Graph-based Representation of Building Circulation With the Most-Remote Points and Virtual Space Objects

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Abstract

This research aims to develop a graph-based representation of building circulation as an extended version of the metric graph structure named UCN (Universal Circulation Network). There are several different methods and algorithms to represent pedestrians' indoor circulation for architectural purposes. The UCN has introduced a BIM-enabled approach to measure walking distances between different space objects using door-to-door connection network. In this paper, we focus on the extended development of the metric graph algorithm to expand its use scenarios such as measuring the exact distance of fire egress. There are two major issues we have encountered in this research and development: 1) finding the most-remote point in a given space objects to measure the distance of fire egress and 2) handling virtually subdivided space objects. This paper describes specific algorithms to resolve this problem on top of the structure of UCN. The major outcome of this development is the extended metric graph structure with the virtual space objects and the most-remote point. The implementation and demonstration depicted in this paper will show how the UCN structure can be enhanced in terms of its capability for visual representation as well as its extensibility of circulation-related analysis.

Keywords

Building Information Modeling (BIM), Building Circulation, Metric Graph, Universal Circulation Network (UCN), Virtual Space, Most-remote Point

1 Introduction

Building circulation has to be evaluated even in early phase of design because its impact is of importance in terms of the quality and the performance of building [1]. The issues of circulation sometimes involve critical aspects of building design such as complex security and spatial allocation problems in courthouse buildings [2]. To analyze the building circulation by manual used to be time-consuming and error-prone, therefore an automated and reliable way of such analysis has been strongly required. For evaluating circulation paths in automation using BIM models [3], we need an abstraction of circulation paths on top of the given BIM models to represent, calculate, and analyze topological network of building circulation, and it is the UCN (Universal Circulation Network) [4,5,6,7]. UCN [7] uses graph representation and implemented effective algorithm for circulation analysis. This paper mostly refers to the UCN [7] and aims to extend its structure of circulation paths by defining two additional aspects of circulation representation: 1) finding the most remote point, and 2) with virtual space objects. For measuring exact fire egress distances, the most-remote point based calculation is necessary [8]. We also have to take care of handling virtual space objects for generating the most-remote point edges on top of UCN structure. In this paper, therefore, we studied how to handle virtual object for checking circulations and find the most-remote point for fire egress as a way of extension of the UCN graph.

2 Review of the Universal Circulation Network

Several approaches to the BIM-enabled visual representation of building circulation have been implemented and examined [7, 15]. In terms of technical aspect, they can be classified as follows: 1) topological graph, 2) center-line-based metric graph, 3) Kannala's metric graph [9] and 4) the UCN (Universal Circulation Network) graph [7]. As described in [7], above graph #1 represents only topological relations between space objects, and #2 and #3 do not reflect human behavioral patterns. The UCN provides a precise method to measure walking distances with appropriately visualized metric graph structure reflecting human behavioral patterns. The UCN-based representation of building circulation, thus, has been adopted in several software tools that are dealing with circulation related issues.

General features in UCN can be summarized as follows: 1) building–object oriented graph representation, 2) application of buffer distances from the wall regarding human scale, 3) application of the shortest path finding algorithm [10], 4) the most visible path, and 5) door-to-door graph visualization using wall-bounded space objects.

Above features are key aspects of the UCN graph implementation so that it reflects realistic circulation patterns and provides precise method of measuring walking distances. In practice, the implementation of the UCN graph has contributed to BIM software developments such as Solibri model checker (SMC) and others in terms of their visualization of building circulation paths and measurement of walking distances.

The main goal of this paper is to extend the structure of the UCN graph. Therefore, we focus on the limitations found in reviewing current implementation of the UCN graph, and they can be listed as follows: 1) its graph edges can be represented only on top of the physical space objects that are bounded by wall objects. It cannot deal with virtually divided space objects that are commonly found in actual BIM models. 2) Its graph edges can be connected only between door-to-door to represent inter-space circulation. It does not generate graphs that are located inside of space objects that have only a single door object.

