EVACUATION EFFICIENCY EVALUATION MODEL BASED ON EUCLIDEAN DISTANCE WITH VISUAL DEPTH

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Abstract

This study proposes an evacuation efficiency evaluation model considering both the spatial configuration and the physical/Euclidean distance of the layout. One of the critical issues in the design of high-rise buildings is the evacuation planning, and a tool for evaluating the evacuation efficiency is highly needed. The conventional evacuation efficiency evaluation tools such as SIMULEX focus on the evacuation time, and thus are inappropriate in specifically pointing out the areas with evacuation difficulty within the layout being analyzed. This study focuses on the configurational properties of space because they are easily connected with the evacuation route based on plan layout. The concept of Visibility Graph Analysis (VGA) is adopted as the starting point for measuring the configurational properties. In addition, the physical evacuation distance is considered as another basic factor for the evaluation of evacuation efficiency in order to describe actual physical setting of the building.

Evacuation Cost can be inferred as the sum of the traveling distance (Distance Cost) and the change of visual information within the evacuation process (Visibility Cost). Distance Cost from a point to exit is proportionate to the evacuation distance. The Visibility Cost is the degree of effort required to visually survey for exit, and it is related to visual point depth. Essentially, the proposed model calculates the Evacuation Cost from a certain point to exit by substituting the summation of Distance Cost and Visibility Cost for the visual depth of the visibility graph. With reference to this, three hypotheses to examine the relation between Distance Cost and Visibility Cost are initially proposed. Moreover, two additional hypotheses which adopt the concept of Angular Analysis are proposed.

In this paper, this new method is applied to an actual high-rise building, I-Park in Seoul, and its results are compared with those of SIMULEX, the evacuation simulation program. The high correlation and stability of the results suggest that the model proposed in this study can replace SIMULEX. The proposed model offers a clear visualization of the evacuation efficiency within a building plan, which can play a major role in the design development process where decisions must be made between alternatives. It can also be used to work out evacuation planning of buildings that are already built.

Introduction

Due to their immense scale, high-rise and huge-scale buildings naturally entail large number of users, including residents and visitors. Thus, predicative evaluation on space usage patterns of potential users is a critical and essential factor in the planning stage of such high-rise and huge-scale buildings. In particular, the speediness and ease of the evacuation for the users in the cases of disasters, such as fires, is an extremely significant element in the planning stage since the matter is directly related to the disaster prevention planning of the high-rise and huge-scale buildings.

041-02 In accordance with the global trend of change in fire safety regulations from the "prescriptive standards" to the "performance-based standards", various evacuation performance evaluation models regarding the evacuation planning of high-rise and huge-scale buildings have been developed based on different theories and methodologies. Among them, evacuation simulation tools, represented by SIMULEX, evaluate evacuation performance mainly through the evacuation time which is calculated by the simulation of residents/users' behavior under disastrous situations. They hold significance in terms of evaluating the overall evacuation performance. However, they have limitations, i.e. the tools can not be used as the indices for the evacuation difficulty of a specific area in a building.

The evacuation performance of a specific building has multiple relations to both the spatial structure of the building and the behaviors of residents/users of the building. This study focuses on finding a method that can reflect spatial structural characteristics of a building in a more active manner in evaluating high-rise and huge-scale buildings by applying the spatial analysis techniques, represented by space syntax.

Visibility Graph Analysis (VGA), one of the spatial analysis techniques that particularly emphasize the role of visual information on space syntax, concerns the effect of the visual information on the choice of movement routes. This study itself is based on the VGA. At the same time, the study proposes evacuation cost analysis technique that evaluates evacuation efficiency by using the actual evacuation distance in the case of a disaster. In other words, the paper assumes the evacuation distance traveled within a spatial structure and the visual features of the spatial structure as the two major factors that influence the evacuation efficiency of high-rise and huge-scale buildings. Furthermore, upon the assumption, this paper proposes a model that quantifies the concept of evacuation cost.

The outline of the paper is as follows. First, the conventional evaluation models of evacuation performance and evacuation efficiency are examined and their problems are presented. Second, in order to propose a novel evacuation evaluation model that complements the above mentioned problems in terms of evacuation distance, VGA technique is examined. Third, based on the previous findings, evacuation cost is defined and three hypotheses which relate to the definition are proposed and tested. As the result of the test, the most appropriate hypothesis is adopted. In the process of testing the hypotheses, the test results were compared to the results obtained from the application of SIMULEX, the widely used tool to evaluate the evacuation performance of high-rise buildings. The typical floor plan of I-PARK, a high-rise residence building located in Samsung-dong, Seoul, was selected for the test. Finally, two additional hypotheses are proposed by introducing the angular analysis to the previously proposed evacuation cost evaluation model. Then, the two hypotheses are again tested on the chosen sample followed by the comparison with the previous test results.

