directed (or one-way) link with one unit of search time). This is shown in Figure 2(a) with a dashed arrow.

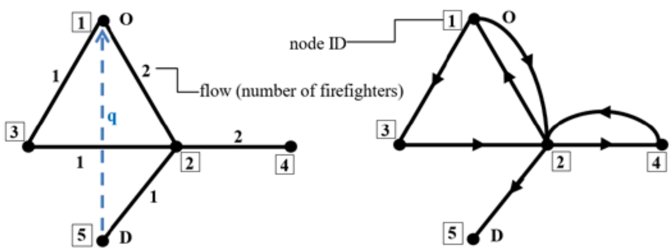

Figure 2, Undirected network and the corresponding augmented-directed network

[1] Note, in some cases, some links are inevitably traversed more than once since they also provide to some dead-end locations

[2] In the literature, G(V, A) is called undirected graph or network, that is, flow on both directions are allowed

[3] We generalize the formulation by assuming that the search time t_{ij} is a function of number of firefighters $t_{ij}(x_{ij})$ which could be a nonlinear function. Therefore problem (1) ... (6) must be considered as a MINLP problem.

Though ignoring the second term of the objective function results in the same total search time, it may not necessarily result in the minimum number of firefighters. For example, in example of Figure 2, the total search time on real (not the dummy) links can easily be calculated as 7[4]. If the second term of the objective function is dropped, the flow values on links (1,3), (2,3), (1,2), (2,4) and (2,5) become 1, 1, 1, 2, 2 respectively, in which total number of firefighters becomes $q = 2$.

2.3. Phase 2: finding the search map based on Vehicle Routing Problem

The next question to be addressed is the search plan. For the small network of Figure 2(a) one can intuitively draw up the search map for the only firefighter which is shown in Figure 2(b). Obviously it is more complicated for real and large-sized networks. To this end, we first build up intuition from the results of problem SP-CPP and Figure 2. Though Figure 2(a) indicates flow values labelled on each link, Figure 2(b) augments the network as per flow values. That is, a link with flow value of 2 is represented twice in Figure 2(b). Now for the only firefighter of the above example, he/she just needs to find his/her search path over the augmented-directed network of Figure 2(b) such that all links are traversed **absolutely only once**[5]. This new problem bears all the hallmarks of the Chinese Postman Problem if the number of firefighters is limited to one. Obviously it is not the case always, so the problem is defined as follows: given a number of firefighters (more than one) and an augmented-directed network (like Figure 2(b)), it is desirable to derive a series of search maps (equivalent to the number of firefighters) such that each link is visited only once. This new definition of the problem now bears a strong resemblance to the "vehicle routing problem" (VRP). The only difference is that in the VRP each **node** has to be visited once, whereas, in our problem each **link** (not node) must be visited only once. The VRP, though, is proven to be of the highest computational difficulty (an NP-hard problem). The VRP is well studied in the literature and there exist a number of good solution algorithms (exact and heuristic). Therefore it is a worthwhile endeavour to transform our problem to a VRP. To do so, each link of the augmented-directed network (Figure 2(b)) is replaced with a node (placed in the middle of the link) and based on direction of the links themselves, the nodes are connected to each other. Figure 3(a) graphically illustrates this process where a new directed network is built upon the previous augmented-directed network. As shown in Figure 3(a), the connection between nodes follows the underlying network shown in grey. For example in the grey network, link (1,3) is only connected to link (3,2), therefore node 2 of the bold network (which represents link (1,3) of the grey network) is connected to node 5 of the bold network (which represents link (3,2) of the grey network).

Given the number of firefighters and the new directed network (bold network of Figure 3(a)) - all derived from solving SP-CPP- we can now proceed to solve the VRP-like problem. Accordingly, for the directed network of Figure 3(a), an intuitive solution of the VRP is depicted in Figure 3(b) in which a route (for the only firefighters) from origin "O" to destination "D", visiting all the nodes –only once- is drawn up.

