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An Explorative Study for Space Analysis Techniques for Tall and Huge-Scale Buildings

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Abstract

It is argued that the design of tall and huge-scale buildings need the quantitative pre-occupancy evaluation for maximized space use efficiency. In order to check the viability of a spatial analysis tool, ERAM (Eigenvector Ratio of Adjacency Matrix) for such purpose, it is applied in the efficiency analysis of a Korean tall and huge-building. The analyses are done both for the horizontal space layout and the vertical layout. At the same time, the actual space usage is also measured on the field. The ERAM analysis results are compared with the field data. The ERAM analysis and prediction of space usage account for 30~40% of the actual space usage observed. Even though the accountability is relative low as compared with other analysis of urban street system, it is argued that the ERAM analysis seems to be an appropriate tool for space usage efficiency check in tall buildings, provided that more research be done to improve the research protocol and methods, especially the mapping and weighting techniques for spaces in tall buildings.

Keywords: Tall Building, Space Syntax, ERAM, Spatial Analysis

1. Introduction

It is a common belief that the post-occupancy evaluation (POE) should be done to apartment buildings and high-rise office buildings in order to assure that the buildings, once built, meet the expectations of the client and users. However, the current POE is usually to analyze only the level of satisfaction based upon subjective responses of the users to questionnaire or interview. Tall buildings have huge size and capacity, and thus they do require the pre-occupancy evaluation which allows estimating and evaluating design efficiency, especially the efficiency of space use.

There are several tools to evaluate the space use efficiency in buildings, including Space Syntax, ERAM (Eigenvector Ratio of Adjacency Matrix), and so on. These spatial analysis tools are relatively well known for their capability to estimate the potential usage of spaces within buildings. Unfortunately, it is hard to find any research or practice in which spatial analysis tools are actually used for the evaluation of huge-scale buildings.

This paper, in the viewpoint, is to apply a spatial analysis tool to a tall and huge-scale building in order to examine the tool’s reliability to estimate the potential space usage through the comparison between the analysis result and the actual space usage. Also the paper explores the way the space analysis tool is utilized for efficient allocation of the vertical flow in tall buildings. For these, an existing domestic tall building is selected as an example; the actual patterns of space use are surveyed; and these are compared with the space usage data generated from the spatial analyses on the horizontal and vertical links of the building. As the result of this exploration, proper process for analyzing space usage in tall and huge-scale buildings may be suggested.

2. Theoretical Background

Characteristics of Tall and Huge-Scale Buildings

By tall buildings, it is commonly referred to those that are over sixty stories. Tall buildings usually have high-density mixed-use commercial spaces at the lower level and also high-density office and/or residential spaces at the higher level. Each floor of tall buildings is linked to the ground floor through the vertical flow like the elevators. The elevators and the adjacent halls are the most densely used spaces of the tall buildings and the relative location of these spaces are crucial to the efficiency of space use in tall buildings.

Spatial Analysis Tools

(1) Space Syntax

Currently the Space Syntax is one of the most well known method in the field of spatial analysis. It presents the layout of architectural or urban spaces in a graph form of nodes and edges (nodes being...
connected to each other by edges), and indexes the topological position of each space. The Space Syntax analyzes, based upon the concept of depth, the connecting relationship of individual spaces using the indices such as integration, control, and intelligibility (Hillier and Hanson, 1984).

An index called integration shows the relative position of a space in terms of its integration into the whole spatial structure of a building. Previous studies (Hillier et al., 1993) show that the integration value of a space fairly well predicts how frequently the space is used in comparison with the other spaces within the same building.

In Space Syntax, axial map and convex map are used for analysis. Axial map represents urban spatial structure; it is the method to draw a straight line on the streets without intruding any adjacent building or lot. Whereas convex map which divides spaces into unit space usually represents spatial structure of interior spaces of the buildings.

![Fig. 1. Examples of Axial Map and Convex Map](image)

(2) ERAM (Eigenvector Ratio of Adjacency Matrix)

ERAM is also an analysis tool for measuring the relational aspects of the spatial layout. While Space Syntax analyzes the topological relation of spatial structure derived from the connecting relation of space in terms of depth, the ERAM model analyzes spatial structure deduced from the connecting relation of space in terms of adjacency matrix which represents the spatial structure of a building, and it produces the probability distribution of users among the spaces within a building, or in other words, the potential for the user occupation in each space in a building (Choi et al., 2003).

3. Framework for Spatial Analysis

Analysis of Horizontal Connection

Tall and huge-scale buildings are generally developed for a mixed-use. A commercial complex is usually located at the low level and it attracts lots of people. It is necessary, for an efficient and safe use of such buildings, to match the people flow and spatial layout from the early stage of design process.