As described in #1, the UCN graph omitted handling virtually subdivided space objects. Virtually subdivided space objects are beyond the scope of the UCN graph which is focusing on overview of building circulation or space programming not on specific agent's path of in-space. Dependent upon requirements of the design guide or specific needs of space circulation, some circulation graphs should be represented in virtually subdivided space object. In this paper, therefore, we notice the requirement of dealing circulation of virtually subdivided space objects.

In case of #2, due to the limitation of the UCN graph structure, it cannot represent the graph in purpose of finding the most remote point from the door object in specific spaces for measuring the egress distance defined in general Fire Code. In this perspective, the objective of this study is extending the UCN graph to virtually subdivided space objects by finding the most remote point in rooms to overcome such limitations.

3 Finding the most-remote point in a given space object

3.1 Extension of the UCN metric graph

It is controversial that the open plan office is not the best idea for office layout, but it is broadly adopted by designers. Consideration of circulation graph in this kind of spaces plays an important role in space programming and quantitative design evaluation. In case of open plan office model, many departments or teams are existed in one big open space area, separated by virtual space object boundaries. In real world, however, office areas do not have every wall and door object for separating departments or teams. Based on door-to-door connection of the UCN graph, it is not available in this kind of spaces besides any open plan designed model. In this case, more consideration is needed on circulation graph algorithm. To focus on these limitations, we aim to extend the UCN graph by handling virtual boundaries of given building model and figuring out circulation graphs in open plan designed model. The circulation graph we propose can be useful to the multi-functional space oriented model.

3.2 Definition of the most-remote point

The most-remote point (MRP) refers to the point which is located in the furthest point from the door according to the definition in Fire Code, for measuring egress distance accurately. Choi et al. [8] represented the concept of MRP as Outermost Node. This study focuses on whole structure of evacuation regulation checking system. In this study, the researchers draw the path by finding outermost node in space using UCN graph structure; however outermost node path does not focus on algorithm of the graph also not deal with virtual space object boundary. Including design guide and other building codes introduce the travel distance rules and measurement method mostly refer to the NFPA 101, and here are some selected regulations [11,12,13,14].

- *The maximum travel distance from the most remote point in any room or space to the center of a door opening directly on an open exterior space shall not be greater than the limits.*
- *Travel distance is the total distance in a building an occupant must travel before reaching an exit. Travel distance is measured from the most remote point in a room to a point where the nearest exit begins.*

In conclusion, the most remote point from the door, which is the furthest point in spaces, is used for a measurement of fire egress distance [12]. In this study, the MRP graph is based on metric graph structure addition to the UCN graph, and it generates the exact walking paths for checking and visualizing the fire egress related regulations.

4 The most-remote point graph in physical space objects

In the UCN graph, for visualizing the path, its algorithm uses only concave points on space object boundaries and door center points. Convex points, also the components of the space object boundaries, are useful to find the most remote point from door objects which are properties required by the N.Y. Building Code for measuring fire egress route distances. The most-remote point should be one of the convex points on given space object boundaries, and this paper suggests the algorithm for finding such points from any given BIM models.

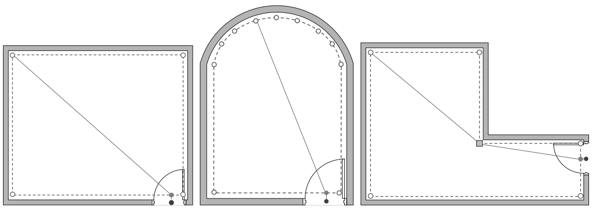

Figure 1. The most-remote point (MRP) graph examples in a space object which has: 1) only convex points, 2) convex points with a concave point, and 3) a series of segments between convex points for a rounded corner