We now proceed to formally provide a formulation for the VRP. Let us consider $G(\overline{V},\overline{A})$ is a directed graph consisting of $\overline{V}$ and $\overline{A}$, sets of nodes and directed links respectively. Traversing the links needs to be subjected to a delay time or cost. Since each link of Figure 3(a) connects two successive links of the augmented-directed network of Figure 2(b), it is plausible to consider average search times of the aforementioned pair links (belong to Figure 2(b)) as delay

[4] Search time on each link is assumed one unit of time, hence we have 7=(1+1+2+2+1)*1

[5] Note that in the previous problem (i.e. (1) … (6)), each link had to be visited at least one, that is, it could be once, twice, three times etc, while in this new arrangement each link of the augmented-directed network must be visited absolutely once

or cost for the respective link of Figure 3(a). Let us denote this new delay by $\bar{t}_{ij}$, q: the number of firefighters to be dispatched (found from solving SP-CPP); $\bar{x}_{ij}$ is a binary variable: 1 if a firefighter traverses link (i, j) and 0 otherwise. SP-VRP[6] :

$$\min \sum_{(i,j)\in\bar{A}} \bar{t}_{ij}.\bar{x}_{ij} \tag{7}$$

$$\sum_{i\in\bar{V}} \bar{x}_{ij} = 1 \qquad \forall j \in \bar{V} \setminus \{\bar{O},\bar{D}\} \tag{8}$$

$$\sum_{j\in\bar{V}} \bar{x}_{ij} = 1 \qquad \forall i \in \bar{V} \setminus \{\bar{O},\bar{D}\} \tag{9}$$

$$\sum_{j\in\bar{V}} \bar{x}_{Oj} = q \tag{10}$$

$$\sum_{i\in\bar{V}} \bar{x}_{iD} = q \tag{11}$$

$$y_i - y_j + N.\bar{x}_{ij} \le N-1 \qquad \forall i, j \in \bar{V} \setminus \{\bar{O},\bar{D}\},\ i \ne j \tag{12}$$

$$\bar{x}_{ij} \in \{0,1\} \qquad \forall i, j \in \bar{V} \tag{13}$$

Total traversing times are minimized by objective function (7). Constraints (8) and (9) ensure each node (excluding the origin and the destination) are visited only once. In constraint (10), total number of firefighters dispatched at the origin is set to q while constraint (9) ensures all firefighters (q) end their search at the destination. Constraint (12) eliminates any sub-tour in which $y_i \mid \forall i \in \bar{V} \setminus \{O, D\}$ is a real variable (Miller et al., 1960). Integrality (binary) variables are also introduced in constraint (13).

The VRP is proven to be among the most difficult optimization problems (known as NP-hard): that is, as the size of network (number of nodes and links) increases, the computational times increases exponentially. To this end, some resort to non-exact (or heuristic) methods which render good (not necessarily best) solutions in a more affordable computational time. Nevertheless we still stick to the exact methods for two reasons: (i) one can intuitively perceive that the directed network shown in Figure 3(a) is highly sparse, that is, it is not fully connected (for example node “O” is only connected to nodes 2 and 3, not any other nodes). In other words, the number of links is kept at minimum level which favourably keeps the size of the network down. (ii) There has recently been a surge of interest in exact methods owing to continuous enhancements in computational technology and optimization methods. In one estimate during the course of a decade, optimization has become a million times faster (Lodi, 2010).

The transformations of the networks (from floor plan, to augmented-directed and the corresponding directed VRP, Figure 2(a) to Figure 2(b) to Figure 3(a)) is coded using Visual Basic (VB) programming language, out of which a series of matrices are produced. Based on these input matrices, the above VRP problem is encoded and solved using MATLAB (MathWorks, 2016).We can now apply the above methodology to a pilot study.