It is not easy to estimate the number of people in any space within a building at a given time, because people are freely floating within commercial buildings. However, tracking survey may help to figure out the flow disposition of people. And a spatial analysis tool such as ERAM may show the same thing on a theoretical basis.

Analysis of Vertical Connection

The vertical flow or movement in tall buildings is carried mainly by elevators. It is not efficient to use all the elevators covering every floor, and thus a grouping strategy is adopted for the efficient operation of elevators. The strategy is largely classified into "zoning system" and "sky-lobby system."

Zoning system has several sections for which the elevators starting from the move-in floor (usually the ground floor) operates (Figure 2). There are separate elevators operating for high-zone, middle-zone, and low-zone of the tall building.

![Fig. 2. Zoning System](image)

Sky-lobby system is usually used for the buildings for mixed-use, or for those buildings with many zones due to their extreme height (Figure 3). One or two sky-lobby floors are installed in the middle part of the building. The sky-lobby floor is a transfer floor in that the express shuttle elevators operate from the ground floor to this floor. From this people use other elevators to get to the higher zones. Usually, sky-lobby floor would have some convenience facilities such as shops and snacks.

![Fig. 3. Sky-Lobby System](image)
For the efficiency of space use, it is important to analyze and evaluate elevator system in the process of designing tall and huge-scale buildings in order to see and check how efficiently the vertical flow is distributed.

4. Spatial Analysis of an Existing Tall Building

Subject

A tall building, Technomart21 was selected as the subject of analysis. The building has 6 underground stories and 39 stories above the ground with the above-ground height of 188.7 m. The site area is 26,446 m², and the total floor area 259,739 m². This building has various types of facilities including underground parking lot, shopping mall, banks, rental offices, health clinic, fitness centers, cinema, cafeteria, and departments of electronic products.

The building has a 39-story business complex tower and 12-story commercial block both of which are horizontally connected. It also has 4 moving walks, 64 escalators and 36 elevators. The researchers decide that it would be a good subject for the spatial analysis of the vertical flows in tall and huge-scale buildings.

Analysis Method

The subject building is first studied in terms of horizontal spatial analysis on the low block where commercial facilities are located, and second, in terms of vertical spatial analysis on the tower section where rental offices are located.

(1) ERAM analysis

ERAM is used for the analysis. It is a theory which, with the concept of probability, models the movement distribution within spaces. It starts with premises that every space within a building has one occupant, and that, as a next step, the occupant is to randomly move to one of the next spaces which are connected to the original space. After the n-th random movement, ERAM(n) value of a space denotes a probable number of occupants in the space, or the probable passage count when the space is a transitional space such as corridor. As noted earlier, ERAM model uses the adjacency matrix of spaces which exactly reflects the relational network of spaces.

(2) Analysis Setup

In ERAM analysis, spaces have to be defined in such a way that they are distinguishable from each other. Here each space, which becomes a unit for the analysis, is regard as a convex space. It is defined as follows:

① The line segment which connects any two arbitrary points in the space is included within the boundary of that space.

② The tangent line drawn from every point on the boundary does not cross the boundary.

To set up the ERAM analysis, convex spaces on every floor plan of the building are drawn. Usually a compartment or room becomes a convex space. A corridor is divided into a series of convex spaces each of which corresponds to the adjacent space (e.g., a shop or an office). That prevents a long corridor from becoming an absurdly huge single convex space.

Then every floor plan is linked one another through the vertical connections such as stairs, escalators or elevators. The whole elevator shaft is regarded as a single space (see the middle figure in Figure 7). The connection between the elevator shaft and the elevator hall on each floor is different from the normal connection between ordinary spaces. It takes time for people to wait the elevator vehicle to arrive at the hall. Also it takes time, when inside, to wait the vehicle to arrive at a desired floor. This makes it necessary to give a specific weight, or relative gravity, to the connection of hall and elevator. For this, a weight of 0.5 as compared to 1 for normal connection is set in the connection of elevator and hall.

Unlike stairs and elevators, escalators have a predetermined direction. A weight of 0 or 1 is given to the escalator depending on its direction (See the third figure in Figure 7.).
The ERAM analysis would provide the theoretical and probable use of each space in the Technomart21 building. In addition, the actual use of spaces is surveyed through the tracking.

The method of the tracking survey is as follows:
1. As the tracking subjects, adults in their twenties or older out of all visitors to the B1, 1st and 6th floors are selected.
2. Tracking of randomly picked individual is initiated from any of the main entrances of the selected floors (B1, 1, 6) and also from 3 or 4 more spots where population largely flows in. It is completed when the tracked people leave the floors under survey.
3. The route of the tracked people is recorded on the prepared floor plan.
4. When the tracked people spend 15 minutes and over at a specific location without moving, or keep moving on for more than 30 minutes, the tracking is finished.