As depicted in figure 1, the dotted lines denote to the buffer lines of space object boundaries. To consider a size of an agent itself, the MRP is on the buffer line of the space object boundary not on the edge of a space object boundary. The most-remote point graph starts form the door center point as same way as the UCN graph and finishes to one of the convex points of a buffered space object boundary which is the furthest from the start point. The distance of the graph, in contrast, should be the shortest one among many possible paths (including free curves) following the Dijkstra's shortest path finding algorithm [10]. To find the furthest convex point, we measure the distance to each convex point of the buffered space object boundaries from the door center point of the space. In case of the rounded corner spaces like figure 1.3), which is commonly found in actual BIM models, the MRP graph represents in the same way as other models, but only different when we find out the convex points of the buffered space object boundaries. We segmentize the curve to equal angle and set of points come along would be convex points which are the materials of the MRP. The angle for segmentizing can be different dependent upon the model and the requirements of detail in evaluation. The process of finding the furthest convex point on a space object boundary is as follows.

1) Draw the buffer line of each space object boundary
2) Find concave points, convex points and a door center point of each buffered space boundary
3) Draw the metric graph of each convex point using concave point (if necessary) and a door center point
   - Rooms having corner or column: using concave points as many as necessary in this order; Door center point → concave points (n) → convex point
   - Rooms which doesn't have corner or column: directly connect to a door center point and a convex point
4) The longest distance graph based on the shortest path algorithm is the most-remote point graph

Following the process above, we define an operator *MGraph( )*, which defines the MRP graph, as follows.

$$MGraph(sb_i, d_i, cx_i) \rightarrow G_{Mi}$$

One of the parameter sb_i refers to space object boundary of the model, d_i is derived from a door object of the model, and cx_i refers to a convex point. Output G_{Mi} is the most remote point graph which generates from those parameters above.

5 The most-remote point graph in virtual space objects

5.1 Application of the most-remote point graph in a room with virtual space boundaries

Virtually divided space objects technically refer to the areas divided by room separators, not by typical space boundary elements such as physical wall and doors. The implementation of the UCN graph omitted the representation of circulation paths for those virtually subdivided spaces such as open office areas, but they are commonly found in actual models. In this paper, we have represented how the circulation paths can be visualized between virtually subdivided space objects without physical walls by using a graph structure as an extended version of the UCN graph. This approach and implementation enabled us to represent and analyze circulation paths within an open space such as partitioned space or cubicle area that are commonly found in office buildings.

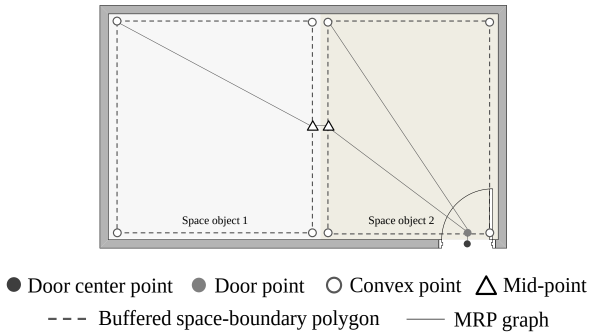

Figure 2. An example of a series of vertices that generate the most-remote point graph in case of virtually divided space object

Two cases of virtually subdivided spaces can be classified: 1) with door objects and 2) without door objects. The graph representation on the first cases can be drawn the same as physical spaces, the second cases, however, should be handled in different way. This graph representation technically require specific points acting like door center points which we decide to a mid-point of a virtual space object boundary as shown in figure 2. In virtually divided space objects, mid-point of the virtual space object boundary can be an average distance for efficient checking. Especially in cases of the space having corners, columns or rounded corner space object boundaries, are using average distance for the MRP graph for more reasonable circulation analysis.