Existing Evacuation Evaluation Model

SIMULEX

SIMULEX program, developed by Thompson and Marchant of Edinburgh University in the United Kingdom, analyzes the evacuation time by simulating the evacuation process of multiple users/residents from their present position to the exit within a building. It is an agent-based program that displays the dynamic evacuation process, and it has an advantage of visually examining the possible problems that may occur during the evacuation. Such features enable easy comprehension of evacuation procedures by non-experts just by observing the simulation that resembles the actual situations. In addition, the total evacuation time can be obtained straightforwardly; thus, establishing evacuation planning gets simplified (Choi, Kang, Park & Lee, 2005). Furthermore, the comparison analysis between the maximum sustainable flow rate, which is indicated in the design guides for evacuation such as the UK regulations, and the flow rate, which is obtained by the simulation output of SIMULEX program, has confirmed the credibility of the simulation results of the SIMULEX program (Thompson & Marchant, 1995b). 041-03

SIMULEX program accepts the building users' initial positions, their characteristics, and response time as input. Then it simulates and displays the delay or the bottleneck situation caused by sudden congestion in some areas in the building, and analyzes the high-rise building by linking each storey with 'staircase' elements. The simulation can be operated by specifying an exit and positioning several agents on various parts of the map of the analysis object. Then, SIMULEX program draws a 'distance map' and calculates the shortest distance from each agent to the exit. Based on the pre-calculated distance, the actual evacuation is simulated while taking in all the information previously inputted.

However, SIMULEX program requires precise inputs of various features of agents that are varied according to analysis situations. Also, the program has its limitations on examining the effect that spatial structural features have on the evacuation performance because it focuses on the reproduction of evacuation behaviors only. In other words, discovering the specific area within the spatial structure where evacuation is difficult is uneasy.

Egress Complexity

Egress Complexity Model, developed by Donegan and others (2002), represents the plan of a building into a network, or graph, composed of nodes and edges. Based on the network, Egress Complexity Model quantitatively calculates whether the plan structure of the building is easy for the users to evacuate (Donegan et al., 2002). It simply relies on the layout property of a building plan and, unlike SIMULEX, it does not consider the behavior of the users. Thus it has an advantage in a sense that evacuation features are easily examined through the calculation of evacuation complexity in the layout design development process.

The distinctive feature of the model is how it calculates the efficiency of evacuation; the model calculates the efficiency by accumulating every stage from each room to the exit, and it has basic similarity with space analysis techniques based on graph theory, such as space syntax. However, it over-simplifies the evacuation process without considering the features such as evacuation distance. Therefore, it has limitation in predicting the actual evacuation situations precisely.

Visibility Graph Analysis (VGA)

Visibility Graph

Turner and others (2002) have started with Benedikt's isovist theory and devised a method that represents visibility into a graph of the environment, and named it Visibility Graph (Turner et al., 2001). Visibility Graph, which is often referred to as Isovist Graph, specifies vantage points within a built-environment as nodes, and visible connections from each point to the others within the isovist from it as edges. The important matter here is the arrangement of the vantage points. They emphasized that the set of isovists generated from arranged vantage points should 'near-fully' describe the spatial structure for analysis, and proposed to array vantage points with regular intervals like grid. In addition, they suggested that the regular interval should be set by taking into account the 'human-scale' (Turner et al., 2001, p.106).

Visibility Graph holds its significance for it crosses out the arbitrariness in the representation of spatial structure. That is, the representation method of Visibility Graph overcame the two problems of conventional space syntax that utilized axial map and convex map: the ambiguity in drawing principles and the variability of results according to different drawers. Hence, by utilizing Visibility Graph, it is possible to analyze in a greater detail as well as through a more consistent principle than by utilizing axial map or convex map. In particular, Visibility Graph yields appropriate results in analyzing huge-scale spaces that are of open-plan characteristics.

Visual Point Depth and Visual Depth

In the conventional space syntax, point depth is an index that displays the depth of the shortest path from the root node to each node within the justified graph that is drawn by a specific root node. Through the frequency distribution of the point depth that is obtained by rooting a specific node, how ordered the spatial structure is from the root node can be examined (Turner, 2001b, p.31.7).

Point depth can also be considered in Visibility Graph that represents a space into grids in a regular interval. This is called Visual Point Depth. Visual Point Depth based on a specific root node indicates the visual depth from the root node to each node. In other words, Visual Point Depth signifies the shortest depth of visual approach from each node to the root node. Here, the visual depth corresponds to the frequency of changes occurred in visual information and signifies that all the nodes within the isovist, which is generated from the root node, is located within 1 visual depth of the root node. In terms of behavioral aspect, it also means the number of turns in directions when traveling.

Evacuation Cost Evaluation Model

Proposal of the Model

This study proposes a vision-distance evacuation cost analysis technique that considers both the distance factor of the evacuation route and the turn of direction factor within the evacuation route according to the visual information. The proposal is based on the assumption that the evacuation efficiency can be acquired by considering the two factors obtained during the evacuation procedure concurrently: the changes in the visual information and the distance of travel. Here, the concept of visual depth in the VGA technique is utilized for the changes in the visual information. This utilization enables easy distinction between the information which can be spotted at a glance and the information which can be obtained when the position has been changed by moving (Choi, Cho & Kim, 2005).

Thus, the change in visual information according to the movement can be considered by the evacuation cost analysis. In order to take it into account that even the points, which lie within the identical isovist generated from the specific root point and has identical visual depth, vary in the actual evacuation time according to the distance to the root point, evacuation cost is calculated by computing a noble visual/Euclidean depth through the combination of the distance information and the visual depth.

Evacuation Cost is the summation of the actually traveled distance (Distance Cost) during the evacuation process and the change in the visual information (Visibility Cost) during the traveling process.