The convex maps of all 11 floors are made and each floor is linked to the floor directly above or below as it is actually connected via stairs, elevators or escalators. Once the whole convex map is completed, analysis is conducted for ERAM(3) and ERAM(9) values for spaces on the B1, 1st and 6th floors.

As a parallel, the tracking survey was performed on the B1, 1st and 6th floors. 171, 107 and 79 people were surveyed respectively.

The accumulated flow of people being tacked is considered as the passage count at a certain space. In other words, the passage count is the same as the number of the tracking lines crossing at a certain space or location on the convex map.

Those locations where two corridors meet (Figure 9) are selected for the comparisons between the ERAM values and the actual passage counts. There are 52 such locations on the B1 floor, and 41 and 56 locations for the 1st and 6th floors, respectively.

Analysis and Comparison Results
The results are summarized in Table 1. The tracking result at the B1 floor shows a lot of people moving around the escalators. The movement gets thinner as the spaces get closer to the periphery from the central main passage. The result at the 1st floor shows that spaces around the escalators are also the most congested. In addition, from the tracking, the main passages can be identified. The results of ERAM analysis also confirm those main passages. Both of the tracking and ERAM analysis results at the sixth floor show the passages of the up and down direction are preferably used to the passages of the right and left.

The correlations between the passage counts from the tracking survey and ERAM(3) & ERAM(9) from the ERAM analysis are in the range of 0.30 to 0.47 (See the bottom row of Table 1).

Considering the fact that the correlation between passage counts and integration values of Space Syntax for several urban streets is usually around 0.7, the current result is somewhat low. There seem to be some explanations for this: (1) there would not be as many free and arbitrary walking happening in this setting (interior of a building) as in the urban streets; (2) this building is connected to a subway station which would cause some bias in the pedestrian traffic near the connecting area; and (3) as compared with the other studies of urban streets, the passage counts have not been actually made in this study. These suggest that some improvement of the current methods (i.e., convex mapping strategy, weighting, and passage counting) should be made.
Table 1. Horizontal ERAM analysis for lower commercial block

<table>
<thead>
<tr>
<th></th>
<th>1st underground floor</th>
<th>1st floor</th>
<th>6th floor</th>
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<td><img src="image2" alt="Image" /></td>
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<td><img src="image5" alt="Image" /></td>
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<td><img src="image10" alt="Image" /></td>
<td><img src="image11" alt="Image" /></td>
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<tr>
<td>Correlation Tracking Survey ERAM(9)</td>
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<td><img src="image15" alt="Image" /></td>
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<tr>
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<td><strong>Correlation Total</strong></td>
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</table>
6. Vertical ERAM Analysis of Vertical Tower

Analysis procedures

For the analysis of vertical tower, ERAM(9) values are used, because the global connecting relation is preferred to the local connecting relation in tall buildings with many floors and some long vertical connections. For ERAM analysis, convex maps of the B1 to 39th floors are made and they are connected by means of stairs, elevators and escalators.

![Fig. 10. Layout of Elevators (ground floor)](image)

Elevator Layout

Passenger elevators in Technomart21 are in operation in pairs. There are four zones in the 39 story business tower. Each zone (noted as A, B, C and D in Figure 10) has two elevators. In the 11 story commercial complex, there are two 'nude' elevators near the void in the central area of the complex (Elevator G in Figure 10), and two elevators at each of the two sub entrances (H, I). In addition, there exists a pair of elevators for cinema use only on the right side of the main entrance (E), as well as a bank of three elevators near the business tower (F).

In Table 2, the ERAM values for the elevators summarized. It seems that there are slight differences among the ERAM(9) values of the elevators in the business depending on the number of stories they cover. The elevators in B and D zones both of which cover 14 stories have higher ERAM(9) values (10.33 and 9.74) than those in A and C zones (8.74 for A and 7.04 for C). The A zone elevators cover 12 stories and the C zone elevators cover only 10 stories.

Compared with the elevators in the commercial complex, those in the business tower tend to have relatively higher ERAM(9) values. While the elevators in the commercial complex are the supplementary means of vertical circulation to the escalators, the business tower elevators are the main means of the vertical circulation.

Among the elevators in the commercial complex, those in G zone at the void of the central area show the highest ERAM value (8.45). Those in the sub entrance zones have only as half much as that (4.75 for H and 4.35 for I), seemingly because they are located at the peripheral corners of the building complex. Those in the F zone have higher values than those in the H and I zone, since the F zone is next to the main passageway of the building. It is interesting to note that the three elevators in the F zone have different ERAM values even though they are at the same location. The difference seems to be coming from different coverage: one runs only for even floors (covering 7 floors, ERAM value of 5.316), the other runs for odd floors (covering 6 floors, 4.028), and the last runs all floors (covering 11 floors, 7.571).