[6] It is an acronym for Search Plan –Vehicle Routing Problem

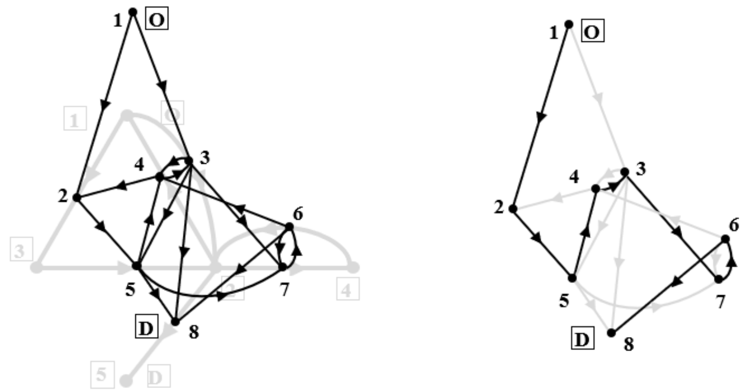

Figure 3, simple example, (a) augmented-directed network is transformed to directed network to comply with VRP, (b) it shows the intuitive solution of the VRP

3. Numerical Evaluations

A floor plan used as a pilot study is depicted in Figure 4, where search times along respective corridors as well as their capacities are labelled (note, nodes 1 and 20 are respectively considered as entry and exit points for the firefighters). In this section we provide two pilot studies, where Figure 4 constitutes the first case studies referred to as pilot-1. We then draw some conclusion on the quality of the search maps or routes, based on which the SP-VRP is refined. We then establish a more challenging pilot study (pilot-2) and show the numerical results.

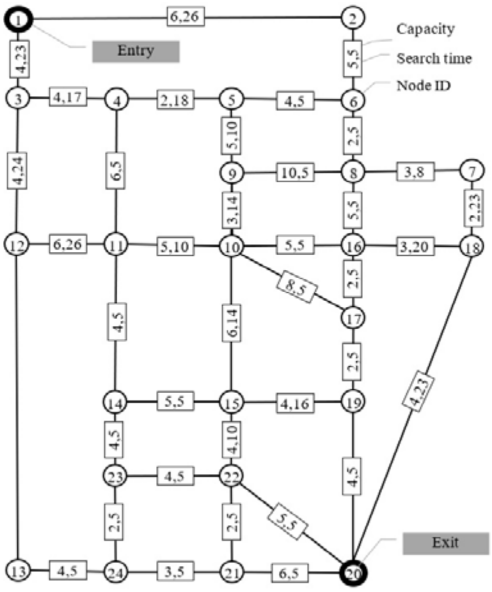

Figure 4 floor plan used as pilot-1

For solving the corresponding SP-CPP we employed solver ANTIGONE of GAMS which took only 1.2 second. As the results, the minimum numbers of firefighters as well as total search time are found to be 4 and 193 respectively. In addition, the total number of firefighters on each link (as flow) is also extracted which is then used as a base to establish the augmented-directed network of the VRP.

We solve the resultant SP-VRP using “intlinprog” of MATLAB a newly released function in the year 2014 (MathWorks, 2014) which took 5 second. Finally the search map corresponding to four firefighters are shown in Figure 5. As indicated in Figure 5, search times vary significantly from 24 to 67 units of time. In other words, one of the firefighters can get his/her search quickly done (24 unit of time) whiles the other one has to carry on the search more than twice as long (67 units of time). A valid question arises as follows: is there any better or fairer search plan by which the firefighters spend almost equal times in the premises? We address this question in the next section.

