Toward BIM-Enabled Decision Making for In-Building Response Missions

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***Abstract*—Decision making for rescue and evacuation is critical for disaster response operations not only in open spaces but also in buildings. For infrastructures with large and complex geometrical layouts, decision making could be facilitated with computer-aided approaches for better accuracy and efficiency. This paper aims to respond to fire in buildings. We combined network analysis with building information modeling (BIM) to facilitate the decision making for response operations. Building geometry is retrieved from the BIM model for graph construction and route finding. In this paper, the visibility graph (VG) and medial axis transform (MAT) are evaluated for graph construction. A hybrid method that combines VG and MAT is proposed, and encouraging results have been shown. Risks based on building materials and traffic of pedestrians are to be adapted for network edge costs to enable the lowest utility route finding in the future. The accuracy and efficiency for emergency decisions are expected to be improved for in-building rescue and evacuation operations.**

***Index Terms*—Building information modeling (BIM), emergency response, visibility graph, medial axis transform, path finding, fire emergency, evacuation, pedestrian.**

I. Introduction

With the transportation modes being integrated into a system of services, the convenience for transport has been significantly improved. Failure of a component in the system could result in severe consequences. As transportation hubs connect systems of transport such as Mass Rapid Transit, Railway, High Speed Rail, and buses, their physical infrastructures usually have complex characteristics. Response to disasters in such environments is challenging to emergency management agencies [1], and the rescue and evacuation decisions are critical to emergency response [2].

Building Information Modeling (BIM) is an approach in civil and architectural engineering for the life cycle management of infrastructures. A database is integrated with a 3D model that stores detailed information of objects and entities. An integrated platform based on parametric computer aided design, it allows interdependent functional design with rule-based error checking and conflict detection [3]. BIM has quickly emerged as the preferred platform for civil and architectural design due to its ease in communication for design alternatives through 3D/4D visualization and its accurate interfacing between complicated building systems.

There has been research focusing on utilizing BIM to facilitate emergency decision making such as evacuation regulation checking [4] and indoor localization [5] for fire hazards. This research proposes the bridging of BIM and network analysis for in-building response operations. The remaining part of the paper is organized as follows. Section II reviews related literature regarding BIM, path finding and in-building response operations. Section III states the objective of the work and Section IV describes the approach. Section V presents testing results. The research findings, contribution, and future directions are discussed in Sections VI and VII outlines the conclusion.

II. Literature Review

This section presents research conducted in the current literature regarding approaches related to in-building response operations. The literature includes BIM, facility and indoor evacuation, applications of BIM in emergency situations, and graph theory for constructing networks and route finding.

BIM has advanced in recent years in the domain of civil engineering [6]. BIM is an integrated approach and technology based on a database which stores building information with an object oriented scheme. In BIM, information is stored with relational attributes and spatial relationships between objects. By involving all stakeholders in the lifecycle of infrastructures and having them to work on a single BIM model, information is coherently stored providing enhanced compatibility and interoperability [7]. Zhang *et al.* [8] applied automated safety checking to BIM models for the detection of hazards.

There have been research efforts on the integration of BIM into building evacuation. Wang *et al.* [9] had develop an add-in toolbox using the Revit Application Programming Interface (API) [10] for the estimation of the capacity and time for building evacuation. The tool checks whether the public space meets standards and serves as a reference for design modifications. For evacuation planning in the pre-design phase of construction projects, there is also research based on BIM for the prevention of bottlenecks and congestions during construction [11].

There are works related to in-building emergency decision making, such as pedestrian simulation models using cellular automata [12], [13] and agent based evacuation [14], [15]. The simulation models assist in the identification of evacuation

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routes in high risk infrastructures, such as subways and transportation hubs [16]–[18]. Pedestrian behavior is to be taken into account and the model accuracy is required to be improved for more precise decision making [19], [20]. There are also the development of intelligent emergency response systems utilizing real-time 3D Geographic Information System (GIS) [21]. In addition, there is also work focusing on real-time data analysis in high risk buildings [22] that receives temperature and carbon monoxide concentration from sensors.

BIM stores the information in the format of Industry Foundation Classes (IFC) [23], and applications of BIM in emergency management have been proposed. Geography Markup Language (GML) and XQuery are suggested to search spatial and relational attributes from the BIM [24]. Fire accident records are transformed into tables and combined with BIM to facilitate decision making [25].

Rüppel and Stübbe [26] proposed a solution for the shortest path finding within a public building and provided rescuers with information in their particular spatial context. Existing BIMs are used for displaying plans on mobile devices and for routing purposes. The indoor navigation system is based on wireless local area network, ultra-wide-band and radio frequency identification. The approach assumes that rescuers are equipped with mobile devices. Through their approach, information such as indoor positions, routes and building information will be displayed in the spatial context.

Rüppel, Abolghasemzadeh and Stübbe [27] presented the concept of a BIM-based Immersive Safety Engineering Environment (ISEE) for the modeling of emergency situations in buildings from endangered people's perspective. With ISEE the evacuation process can be visually evaluated.

Graph networks are the basis for route decision making. Network construction algorithms provide the means to bridge geometry layout with network analysis. In the following, two network construction algorithms are introduced.

Skeletonization and Medial Axis Transform (MAT) have been studied in graphical computation [28]. The concept of straight skeleton is to skeletonize the geometric space. The straight MAT algorithm [29] produces a skeleton graph of a 3D indoor space [30]. The network is reduced with less number of vertices, providing higher computational efficiency. Taneja *et al.* [31] used straight MAT to transform IFC-based information into a geometric topology network, which could be the model for navigation assistance.