[Evacuation Cost] = [Distance Cost] + [Visibility Cost]

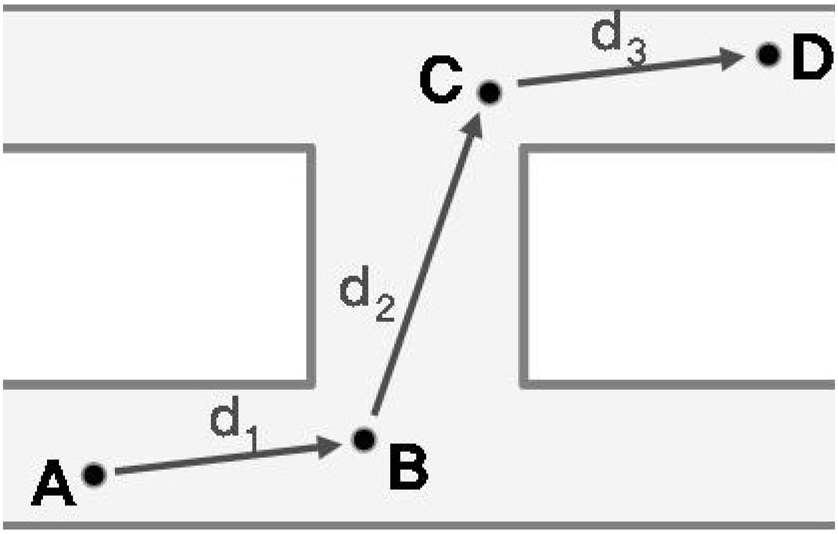


Figure 1:

An example of the evacuation process

Now let's look at the computation process of Evacuation Cost. In figure 1, if point D is assumed as the exit, the Evacuation Cost of the resident currently located in point A under the emergency situation is the effort that the resident requires in order to travel from A to exit D. This is same as the total cost of the route that minimizes the sum of Distance Cost and Visibility Cost among the various possible route through which the resident can travel from A to D.

This study adopts the method that is used by Visibility Graph when calculating the point depth. In the VGA technique, the depths between two grid nodes that are visually linked are substituted by 1 consistently in the process of point depth calculation. However, the present paper calculates Evacuation Cost by substituting the depth between two visually-linked grid nodes with the cost required to travel between one grid node to the other grid node. Through the method, a specific node is selected as the exit and by setting the specific grid node as the root node, "The Minimum Evacuation Cost Justified Graph" can be drawn. Also, evacuation costs from every position within the plan for analysis can be computed by the method that calculates Visual Point Depth from the root node. The method was mentioned in the previous chapter [i].

$$EC = \sum EC_i = \sum (DC_i + VC_i)$$

EC_i : the evacuation cost from the i-1st node to ith node
DC_i : the distance cost from the i-1st node to ith node
VC_i : the visibility cost from the i-1st node to ith node

In order to add the distance cost and the visibility cost, a scale conversion of the two costs is required. By assuming that the distance cost is proportionate to the traveled distance, the distance cost conversion coefficient (the inverse of the distance between the grid nodes) is multiplied to the actual distance cost for the scale conversion. At the same time, the visibility cost is assumed to be proportionate to the visual depth and the visibility cost conversion coefficient is multiplied in order to compute the visibility cost of the visual depth 1 between two adjacent nodes [ii].

041-06

Here the summation method of the distance cost and the visibility cost should be noted. The distance cost can easily be understood by considering the distance of the actual evacuation route as the substitution of the distance cost. However, the visibility cost is related to the behavioral aspect and it requires a clear standard that estimates the effects that the visibility cost has on the evacuation cost. Therefore, the present study sets three hypotheses in order to discern what kind of effect or how much effect the visibility cost, defined as the cost for turning direction, has on the evacuation cost compared to the distance cost. Hypothesis 1 is based on the ‘distance map’ of SIMULEX. On the other hand, Hypotheses 2 and 3 are based on the concept of the model-based control and of the information-based control respectively, which correspond to the concept of motor control well known in the fields of experimental psychology and kinetics.

Hypothesis 1: Evacuation cost is identical to the evacuation distance.

Hypothesis 1 is based on the assumption that the distance traveled by an evacuee is the only cost factor in the evacuation. This does not consider the visibility cost in evacuation cost. In other words, Hypothesis 1 considers the visibility costs between two adjacent nodes as zero. According to this, distance is the only significant evacuation cost factor. Hence, it is theoretically similar to the ‘distance map’ of SIMULEX as well as many other distance-based evacuation models. This also has significance in its role as the comparative hypothesis to the Hypotheses 2 and 3.

$$VC_i = 0$$

$$EC = \sum EC_i = \sum DC_i$$

Hypothesis 2: Evacuation is a planned response.

Hypothesis 2 is based on the assumption that an evacuee predicts or preplans the overall evacuation route in the primary stage of travel and then the evacuee actually travels according to the prediction or the plan. This hypothesis highlights the greater effort needed in the prediction from a specific position when the visual depth of the position from a certain point is deeper. Thus, it substitutes the cost required by the evacuee in the prediction of overall evacuation route with the concept of visual depth. The actual computation procedure is as follows. First, the visibility cost is computed by accumulating the visual depths of nodes within the evacuation route. Next, the visibility cost is added to the distance cost and eventually the evacuation cost is obtained. Here, the visibility cost is computed by multiplying the visibility cost conversion coefficient(α) to the summation of visual depths between the root node and each of the other nodes.

$$VC_i = a \times \sum vd_i$$

$$EC = \sum EC_i = \sum (DC_i + VC_i) = \sum (DC_i + a \times \sum vd_i)$$

vd_i : visual depth from i-1st node to the ith node
α : visibility cost conversion coefficient

Hypothesis 3: Evacuation is an intuitive response.