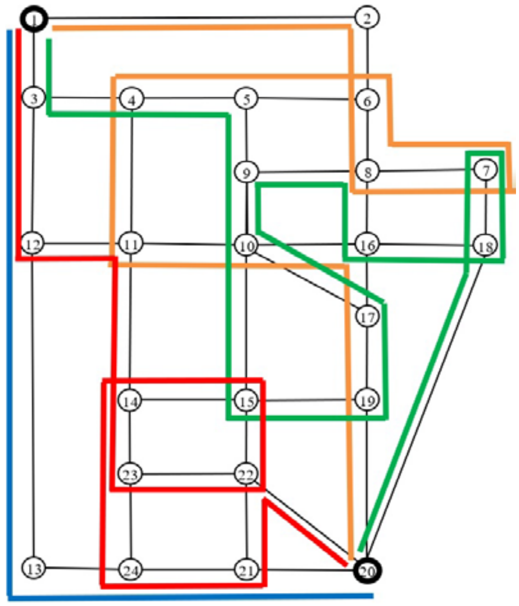

Figure 5 Results of pilot-1, search maps (routes) found for four firefighters

Let us first to make the above floor plan more challenging and complicated. As noted before, rooms, chamber and doors along a corridor are all represented by a single link. Hence, in order to make the search challenging and more difficult we artificially add all possible diagonal lines to the network of Figure 4. The SP-CPP is first solved in 1.9 second which resulted in 5 firefighters and total search times of 409 units of time. Similar to what was described for the pilot 1, the SP-VRP was solved

The results indicate, search times vary from 43 to 139 units of time – with the total of 409- which shows a much deeper gap (compared to pilot-1). Ideally, we would like to have evenly distributed search times for each firefighters (i.e. $82 \approx 409/5$). More precisely, it is of paramount importance to reduce the longest search time, in other words, we would like to get the last firefighter (the longest search time) quickly out of the building. Therefore, the SP-VRP needs to be rewritten to first distinguish each path and second to add an upper bound to the search time of a particular path. SP-VRP-R :

$$\min \sum_{k=1}^{q} \sum_{(i,j)\in \bar{A}} \bar{t}_{ij} . \bar{x}_{ij}^{k} + T \tag{14}$$

$$\sum_{i \in \bar{V}} \bar{x}_{ij}^{k} = 1 \qquad \forall j \in \bar{V} \setminus \{\bar{O}, \bar{D}\},\ k = 1..q \tag{15}$$

$$\sum_{j \in \bar{V}} \bar{x}_{ij}^{k} = 1 \qquad \forall i \in \bar{V} \setminus \{\bar{O}, \bar{D}\},\ k = 1..q \tag{16}$$

$$\sum_{j \in \bar{V}} \bar{x}_{Oj}^{k} = 1 \qquad k = 1..q \tag{17}$$

$$\sum_{i \in \bar{V}} \bar{x}_{iD}^{k} = 1 \qquad k = 1..q \tag{18}$$

$$y_i^k - y_j^k + N.\bar{x}_{ij}^{k} \le N - 1 \qquad \forall i, j \in \bar{V} \setminus \{\bar{O}, \bar{D}\},\ i \ne j, k = 1..q \tag{19}$$

$$\bar{x}_{ij}^{k} \in \{0,1\} \qquad \forall i, j \in \bar{V}, k = 1..q \tag{20}$$

$$\sum_{k=1}^{q} \bar{x}_{ij}^{k} \le 1 \qquad \forall (i, j) \in \bar{A} \tag{21}$$

$$\sum_{(i,j)\in \bar{A}} \bar{t}_{ij} . \bar{x}_{ij}^{k} \le T \qquad k = 1..q \tag{22}$$

In the above formulation, all search paths are distinguished using superscript k where $k = 1..q$. Compared to SP-VRP, constraint (21) gurantees no overlap among search paths over the directed network. Furthermore, constraint (22) proposes an upper bound to the search times denoted by T which is minimized in the objective function (14). We referred to the above problem as SP-VRP-R (i.e. refined SP-VRP).