Visibility Graphs (VG) is another type of graph construction, which has been used for applications such as optimal set covering of emergency evacuation guidance signs [32]. A VG is a network having end points of obstacles as its vertices and visible rays between vertices as edges. A VG always contain the shortest link from one vertex to another in complex building spaces [33]. When the graph is constructed, the network of the space is derived and shortest paths between Origin and Destination (OD) pairs can be found by using shortest path algorithms, such as Dijkstra's algorithm [34], [35].

For the same geometric layout, the MAT has shorter network construction times while the VG gives shorter path costs. The VG produces networks with very dense edges when there are long halls or corridors. If there are great numbers of vertices in the network, which is usually the case for emergency rescue or evacuation in complex building geometries, the running time for decision making could be significant for the VG.

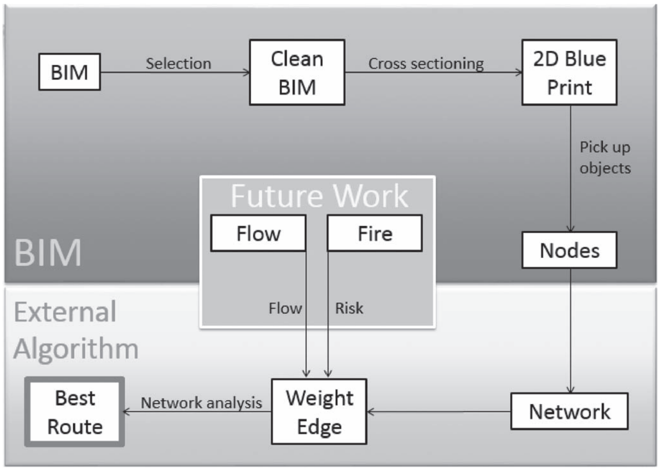


Fig. 1. Process of proposed work.

III. OBJECTIVE

During an emergency such as a fire, on-site evacuees, instant information transmission, and resource assignment complicate disaster response [36]. There is the need to have rescue and evacuation decisions timely and efficiently made for an effective emergency response.

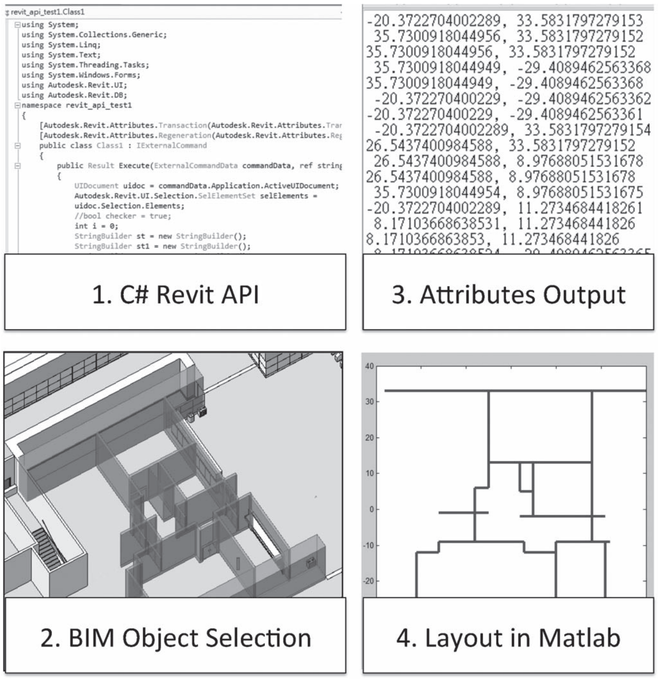
The aim of this work is to utilize a BIM model as the data input for the construction of a graph to enable automated in-building routing decisions, which could potentially be rescue routes for responders or evacuation routes for victims. The proposed approach takes the indoor geometry from a BIM model for the construction of a road network based on which decisions are made. A graph construction algorithm is to be formed which has an acceptable running time while facilitating accurate decisions.

IV. APPROACH

To achieve the objective, the process shown in Fig. 1 is proposed. The first step in the process is Selection that fetches the geometrical layout and attributes of the area-of-interest from the BIM model to reduce complexity. The resulting model is a Clean BIM model with reduced information, and the region of interest to be analyzed is extracted by Cross sectioning. The coordinates of objects in the BIM model are then extracted. The graph is constructed with weights on its edges for the Network analysis, which produces a Best Route. The following sections describe these steps in more detail.

A. *Information From the BIM*

Objects' information from the BIM is first selected by using the REVIT API together with Microsoft's Visual C#. This helps users to select objects and their attributes stored in the BIM, such as geometry and parametric data.



```
revit_api_test1.Class1
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.Threading.Tasks;
using System.Windows.Forms;
using Autodesk.Revit.UI;
using Autodesk.Revit.DB;
namespace revit_api_test1
{
    [Autodesk.Revit.Attributes.Transaction(Autodesk.Revit.Attributes.Tra
    [Autodesk.Revit.Attributes.Regeneration(Autodesk.Revit.Attributes.Reg
    public class Class1 : IExternalCommand
    {
        public Result Execute(ExternalCommandData commandData, ref strin
        {
            UIDocument uidoc = commandData.Application.ActiveUIDocument;
            Autodesk.Revit.UI.Selection.SelElementSet selElements =
            uidoc.Selection.Elements;
            //bool checker = true;
            int i = 0;
            StringBuilder st = new StringBuilder();
            StringBuilder st1 = new StringBuilder();
```