Hypothesis 3 is based on the assumption that the evacuation procedure is the repetition of the intuitive mechanism following the evacuation route which continuously ‘emerges’ during the traveling process of an evacuee. While Hypothesis 2 emphasizes the planning aspect of the evacuation procedure (perception→model→planning→ action), Hypothesis 3 highlights the intuitive aspect of the evacuation procedure (perception→action). Whenever evacuees encounter new information such as forked roads within the evacuation route, they judge intuitively based on the visual information on that specific spot and efforts are required for the cases such as the turn of directions according to the judgment. Here, the visibility cost is computed by multiplying the visibility cost conversion coefficient(α) to the visual depth between two adjacent nodes.

$$VC_i = a \times vd_i$$

$$EC = \sum EC_i = \sum (DC_i + VC_i) = \sum (DC_i + a \times vd_i)$$

Table 1:

An Example of Computing the Evacuation Cost (Point A → Point D)

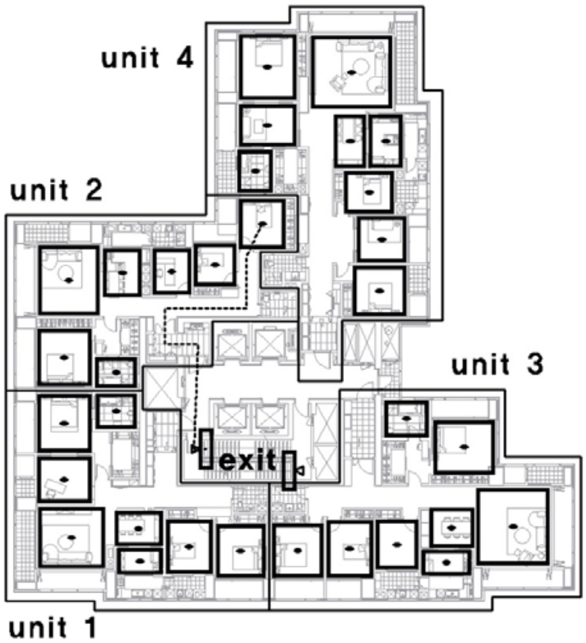
	Distance Cost	Visibility Cost	Evacuation Cost
Hypothesis 1	$d_1+d_2+d_3$	·	$d_1 + d_2 + d_3$
Hypothesis 2	$d_1+d_2+d_3$	α+2α+3α	$[d_1+α]+[d_2+2α]+[d_3+3α]$
Hypothesis 3	$d_1+d_2+d_3$	α+α+α	$[d_1+α]+[d_2+α]+[d_3+α]$

Hypotheses Testing

This study developed a novel application named “SaDistVisibility” for computing the evacuation cost. SaDistVisibility is an application that is developed using Visual Studio .NET 2002 SDK (Visual C++ 7.0 compiler), a software development toolkit of Microsoft Corp., and ObjectARX 2006 SDK, the AutoCAD 3rd Party development toolkit of Autodesk, Inc.. The program can be loaded on AutoCAD 2004-2006 Applications and operates by executing specific commands on AutoCAD. In addition to the indices obtained by VGA technique, the program provides the evacuation costs from each grid node to exit when the root grid node is selected as the exit within the application program. Each analysis result is displayed in a color spectrum (red>yellow>green>blue) [iii], and the result data of each grid node are saved in the AutoCAD Drawing File format (*.DWG). Also, all the result data can be exported in Microsoft Excel File format (*.XLS).

This study selected the typical floor plan of I-PARK, a 47-storey skyscraper located in Samsung-dong, Seoul, as the example for analysis. In order to analyze correlation between the result of SIMULEX and that of Evacuation Cost Analysis, the ‘evacuation cost’ data and the ‘evacuation time’ data from the 32 unit rooms of the typical floor including bedrooms, living rooms and kitchens to the threshold of the stairway were made into variables. First of all, SIMULEX 11.1.3 was used to obtain the raw ‘evacuation time’ data after conducting seven experiments from each room to the exit and the average values of the data for each room were taken as the ‘evacuation time’ data from each room. Also, for Evacuation Cost Analysis, the plan of the typical floor was partitioned into grids with 0.5m intervals. In cases of Hypotheses 2 and 3, the visibility cost conversion coefficient (α) was changed from 0.5 to 4.0 and ‘evacuation cost’ data which correspond to the changing value of α were calculated.

The merit of Evacuation Cost Analysis Technique proposed by the present study is the easiness in distinguishing the evacuation efficiency from each position on the plan. Figure 3 is the result of analyzing based on Hypothesis 3 when the visibility cost conversion coefficient (α) was set at 1.0. The darkness indicates the area where evacuation cost is high, while the lightness indicates the area where evacuation cost is low. Generally, the farther from the exit the position is and the greater the number of turning directions is, the higher evacuation cost gets. Furthermore, due to the consideration of the visibility cost, sudden increase of the evacuation cost is clearly seen in several parts of the analysis result plan along the occlusivity lines (Benedikt, 1979) of some points.