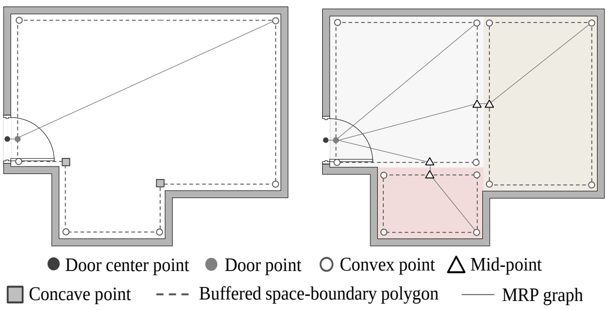

Figure 3. Examples of the most-remote point graph in a room: 1) a single space object, and 2) three space objects that are separated by virtual space object boundaries

Figure 3 shows how the MRP graph can be varied by the existence of virtual space object boundaries. According to one of the key aspects of the MRP graph, starting from a door center point, we can notice the number of the MRP graph can be determined by the number of doors in a space object. As shown in figure 3, however, not only the number of door objects but also the number of virtual spaces can be a prime determinant of structuring the MRP graph. Thus, the number of the MRP graph can be calculated as below.

$$nA = m \quad (1)$$
$$nD = n \quad (2)$$
$$nG_M = m \times n \quad (3)$$

, where nA denotes the number of the area (1), nD denotes the number of the door object (2) and nG_M denotes the number of the MRP graph (3). In case of the model which has more than 2 doors can be drawn as the UCN graph which is based on door-to-door connection. However, the UCN graph and the MRP graph are in different sectors in perspective of utilization also the implementation. Thus, the number of circulation graph in one space is like below.

$$nG_U = \frac{n(n-1)}{2} \ (n \geq 2) \quad (1)$$
$$nG_S = nG_M + nG_U \quad (2)$$
$$nG_S = m \times n + \frac{n(n-1)}{2} \quad (3)$$
$$\therefore nG_S = n(m + \frac{n-1}{2}) \quad (4)$$

, where nG_U denotes the number of the UCN graph and nG_S denotes the number of the MRP circulation graph. Total number of the graph is not for entire building circulations; it is limited only in a space.

5.2 The most-remote point graph in three or more virtual space objects

The most remote point graph of two virtual areas in one space follows section 5.1. On the other hand, in case of the model which has three or more virtual areas should be handle in different way because the edges of overlapping space boundaries cannot be merged to one when touching line cope only partial space boundary.. Another process is required in this case to visualize the MRP graph.

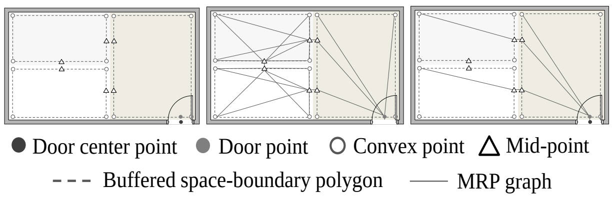

Figure 4. 1) Finding mid-points on every virtual space boundary, 2) generating a collection for all edges to define the MRP graph, and 3) determining three final MRP graphs

As shown in figure 4, the graph follows the order as follows; convex point → virtual door center point → virtual door center point →(n)…→ door center point. In this process, the metric graph could be detoured, thus, it would be the longest one as shown in figure 4.2). It represents entire set of edges can be derived from given spatial condition, and the final edges should be satisfied by the 'most remote' point as well as the 'shortest' path finding algorithm. The algorithm needs two steps: 1) Find the shortest graph in each convex point and then, 2) Compare to each graph and measure the distance for finding the longest one. Below figure 5 is the workflow of the algorithm to find the MRP Graph.

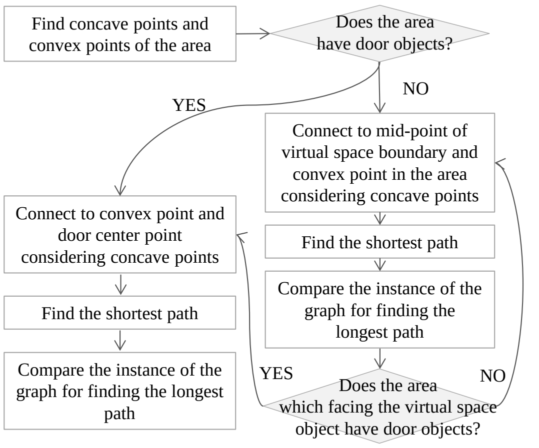

Figure 5. Overview workflow for finding the most remote point and determining the MRP graph