1. C# Revit API

```
-20.3722704002289, 33.5831797279153
 35.7300918044956, 33.5831797279152
35.7300918044956, 33.583179727152
 35.7300918044949, -29.4089462563368
35.7300918044949, -29.4089462563368
 -20.372270400229, -29.4089462563362
-20.372270400229, -29.4089462563361
 -20.3722704002289, 33.5831797279154
26.5437400984588, 33.583179727152
 26.5437400984588, 8.97688051531678
26.5437400984588, 8.97688051531678
 35.7300918044954, 8.97688051531675
-20.3722704002289, 11.2734684418261
 8.17103668638531, 11.273468441826
8.1710366863853, 11.27346841826
```

3. Attributes Output

2. BIM Object Selection

4. Layout in Matlab

Fig. 2. Process of constructing a network directly from BIM.

In this research, the REVIT API is used for information retrieval such as the coordinates of doors and walls. The x and y coordinates are taken form BIM, and the in-building geometry is ported to MATLAB, for this prototype application. Fig. 2 shows the process of data retrieval from the BIM model and the corresponding geometrical layout in MATLAB.

B. Network Construction

For the network construction, we propose a hybrid algorithm called A-MAT-VG that adapts the MAT and VG network constructions to achieve faster execution time for network analysis while maintaining accuracy. The A-MAT-VG algorithm is outlined through the pseudo code shown in Table I, with *obs* representing obstacles, d are doors in the space, Ex are the exits, *StartP* are the evacuees, and M the incidence matrix representing the network. The $\textsc{Box}(path, obs, d, M\_vg, Ex)$ function returns vertices and edges that are within the rectangular region containing the *path*. The rectangular region is specified with the lower left corner set to minimum horizontal and minimum vertical coordinates of the path, and with the upper right corner set to maximum horizontal and maximum vertical coordinates of the path.

The first step in the A-MAT-VG algorithm is to obtain incident matrices from the MAT algorithm and VG algorithm, illustrated in Tables II and III respectively. These networks are to be constructed only once prior to the emergency and saved for future execution of this algorithm when needed. Then the shortest path for each of the evacuees to the closest exit in evacuation missions, or the closest exit leading to the evacuee in rescue missions, is determined. The shortest paths are refined by finding shortest paths within each of their boxed VG network. In other words, the box function will select those edges and vertices from the VG network producing a reduced incident matrix M_vgb for a more efficient path analysis for each of the evacuees/rescuers. In this work, the shortest path analysis modulated in the GETPATH function is achieved through running the Dijkstra's algorithm.

TABLE I
THE A-MAT-VG ALGORITHM

```
A-MAT-VG (obs, d, Ex, StartP) :
    M_mat = MAT(obs, d)
    M_vg = VG(obs, d)
    path_mat = GETPATH(obs, d, M_mat, StartP, Ex)
    for each evacuee (i)
       if path_mat(i) exist
          [obsb, db, Exb, M_vgb]
            = BOX(path_mat(i), obs, d, M_vg, Ex)
          path(i)
            = GETPATH(obsb, db, M_vgb, StartP, Exb)
    return path
```

TABLE II
THE VG FUNCTION

```
VG (obs, d):
    for(each node n1 in obs)
       for(each node n2 in obs excluding n1)
           if(link between n1 and n2
                      not penetrate obstacles)
               out link (n1,n2) in M
    return M
```

TABLE III
THE MAT FUNCTION

```
MAT (obs, d):
    for(each node n1 in obs)
       for(each node n2 in obs)
           if(obs(n1)-concave and obs(n2)-convex
                        with respect to each other)
               L = link between n1 and n2
               V′ = mid point of L
               put (L,V′) in LL
    for(each node n1 in obs)
       if(n1 formed by two walls)
           put bisector rays at convex angle of
                        n1 in L1
    for(each ray i in L1)
       for(each ray j in L1)
           if(i has intersection point with
                   j not penetrating obstacles)
               P1 = intersection point
               put (i,j,P1) in L2
    for(each set g in L2)
       put bisector rays at concave angle of g
                      in R
    for(each ray h1 in R)
       for(each ray h2 in R)
           if (h1 has intersection point with
                   h2 not penetrating obstacles)
               put intersection points in P
       put nearest P in P2
       if(P is empty)
           put V′ of LL that is nearest to h1
               into P2 without penetrating obstacles
    for(each element i in P1 and corresponding
                   element j in P2)
       put link (i,j) in L3
    put link between V′ in L3 without penetrating
              obstacles
    remove repeated segments in L3
    put links between doors and segments in L3
    return L3
```

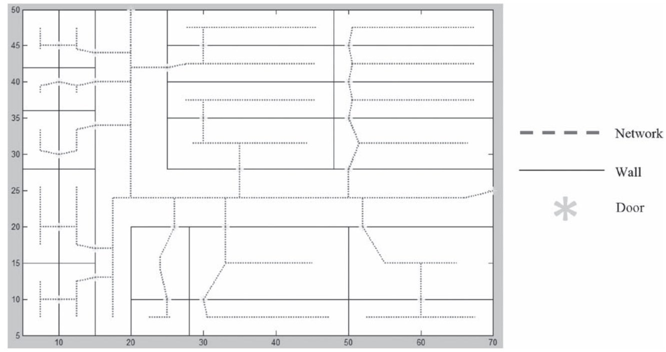


Fig. 3. The step one of hybrid algorithm.