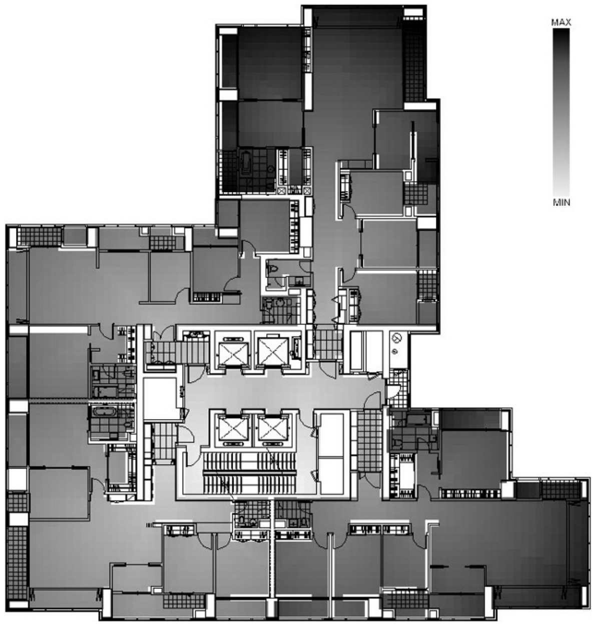


Figure 2:

Plan of the analysis sample (left)

Figure 3:

Output of the Evacuation Cost Analysis: Hypothesis 3 (α = 1.0)(right)

The correlation analysis between the analysis outputs for three hypotheses and the results from SIMULEX evacuation time is shown in Table 2. In general, high correlation was witnessed. Hypothesis 1 considers only the distance cost. SIMULEX is a simulation program that reproduces evacuation behaviors through the 'distance map' that displays the shortest route to the exit. Therefore, high correlation between the analysis results of Hypothesis 1 and SIMULEX can be inferred. On the other hand, the analysis result of Hypothesis 2 illustrates lower correlation compared to that of Hypothesis 1. Thus, the computation method of visibility cost in Hypothesis 2 can be interpreted as not so appropriate. However, the analysis results of Hypothesis 3 shows slightly higher correlation compared to that of Hypothesis 1. Also, it can be clearly seen that the visibility cost conversion coefficient (α) is most appropriate when it is set at 1.0. This signifies that the best result is obtained when the visibility cost of one unit of visual depth corresponds to the distance cost for the grid interval. Figure 4 is the scatter diagram that illustrates the cases when each hypothesis displays the highest correlation coefficient (R2). As it can be noticed from Figure 4, in the case of Hypothesis 1, there exists some deviation from the regression line. On the other hand, in the case of Hypothesis 3, the deviation is very slight; the result shows almost the identical distribution with the regression line. (SSE of Hypothesis 1 = 77.7492, SSE of Hypothesis 2 = 141.7275, SSE of Hypothesis 3 = 41.9141) This result further augments the validity of Hypothesis 3.

According to the results above, Evacuation Cost Analysis Technique proposed by the present study shows almost identical result with SIMULEX, the prevailing evacuation simulation methods, when Hypothesis 3, which interprets evacuation process as an intuitive response, is adopted. Therefore, evacuation cost should include the costs of intuitively judging the direction and making the turn based on the visual information obtained from the positions where new visual information is available, i.e. the positions where the turn of direction is possible. The corresponding cost is equivalent to the interval between the grids (0.5m in this study), which is same as the distance cost with one or two steps traveled further.

α	Hypothesis 1	Hypothesis 2	Hypothesis 3
0.5	**0.9779**	**0.9626**	0.9878
1.0		0.8686	**0.9884**
2.0		0.6470	0.9716
3.0		0.4817	0.9365
4.0		0.3741	0.8911

Table 2:

Output of Regression Analysis on Evacuation Cost and Evacuation Time: R^2 according to α

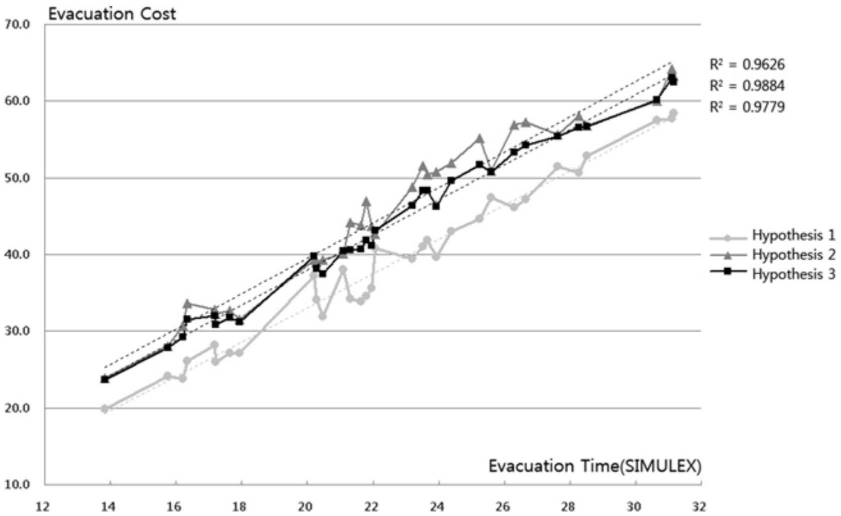


Figure 4:

Scatter diagram of Regression Analysis for each hypothesis

Adoption of Angular Analysis

Proposal of the Model

According to the results of the previous chapter, visibility cost in the computation of evacuation cost proves to be significant. In terms of behavioral aspect, it was already stated that visibility cost is equivalent to the number of turn of directions during the travel. The hypotheses of the previous chapter treated all the turn of directions identical and 1 was allocated to visibility cost. However, 10° turn and 90° turn have great difference not only in the degree of the turn but also in the amounts of change in visual information and of efforts required for the turns. Also, the 180° turn means retracing one's steps, which requires significant amount of effort and cost. When considering the evacuation situation, such difference in the degree of turns looms larger than in general cases. In other words, the easiness of turn of direction within the evacuation route is influenced by the direction previously pursued.

Dalton raised the issue of "Manhattan problem" and proposed fractional analysis as its solution. Turner proposed angular analysis which combines fractional analysis and his VGA technique. These analyses are based on the concept of fractional/continuous depth which goes against the integerized concept of discrete depth that makes the conventional premise of the space syntax. They set turning angle from a certain axial line to another adjacent axial line as the explanatory variable of the depth values. Thus, these analyses assume that the depth between adjacent axial lines is the function of the turning angle between the two axial lines. The difference between the two analyses lies in the different functions. The mathematical expression of Dalton and Turner's assumption is as follows.

$$D = \sum d_i = \sum f(\theta_i)$$

di : depth from i-1st node to the ith node
θi : turning angle from i-1st node to the ith node

Based on Hypothesis 3 tested in the previous chapter, the current chapter will set hypotheses regarding visibility cost which constitutes evacuation cost in terms of angular analysis. Then the paper will go on to test the hypotheses. In other words, under the premise that the visual depth which makes the foundation of visibility cost is a continuous function (of angles) rather than a discrete function, two hypotheses regarding the visual depth function is established and tested. The process will improve the computational method that this paper proposes to a more precise level and to a greater similarity with the actual evacuation behaviors.

041-10

Prior to setting hypotheses, the method of how to generate axial lines which become the bases for computing angles should be determined. Dalton primarily started from the axial map, and Turner set the edges between each grid node of visibility graph as axial lines. This paper is originally based on the visibility graph developed by Turner; thus, it will adopt the method suggested by Turner. However, while each axial line that were generated from edges functioned as the unit space in the study of Turner, the present study restore the grid nodes to the unit spaces by reducing each of the axial line generated from edges into the original grid nodes. Expressing these ideas in mathematical terms is as follows.

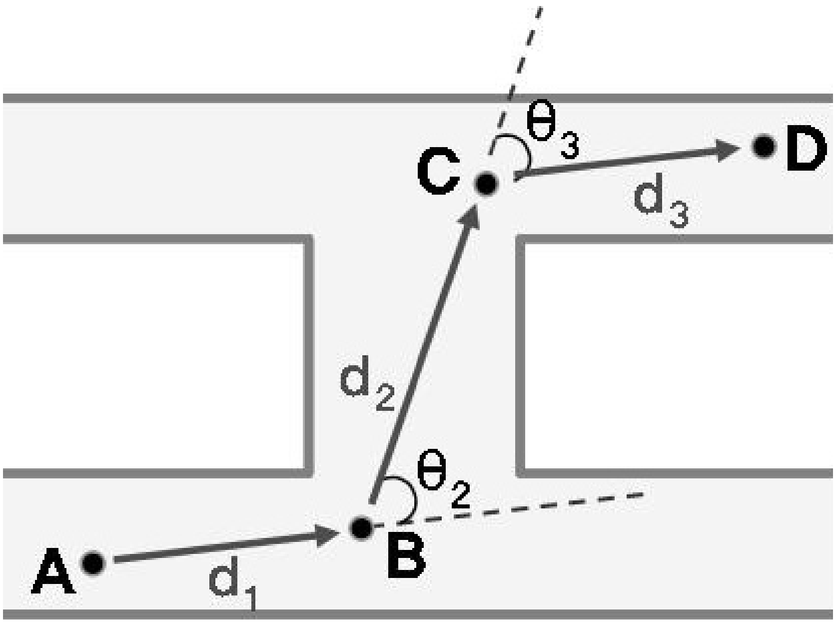


Figure 5:

An example of the evacuation process: Angular Analysis

$$VC_i = a \times vd_i = a \times f_{vd}(\theta_i)$$

$$EC = \sum EC_i = \sum (DC_i + VC_i) = \sum (DC_i + a \times vd_i) = \sum \left(DC_i + a \times f_{vd}(\theta_i)\right)$$

Hypothesis 3-1: Visibility Cost is a sine function of turning angles.

Hypothesis 3-1 is based on the assumption of Dalton. The hypothesis is founded upon the assumption that the visual depth between two adjacent grid nodes within a certain evacuation route is a sine function of the turning angle between the direction of the edge linking the two grid nodes and the direction of the edge linking the two grid nodes of the previous stage. When trigonometric functions such as sine function are used as visual depth function, the degree of difference in the behavioral effort according to the change in turning angle can be reflected in visual depth. For example, compared to the difference in the required effort between the shortest route followed by the turning angle of 0° and that followed by 10°, the difference in the required effort between the shortest route followed by the turning angle of 80° and that followed by 90° should be much smaller [iv]. Here visibility cost is obtained by multiplying the visual depth by the visibility cost conversion coefficient (α).

$$f_{vd}(\theta_i) = \begin{cases} \sin\theta_i & (0 \le \theta_i \le \pi/2) \\ 2-\sin\theta_i & (\pi/2 < \theta_i \le \pi) \end{cases}$$

Hypothesis 3-2: Visibility Cost is the linear function of turning angles.