In addition to the workflow shown in figure 5, a specific precondition is required; 'The graph shouldn't pass again same virtually subdivided area'. If the workflow does not include that precondition, then the graph should be detoured and have repetitive form, as well as it would not be the shortest path. The last part of the diagram, 'Connect to convex point and door center point considering concave points' and 'Find the shortest path' is following the UCN graph as described in this paper.

Figure 6 depicts an extended version of the UCN graph generation process with virtually subdivided space objects and the most-remote points. Two new operators, *MGraph()* and *CMGraph()*, have been added on diagram of the UCN graph for handling virtual space boundaries and the MRP-based circulation paths. The operator *MGraph()* is in charge of finding the most remote point in each space object and determining its graphs, as well as finding the mid-points on each virtual space object boundary. As denoted in section 4, one of the parameters of *MGraph()*, d_i can be the mid-points on virtual space object boundary in case of virtually subdivided area. *MGraph(), thus,* applied in virtually subdivided areas recognized as physically bounded space objects. The operator *CMGraph()* applied to combining two graphs; the most remote point graph and space metric graph, so that the MRP-based circulation graph is the derived graph from *CMGraph()* .

CMGraph() = {MGraph(), SGraph(), WGraph()}

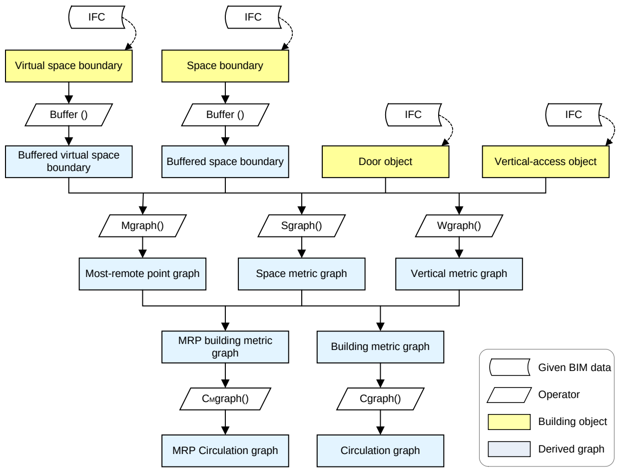

Figure 6. Overview of the extended UCN generation process, with virtual space objects and the most-remote points

6 Demonstration of the MRP graph

6.1 Examples of the most-remote point graph in various spaces

To demonstrate more cases, figure 7 shows the MRP graph in the model with many virtual space boundaries. As shown above, we can find the 6 MRP graphs from one set door in one open plan office divided by 5 room separators and the graphs are drawn by the algorithm we described in this paper. There can be an issue in purple colored virtually subdivided area with the location of mid-point. To follow the workflow of figure 5, we consider only in purple colored area for the first step of finding the MRP graph. The purple colored area has two mid-points, so that there are 8 possibilities for the MRP graph. Among 8 possibilities, we should find the longest path with following the shortest path finding algorithm and then proceed to the next step which is the pink colored area. This process is of importance especially the area subdivided in many virtual space boundaries like the model of figure 7.

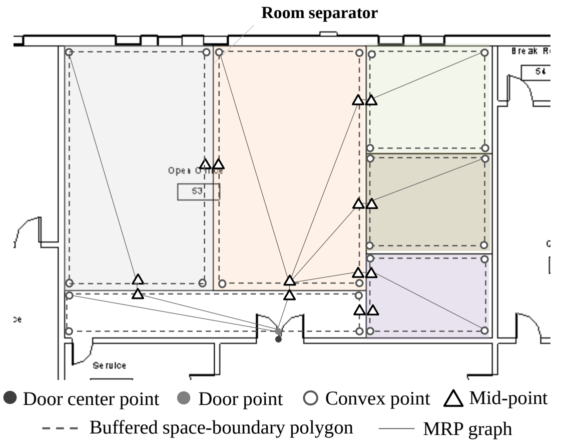

Figure 7. An example of actual BIM model which has virtually subdivided space objects and its MRP graphs example using proposed algorithm