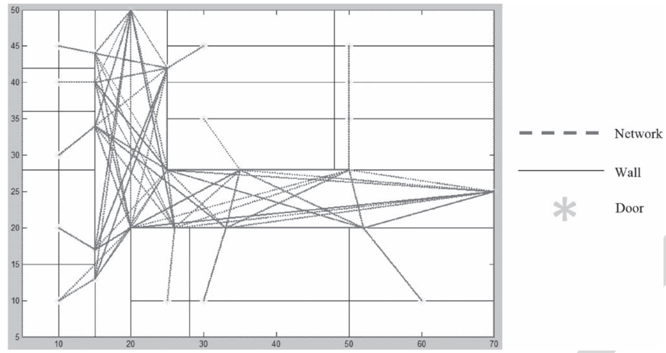


Fig. 4. The step one of hybrid algorithm.

V. TESTING

In this section, testing of the proposed approach through illustrative examples and its comparison with the VG and MAT in a larger scale example is presented. Sensitivity analysis of the A-MAT-VG with respect to varying numbers of evacuees and a field trial with human and robot traveling on the suggested paths are also conducted.

A. Illustrative Example

In the following, an illustrative example of finding the shortest path in the A-MAT-VG is presented. The MAT and VG networks are first constructed as illustrated respectively in Figs. 3 and 4.

After constructing the MAT and VG networks, the first pass shortest path analysis by calling the GETPATH function using the MAT network from the evacuee to the closest exit is conducted as shown in Fig. 5.

Based on the resulting shortest path, the box for the vertex and edge selection in the VG network is defined as shown in Fig. 6. The VG elements in the box are then used for the second pass shortest analysis. In this step, the size of the network is greatly reduced due to the boxing, and the path is refined as shown in Fig. 7.

The result of the A-MAT-VG may not be the same as the result of VG, as shown in Fig. 8. If in the first past shortest path analysis the route leads to a different exit (Exit 2 in Fig. 8) from the choice of just using the VG network (Exit 1 in Fig. 8), the second pass shortest path analysis in the A-MAT-VG may not be able to provide a route to the optimal exit (Exit 1). However, the result of the A-MAT-VG performs better than MAT in terms of path cost.

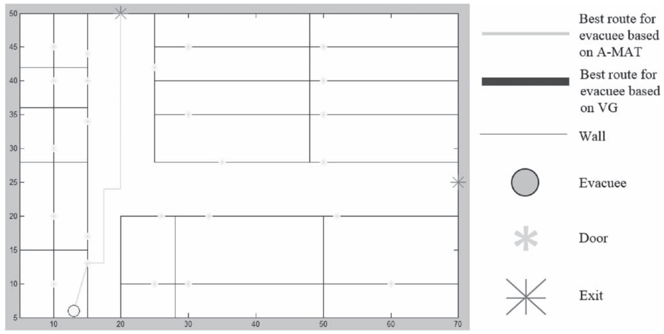


Fig. 5. The step one of hybrid algorithm.

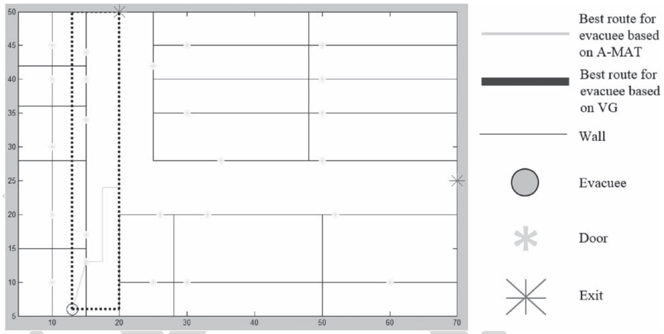


Fig. 6. The step two of hybrid algorithm.

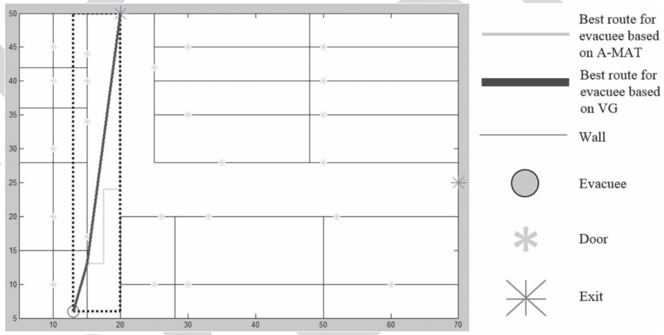


Fig. 7. The step three of hybrid algorithm.

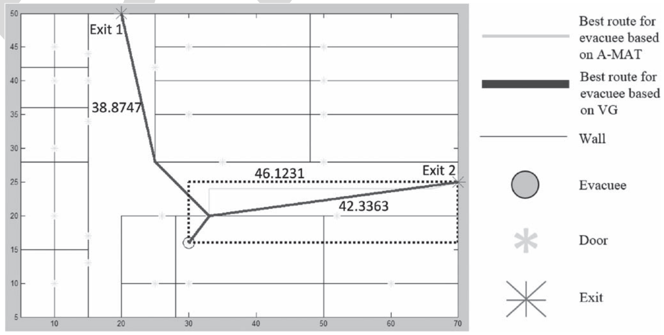


Fig. 8. Special case exit selection of A-MAT-VG.