Hypothesis 3-2 is based on the Turner's assumption. The hypothesis is founded upon the assumption that the visual depth between two adjacent grid nodes within a certain evacuation route is a linear function of the turning angle between the direction of the edge linking the two grid nodes and the direction of the edge linking the two grid nodes of the previous stage. Thus, unlike Hypothesis 3-1, Hypothesis 3-2 hypothesizes that the degree of effort required for the turn of direction is proportionate to the degree of the corresponding angle of the turn. Visual depth is defined as the value of turning angle divided by 90°, so that the visual depth of the turning angle with 90° can be treated as 1 and that of the turning angle with 180° can be treated as 2 as in the case of the first hypothesis.

$$f_{vd}(\theta_i) = \theta_i / (\pi/2)$$

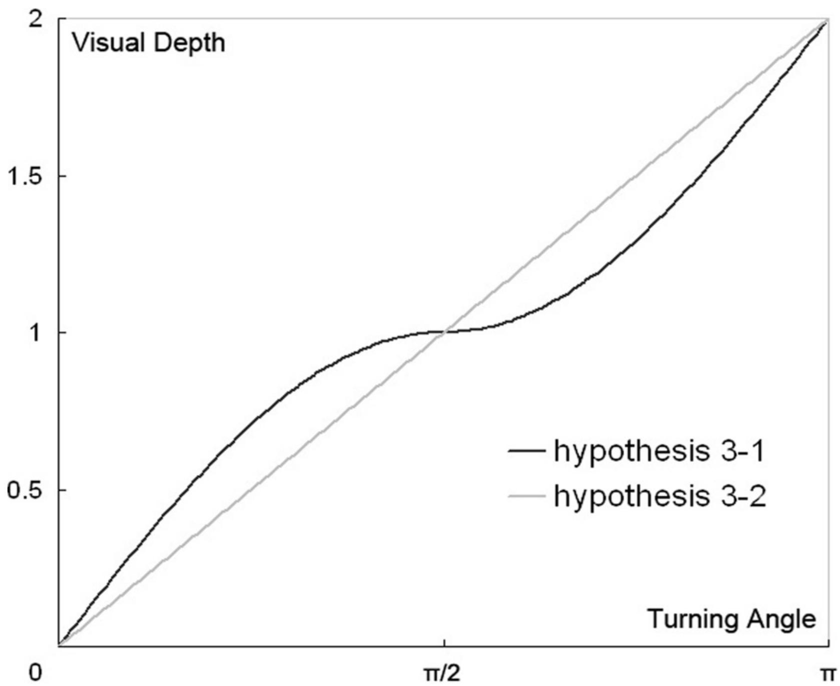


Figure 6:

Function graph of the visual depth for each hypothesis: Angular Analysis

Table 3:

An Example of Computing Evacuation Cost according to Angular Analysis (A→D)

	Distance Cost	Visibility Cost	Evacuation Cost
Hypothesis 3	$d_1+d_2+d_3$	α+α+α	$[d_1+α]+[d_2+α]+[d_3+α]$
Hypothesis 3-1	$d_1+d_2+d_3$	α+αsinθ$_2$+αsinθ$_3$	$[d_1+α]+[d_2+α\sin θ_2]+[d_3+α\sin θ_3]$
Hypothesis 3-2	$d_1+d_2+d_3$	α+αθ$_2$/(π/2)+αθ$_3$/(π/2)	$[d_1+α]+[d_2+αθ_2/(π/2)]+[d_3+αθ_3/(π/2)]$

Hypotheses Testing

The example for analysis used to test Hypotheses 3-1 and 3-2 was identical as the one selected to test Hypotheses 1, 2, and 3. The typical floor plan at I-PARK was used to test Hypotheses 3-1 and 3-2 and the previous outputs of SIMULEX were reused. During evacuation cost analysis of Hypotheses 3-1 and 3-2, the intervals between grids were 0.5m and the visibility cost conversion coefficient (α) was changed between 0.5 and 4.0. Figure 7 (1) and (2) illustrate the results of analysis on Hypothesis 3-1 and 3-2 respectively. Both of the results were obtained when the visibility cost conversion coefficient was set at 1.0. When compared to the result on evacuation cost of Hypothesis 3 (figure 3), both of the recent analyses show much smoother changes in the evacuation costs. In particular, the sudden increases near the occlusivity lines have noticeably decreased.