The SP-VRP-R is applied to pilot-2 to derive 5 search paths such that the duration of the longest search path is kept as short as possible. The results are shown in Figure 8 where search times vary from 32 to 109 unit of time – with a total of 409. As can be seen, compared to previous attempts (pilot-2 with SP-VRP) the longest path has reduced significantly (139 vs 109), while the total search time remained the same.

It is ovious that the SP-VRP may have more than one solution. Though mathematicians prefer to deal with problems with unique solutions not multiple solutions, we as engineers can tap into it and seek a more desirable solution –as found in SP-VRP-R.

The computational time of the SP-VRP-R lasted only 8 seconds. All in all, for a large sized floor plan, total computational time doesnot exceed a minute. This is very important in real-time emergency responses, where the situation is highly dynamic and fluid to the extent things such as falling debris and fire spread may change indoor accessibilities. As such, the proposed methodology can also be integrated in a real-time emergency management system to address emergency situations head-on and on the spot.

4. Conclusion

The importance of timely responses in indoor emergency situations is beyond any doubt. Land scarcity - especially in city centres- forces cities to grow vertically, buildings are being aggregated to mixed land-use premises, and those have made indoor environments highly complex. This in turn makes the search and rescue operations extremely difficult. As such, navigation is becoming a must. To this end, communication technologies, detection devices, monitoring units and sensors are becoming affordable and omnipresent to the extent building are adapting to them and becoming smart and intelligent. All these emerging technologies pave the way for the virtual reallity to build up a real-time 3D invironment. The aim is to facilitate and streamline navigation path finding, as well as search and rescue operations. In light of harsh, unpredicted and highly dynamic conditions during emergency situations (such as fire, blast, flood, earthquack to name a few), reliability of such new technologies is a significant concern. Nevertheless (be it a smart and intelligent premise or not) buildings need to be supplied with search plans for the first-responders. A search plan can simply be a search map in which the minimum number of firefighters and their respective search routes are shown. Such maps can be communicated with emergency response agencies and authorities and can also be made available in the premises: installed on boards – similar to exit maps. This study addresses such a need. The question of interest is, given a floor plan of a building, (i) what is the minimum number of firefighters to conduct the search at the minimum possible time, (ii) what is the search map (path) of each firefighter such that the entire floor is searched and investigated.

In complying with the nature of the problem, we developed a two-fold methodology. We first found out that the problem is intrinsically of the famous Chinese Postman Problem (CPP), where a postman (or postwoman) needs to traverse all the roads (or links) of a network. The main difference is that the a floor (of a building) – depending on the its size and complexity - may need more than one firefighter, while the CPP is subjected to only one postman (or postwoman). Therefore -in the first phase- we solve an integer programming problem to identify minmum number of firefighters while total search times is minimized. As a result, one can identify how many times a link is visited by firefighter(s). In the second phase, this information is then exploited to arrive at a directed and augmented network for which we need to solve a vehicle routing problem (VRP).

We applied the methodology to a large-sized floor plan and elaborated on the numerical results. As shown, the total computational time (for both phases combined) is a few seconds. From a real-time response point of view, affordable computational time is of the highest importance. It enables us to address dynamic indoor environments during emergency situations where the floor plan might be rapidly changing.

Though the focus of this reseach was indoor response, one should not ignore outdoor conditions. The authors believe that a successful and reliable response plan must get outdoor and indoor operations synchronized and highly coordinated. The same methodology can also be applied to vehicular movement from fire stations to emergency-hit locations. Priority of responses, the stochastic nature of the events and the scarcity of available aids are significant elements that need to be thoroughly addressed in the future.

This research appeals to municipalities, zoning authorities, emergency management agencies, designers/contractors, regulators and legislative bodies to call for making the “search map” a must. The intuitive methodology proposed in this study can effectively streamline this process. Since the methodology supports CAD files, the entire process can be easily conducted online, so that one can upload a floor plan (as a CAD file) and download the search map. The same data can simultanously be communicated with emergency response agencies to be included in their planning for emergency situations.

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