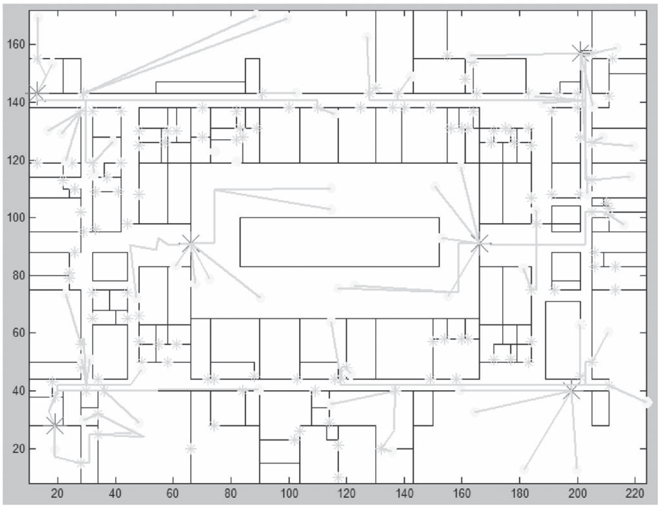


Fig. 9. The result of MAT.

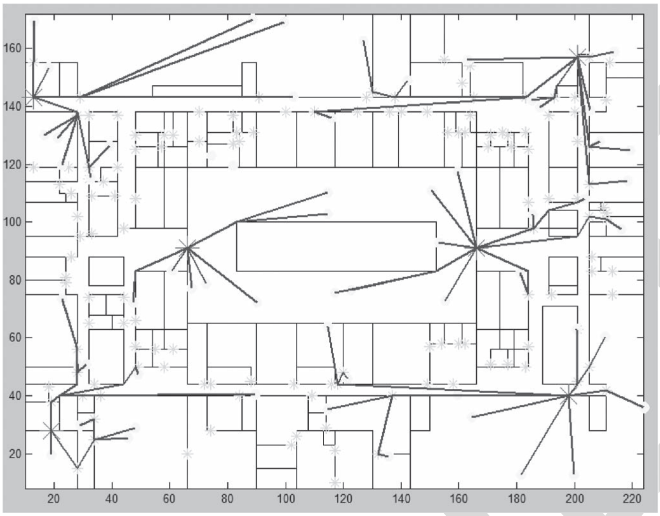


Fig. 10. The result of VG.

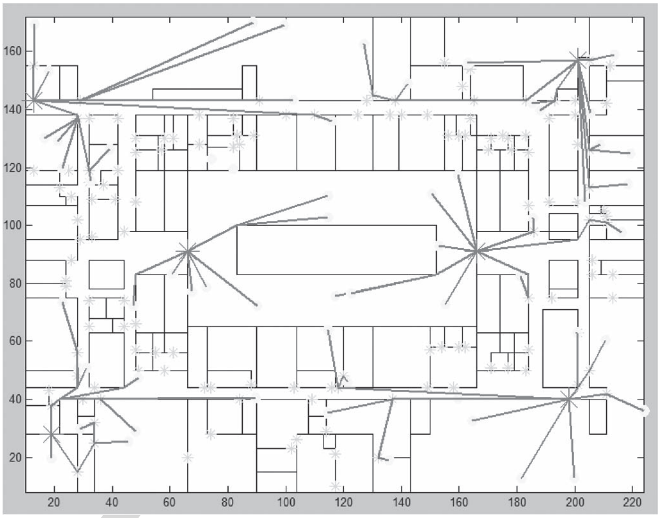


Fig. 11. The result of A-MAT-VG.

TABLE IV
ANALYSIS TIME AND TOTAL COST

	MAT	VG	A-MAT-VG
Construction time (s)	685.422	3953.318	MAT + VG
Analysis time (s)	26.234	101.453	30.895
Travel cost (m)	1886.869	1657.978	1661.383

TABLE V
TOTAL NUMBER OF VERTICES IN THE LARGER CASE

	MAT	VG	A-MAT-VG
Nodes	35040	66780	36360

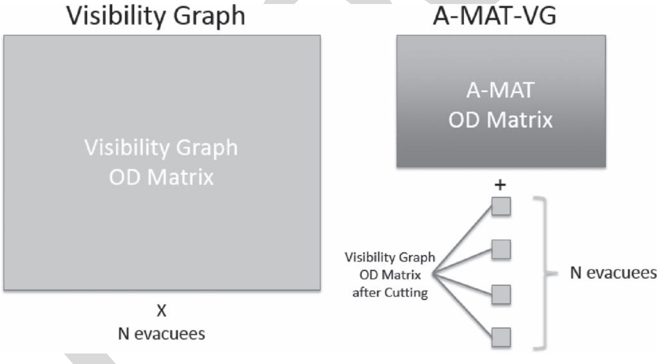


Fig. 12. Data structure comparison of VG and A-MAT-VG.

B. Comparison in Larger Scale

We applied the A-MAT-VG to an example comparable in complexity to the 4th floor of Taipei main station with 60 evacuees randomly placed in the space, with six exits for the comparison of the A-MAT-VG with the VG and MAT.

As shown in Figs. 9–11, the results of MAT, VG, and A-MAT-VG are in general similar. The reason of some slight differences is the property discussed in the previous section: the A-MAT-VG model may exclude the nearest exits in the first pass shortest path analysis. As a result, the total cost is greater than or equal to the VG model. Table IV shows the network construction time, the analysis time and total cost. The total cost is the sum of all traveling distance of evacuees The A-MAT-VG could result to close to optimal routes with much shorter analysis time comparing with VG.