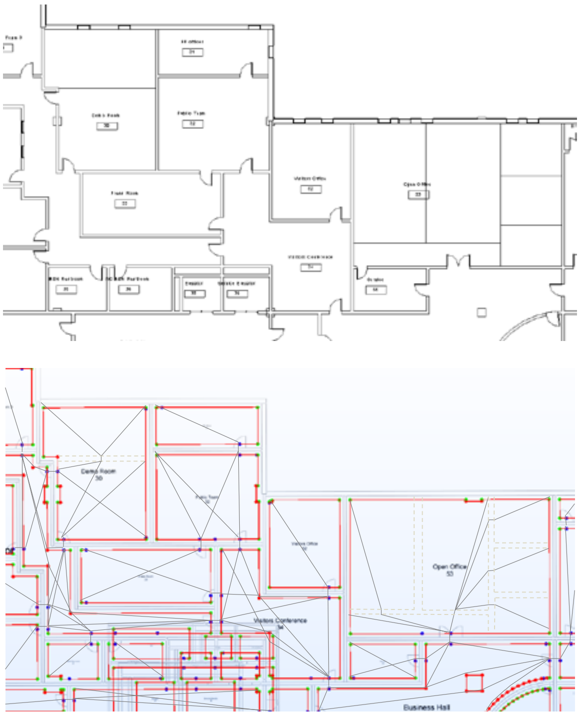

Figure 8. 1) A test BIM model which has virtual space boundaries, and 2) its MRP graphs generation using an exported IFC (a footprint view of 3d model)

Figure 8 shows the model of figure 7 with additional spaces also showing the MRP graph on top of the UCN graph in various spaces. Figure 8.2) shows the possible representation model with the MRP graphs in IFC viewer, and it is based on implementation of the UCN graph. As shown in figure 8, the MRP graph can be drawn even the spaces that have properties set to corridor or hall because the MRP graph starts from every door objects. This helped to show both the MRP graph and the UCN graph for representing an entire component of building circulation visualization.

6.2 Extending UCN with in-space graph in BIM model

By combining the UCN graph and the MRP graph structure, the MRP-circulation graph can be represented. If a pair of start and end space objects have been assigned, we are able to generate the MRP circulation graph and measure a total distance of an agent's evacuation distance. The UCN graph can be extended to rooms with the MRP graph so that the MRP graph is an add-on of the UCN graph. For representing an entire set of building circulation using graph structures, both the UCN graph and the MRP graph set are required. The UCN graph is in charge of generating door-to-door graphs, and the MRP is in charge of handling in-space graph edges especially for connecting the most remote point.

7 Summary

In this paper, we extended the metric graph structure based on the former implementation of UCN. To find out the most remote point in a specific room and to handle virtually divided rooms without physical wall objects are the major outcomes of this paper. Virtually subdivided rooms still have several space objects in BIM model, but the former study and implementation of the UCN graph only deals with physically bounded space objects. As a result, virtual space objects have been neglected in the circulation graph generation, including another important end-node: the most remote point (MRP). The MRP graph can be utilized in assessing Fire Code and measuring exact walking distances in case of fire as the code regulated. The algorithm and the implementation process depicted in this paper suggest a generic approach to the issues based on the UCN graph, and demonstrate how to facilitate them for a better representation of building circulation. In this paper, we notice that the UCN graph has much more potentials in future work and to be extended in many parts as we suggested in this paper. We tried to show the significance of the BIM-enabled assessment to be extended for further requirements such as Fire Code that used to be missing in the former implementation. We hope many studies motivated in this extension of the UCN graph and broaden the scope of the BIM applications.

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