Figure 7:

Output of the Evacuation Cost Analysis: (1) Hypothesis 3-1, (2) Hypothesis 3-2 (α = 1.0)

The correlation analysis between the analysis outputs of Hypotheses 3-1 & 3-2 and the output of SIMULEX is shown in Table 4. Both of Hypotheses 3-1 and 3-2 show relatively low correlation compared to Hypothesis 3; however, when the visibility cost conversion coefficient is set 1.0, they show greater correlation than Hypothesis 1. When the changes in the correlation coefficient according to the change in the visibility cost conversion coefficient are considered, it is clear that the distance cost equivalent to the grid interval is most appropriate for the visibility cost of visual depth 1 in both of the hypotheses 3-1 and 3-2. However, considering the fact that the correlation coefficients of Hypotheses 3-1 and 3-2 show decrease (although not in a great scale) compared to that of Hypothesis 2, it can be inferred that Angular Analysis enables detailed computation of Evacuation Cost but it does not improve the prediction for the actual evacuation behaviors.

Of course, the interpretation above can be controversial because the analysis results of Evacuation Cost were compared not to the actual evacuation behavior but to the output from SIMULEX. There exists possibility that such interpretation has neglected the significance of utilizing the Angular Analysis although it actually is valid. However, considering the difficulty of examining the actual evacuation behavior, it is practically more valid to prove the significance of Angular Analysis in the behaviors of general travel before proving its significance in the evacuation situations.

α	Hypothesis 3	Hypothesis 3-1	Hypothesis 3-2
0.5	0.9878	0.9862	0.9848
1.0	**0.9884**	**0.9869**	**0.9868**
2.0	0.9716	0.9625	0.9747
3.0	0.9365	0.9131	0.9430
4.0	0.8911	0.8523	0.9008

Table 4:

Outputs of Regression Analysis on Evacuation Cost and Evacuation Time according to Angular Analysis: R^2 according to α

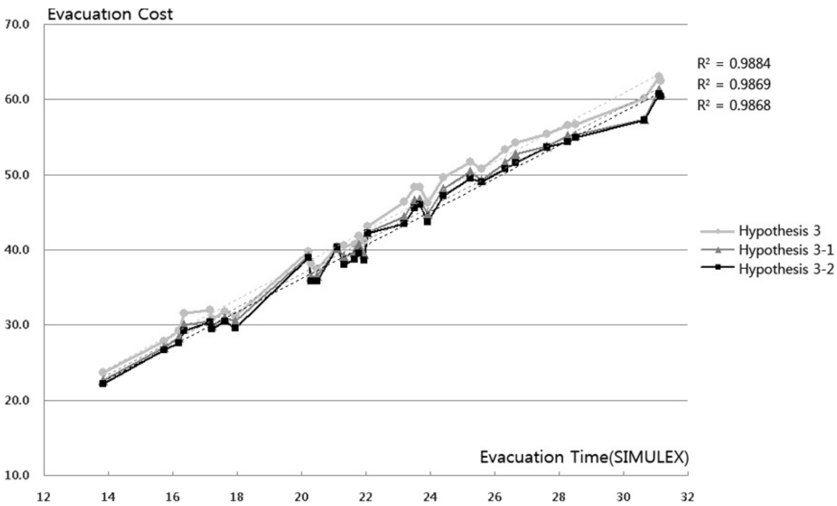


Figure 8:

Scatter diagram of Regression Analysis for each hypothesis: Angular Analysis

Conclusion

This paper proposes a new technique that evaluates the evacuation efficiency. The paper defines evacuation cost as the efforts required in evacuation and both distance cost based on the physical/Euclidean distance and visibility cost based on visual information are considered when computing evacuation cost. By taking the two cost concepts into account, the paper predicts the evacuation efficiency of each position within a certain spatial structure through the plan analysis in a more effective manner. It can be concluded that the evaluation model proposed by this paper can sufficiently replace the conventional SIMULEX program since very high correlation and the linear relation between them were observed.

Furthermore, evacuation cost analysis technique proposed by this paper can easily distinguish specific areas with evacuation difficulty because it shows the analysis results of each position on the analysis plan. Therefore, the results obtained through evacuation cost analysis technique can be used as the supplement materials that evaluate the configurational property of the spatial structure. In addition, evaluation on evacuation cost can be conducted during the design development and the evaluation results can be used as the feedback on the improvement of the designing and planning.

The evacuation cost evaluation model proposed by this paper does not consider the actual and dynamic situations such as bottleneck phenomenon during the evacuation. In order to counter the problem, the choice index regarding every grid nodes within the spatial structure analyzed should be computed during the stage of drawing Minimum Evacuation Cost Justified Graph (MECJG) and this value should be taken as the potential bottleneck index of each grid node. Here, the choice index represents the frequency that a certain node is situated within the shortest path between the other nodes. Thus, the choice index obtained from MECJG signifies the potential that a specific node can be located within the shortest evacuation path and this can be interpreted as the potential of bottleneck phenomenon around the node. Further research on this subject should be sought in the future.

In addition, like the VGA technique the Evacuation Cost Evaluation Model proposed by this paper has limitation for the use in the single-storey space. Further study is required on the combination of the present analysis and the analysis on the evacuation efficiency of vertical passages, which is critical in the evacuation plan of high-rise and buildings.

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i. When more than two grid nodes are selected as exits, the minimum evacuation cost route towards the exit grid node that minimizes the minimum evacuation cost between each grid node to each of the exit rid node should be selected.

ii. The reason for multiplying the visibility cost conversion coefficient (α) to the visual depth is to unify the scales of the distance and visibility cost which are added to obtain the evacuation cost.

iii. In this paper, all the results are displayed in a grayscale spectrum for publication.

iv. In the text the degree was used as the unit of angle for the ease of explanation, but in the equation the radian was used.