The A-MAT-VG model could save analysis time compared to the VG. For the total cost, the difference between A-MAT-VG and MAT is 225.486 meters (m), and the difference between A-MAT-VG and VG is only 3.405 m. In other words, the result of A-MAT-VG and VG is very close to each other.

The time for path analysis is mainly dependent on the size of the network, which is stored in an incidence matrix in this study. In Table V, the number of nodes considered during the calculation is significantly different for the two methods. In VG the whole incidence matrix (including 1113 nodes) is calculated for each evacuee. However, in A-MAT-VG, the region is partitioned and the nodes are far less in the second pass shortest path analysis as shown in Fig. 12. Because of

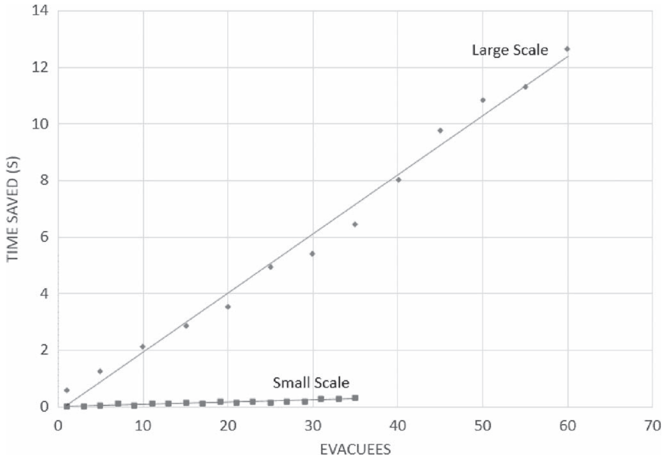


Fig. 13. The time saved by the A-MAT-VG model.

the reduction in vertex number, the OD pairs in a network data structure such as an incident distance matrix is reduced, resulting to reduction in execution time for the path analysis in A-MAT-VG.

C. Sensitivity Test of A-MAT-VG

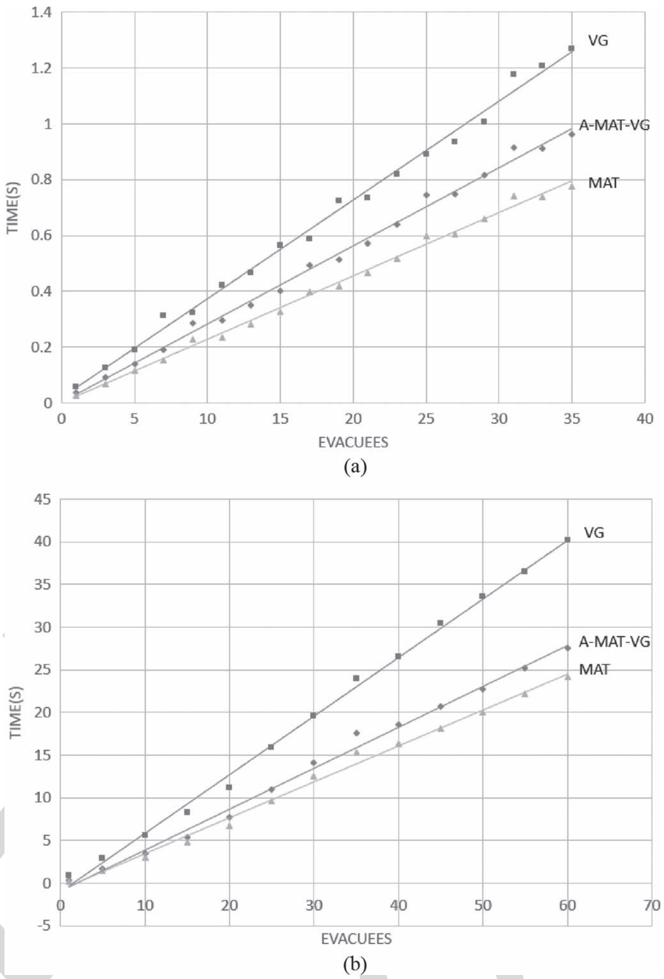
The gaps in terms of execution time and accuracy between VG and A-MAT-VG have different magnitudes in small scale and large scale. We performed an analysis on varying the number of evacuees, and the result of A-MAT-VG is compared with MAT and VG respectively. To prevent the situation of overly dense of randomly placed people in small scale problems, the maximum number of evacuees is set to 50. The results presented in the following are the average of 15 analyses.

In Fig. 13, the relationship between the time reduction by using the A-MAT-VG in comparison with the VG method is shown. The more people in the problem, the more reduction there were in execution time.

By adding more evacuees in both scales to see the variation of analysis time, the result of Fig. 14 is received. The performance of these three algorithms in different scales reveals that the A-MAT-VG is applicable in large scale.

D. Trial

We have conducted trials for the investigation of the output given by the A-MAT-VG in the field. The trials do not consider the effect of the crowd, but only the effect on a single traveler in free flow. Two types of travelers are considered: a human and a robot. The robot being used was a Brookstone Wireless Rover 2.0. For each of these types of travelers, two cases are tested in a physical space with the routing decisions marked using chalk on the ground. In the first case, as shown in Fig. 15, the results produced by the A-MAT-VG and the VG are the same with path length 6.69 m. In the second case as shown in Fig. 16, the A-MAT-VG selects a different exit in the first path route analysis. As a result, the A-MAT-VG has a path length of 6.89 m, while the VG produces a path length of 6.37 m.



(a)

(b)

Fig. 14. The analysis time of three algorithms in (a) small and (b) large scale.

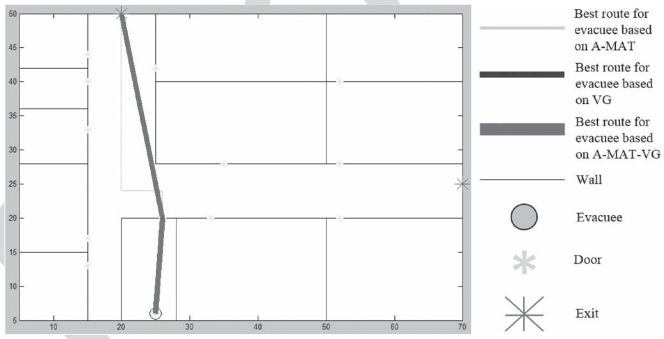


Fig. 15. Trial case 1: A-MAT-VG having same result as VG.

Results of the trials are listed in Tables VI and VII. For each of these cases, we have performed 15 test walks carried out by two students in turn. In the tables, the A-MAT-VG is referred as Hy as a shorthand. In Case 1, the route is the same for the VG and the A-MAT-VG. The performance in terms of travel time is better than the MAT. In Case 2, the performance of Hy is not as efficient as the VG, but still better than the MAT.

For the robot's case as shown in Table VII, the results are consistent as those for the human's case.

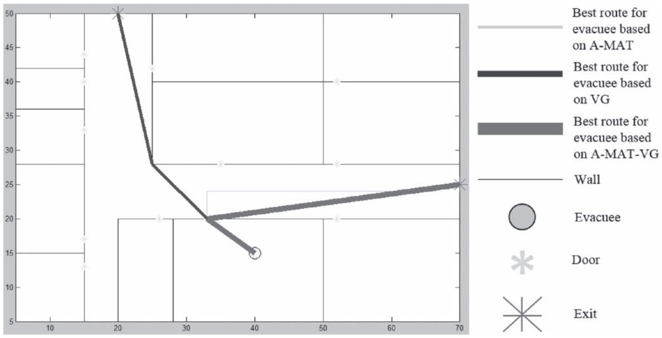


Fig. 16. Trial case 2: A-MAT-VG having different result as VG.

VI. DISCUSSION AND FUTURE WORK

As there are larger numbers of edges in the VG network, running time for both the network construction and path analysis are longer than the MAT. However, the path cost derived by the VG analysis is better than the MAT network; lower path costs are produced using the VG as the vertices and edges are more optimally distributed in terms of geometry. A-MAT-VG adapts the MAT network to analyze the routes in the first pass path analysis, for the seeking of a reduced graph in proximity of the route, and a second pass analysis is carried out for a more detailed path using the VG. In particular, when there is the need for a more precise decision, the VG approach provides decisions with better resolution. From the case studies, the A-MAT-VG does not provide much benefit in terms of execution time reduction in small scale problems. The VG could be used directly for better precision. In large scale problems, the saving in execution time becomes significant in A-MAT-VG.

Regarding the construction of networks from BIM models, there are still challenges. Irregular geometrical shapes, such as non-linear walls, complicate network construction. However, it is common in infrastructures to have irregular shapes of elements, and handling of such exceptions should be targeted as a further extension.

Additional future directions include adding of weight values from attributes, such as flow of evacuees and risks, to network edges. Multi-attributes could be aggregated into a utility value based on

$$Utility = \alpha \cdot distance + \beta \cdot risk + \gamma \cdot congestion \qquad (1)$$

where α, β, and γ are real number weights that sums to unity, *distance* is the length of the edge, *risk* is the effect of the disaster such as temperature or smoke, and *congestion* is the flow condition on the edge. In other words, edge costs would have higher values if the edge has congestion, fire or smoke. The proposed methodology could be a decision tool that takes network flow information and fire predictions as input for routing of rescuers and/or evacuees.

There are simulation models that capture the dynamics of pedestrians, and a three level schema for pedestrian simulations has been proposed [37]. These three levels are strategic, tactical, and operational, respectively representing the pedestrian dynamics of activities, short-term decisions, and walking behavior. The routes produced from this paper are potentially suitable for tactical decisions for pedestrian simulations. The routes could potentially be used to guide pedestrians and serve as inputs to operational level models such as floor field Cellular Automata (CA) [38] and social force [39] for the consideration of individual's behavior. Individual decisions and their interaction with others in a time dependent manner can then aggregate into a system behavior of the evacuation and rescue missions. Dynamic traffic assignment into the road network [40], such as the MAT network in the A-MAT-VG approach, could potentially enable a more accurate decision making. The network produced in this study could also serve as input to graph based event-driven modeling for dynamic pedestrian route choices [41].

TABLE VI
HUMAN TEST CASES

Case	Case 1		Case 2		
	VG/Hy	MAT	VG	Hy	MAT
Time (Sec)	04.660	06.650	05.630	05.610	06.660
	04.330	06.480	05.210	06.050	07.180
	04.600	06.780	04.750	05.780	07.160
	04.760	06.360	05.350	05.660	06.260
	05.300	06.730	04.850	06.400	06.710
	04.460	06.480	05.450	05.830	06.230
	04.760	06.250	05.920	06.080	07.100
	04.550	06.430	04.830	06.330	07.200
	04.720	06.640	05.330	05.980	06.940
	04.630	06.520	05.460	05.760	06.870
	04.800	06.710	05.850	06.130	07.080
	04.660	06.430	04.980	06.270	07.120
	04.520	06.280	04.770	06.550	06.960
	05.100	06.390	05.580	06.260	07.410
	04.890	06.440	05.310	05.870	07.230
AVG	04.716	06.505	05.285	06.037	06.941

TABLE VII
ROBOT TEST CASES

Case	Case 1		Case 2		
	VG/Hy	MAT	VG	Hy	MAT
Time (Sec)	14.880	20.000	11.910	15.980	18.000
	13.260	23.080	13.800	17.180	17.280
	14.400	19.630	12.830	16.750	17.930
	14.180	20.260	13.100	15.630	18.100
	14.850	19.780	12.430	17.080	18.200
	13.860	19.100	13.430	16.550	18.800
	13.980	20.130	11.480	15.850	18.500
	13.660	19.980	12.600	16.430	17.960
	14.380	19.750	12.960	17.120	18.120
	14.130	20.580	12.910	16.770	18.960
	14.610	20.790	13.080	15.940	18.110
	13.980	20.350	11.970	16.520	17.950
	13.770	19.870	12.560	16.430	18.360
	14.120	20.190	12.930	17.010	18.540
	14.270	20.360	11.870	16.270	18.430
AVG	14.155	20.257	12.657	16.501	18.216

In the current study, decisions are made only for individuals, and the behavior of groups is not considered. Pedestrians in a group are much more likely to choose a common route, and some might look for each other [42], [43] in normal conditions and potentially in emergencies.

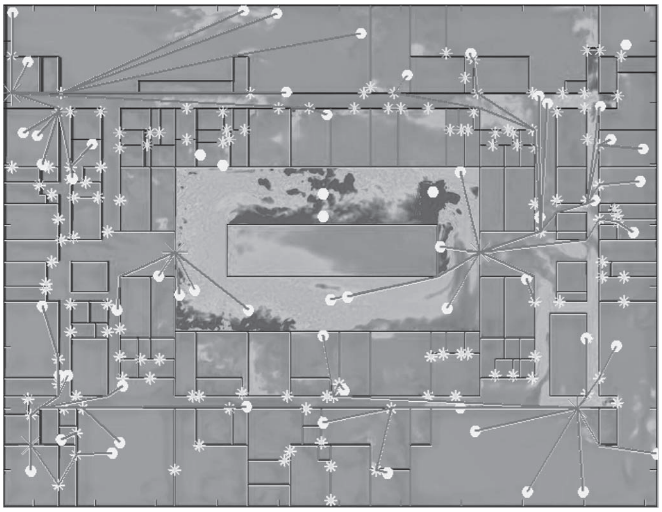


Fig. 17. Analysis with fire prediction.

TABLE VIII
THE ALTERNATIVE A-MAT-VG ALGORITHM

```
A-MAT-VG (obs, d, Ex, StartP) :
    M_mat = MAT(obs, d)
    path_mat = GetPath(obs, d, M_mat, StartP, Ex)
    for each evacuee (i)
        if path_mat(i) exist
            [obsb, db, Exb, M_vgb]
                = Box(path_mat(i), obs, d, M_vg, Ex)
            M_vgb = VG(obsb, db)
            path(i)
                = GetPath(obsb, db, M_vgb, StartP, Exb)
    return path
```

The BIM enabled virtual environment could also provide the opportunity for artificial transportation systems [44] with augmented reality and virtual reality capabilities for training, and information provided by the BIM model could enable more detailed analysis. Based on the geometry of space and material property of the building, fire propagation could be predicted by simulation such as the fire dynamics simulator [45], which potentially could be used as the source of information for the *risk* in the utility function for network analysis. The proposed work is envisioned to provide emergency routes as shown in Fig. 17. In addition the layout of piping and HVAC systems in the BIM model together with real time sensor inputs can be utilized for the fire analysis. By bridging between BIM and conventional network analysis considering heterogeneous attributes, more precise and efficient decisions are expected.

In terms of analysis performance, there is also the possibility of expediting the route analysis by using parallel computation on the shortest path analysis [46]. The A-MAT-VG could also be modified into an alternative algorithm as shown in Table VIII. The VG network could be constructed for each of the evacuee/rescuer only after the boxing. This potentially saves execution time by not constructing the large VG network. However, the VG network for each the evacuees/rescuers are generated on the fly, repeatedly, and could result in longer execution time. If all paths from the first pass shortest path do not traverse through large region of the space, the alternative A-MAT-VG could potentially save time not building the VG network for the entire space. On the other hand, if there are many paths that box large number of vertices, the original A-MAT-VG constructs the VG network for the entire space only once and all subsequent VG networks in the second pass shortest path analysis will query this single large network, and thus saves execution time.

VII. CONCLUSION

In this paper, we presented the method for graph construction directly from BIM models. The VG network is more suitable in small scale path analysis and the MAT network for large scale problems. However, the accuracy of VG is better than MAT. We proposed the A-MAT-VG, to reduce the execution time of path analysis and to preserve accuracy close to the VG approach. For the edge costs, factors such as length, flow and risk should be transformed into reasonable weight values and be combined into utility costs. Especially the factor of pedestrian flow and the capacity of each network link should be included for evacuation problems. The BIM enabled network could potentially provide network analysis to the field of emergency evacuation and rescue.

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