Those in the E group are located on one side of main entrance, but it is for 9th and 10th floor only. Thus they have the lowest value (1.27).

Even though tracking survey was not conducted for the vertical connections, simple observations yields the followings. The business tower has a single core with four banks of 8 elevators. These elevators work as the main route for the vertical circulation and cover relatively many floors. These elevators and the elevator halls look crowded and used very frequently by many people. The 'nude' elevators (Zone G) at the void in the central area of the commercial complex are easy to find and thus used by many people. Those in the F zone are also easy to find from the main entrance and thus used very frequently. However, those in the zones H and I are used less frequently and the reason for that is simple to know. They are at the peripheral corners of the building and away from the center.

The above observations can be made without looking at the ERAM(9) values, and they match the implications of the ERAM(9) values. Thus it can be said that, in the design evaluation process for the efficiency of space usage, the ERAM(9) values may be useful as a supplementary to the qualitative evaluation..

Comparison of ERAM(9) values of each floor

![Table 2. Elevator ERAM Values](image)
The following figure shows the mean value of ERAM(9) for all spaces on each floor except the elevators. The ERAM(9) value of each space is a relative value, and the original value for each space set to be 1. Thus if, after the ERAM analysis, the mean value of a floor is more than 1, it means that the floor is used more frequently than others. Conversely, if the value is less than 1, the floor is less frequently used.

![Fig. 11. Distribution of Mean ERAM(9) on Each Floor](image)

In this sense, the B1 and 1st floors are the most frequently used floors. The floors from the second to 10th are likely to be moderately used, and the high level floors are used the least frequently.

The B1 and 1st floors are the places where lots of people move in from the subway or outside. Also all the elevators stop at these floor as well as the escalators. Thus it makes sense that these floors have higher ERAM values. The floors from the 2nd to 7th have different ERAM values. The even number floors have slightly higher values than the odd number floors. This difference is likely to be caused by some differences in floor plans. Unlike the 2nd to 7th floors, the 8th floor does not have a void space and it has a different layout of corridors as well. Thus it has a higher value than the others. All the elevators of the business tower stop at the 9th floor as well as the cinema-only elevators. This makes this floor have a higher value. The value of the 11th floor is the lowest of all, because this floor is right above the cinema complex and it has a series of projection room all connected by a long corridor. The whole 13th floor, which has a higher value, is used exclusively by the company which owns and operates the building, and thus has a different spatial scheme than the other floors. The floors above the 13th, which comprise the business tower, have similar values. However, the 20th and 28th floors have slightly higher values because these floors are designated for the elevator transfers and four, instead of two, elevators stop there.

7. Conclusions

With Technomart21 as a typical example of tall and huge-scale buildings, the research investigated the actual space usage and conducted the spatial analyses for the theoretical predictions of the space usage. These two were compared with each other in order to see if the application of ERAM model to tall and huge-scale buildings is viable. The results of the research show that the existing ERAM model which used to be applied to the small-scale space is not really sufficient in precise estimation of the distribution of the horizontal and vertical flow in tall and huge-scale buildings. However, even though the method used in the research did not actively incorporate weights according to the space size and function, the analysis results were accountable for 30 to 40% of prediction for the space usage. This provides at least a reasonable foundation for the theoretical viability of the ERAM model. Also, while it is still at the exploratory stage, the ERAM model showed a possibility to be applied for the efficiency analysis of the vertical flow such as elevators in tall and huge-scale buildings.

For the spatial analysis tools such as ERAM to be applied to the design project for tall and huge-scale buildings in more precise and reasonable way, it is necessary to carry out further researches in order to elaborate the analysis protocols and methods such as the mapping of spatial structure, the provision of weights to each space according to its occupational size and function, etc.

Also, through wide research on tall and huge-scale buildings in existence domestic and abroad, the viability of spatial analysis tools is to be solidified, and their limitations and potential improvement are to be acknowledged.

Acknowledgement

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Endnotes

1 The ERAM theory was conceived and developed by the researchers
at the Architecture and Urban Space Laboratory at Seoul National University.
2 Even though tall buildings are generally referred to those over 60
stories, it is hard to find buildings over 60 stories at the moment. There
are some apartment complex buildings over 60 stories, but since they
are private buildings, it is impossible to conduct any on-site
observations and any other type of research. Therefore, among the
buildings over 30 stories, this building was selected for the research.
3 By multiplying the matrix by itself, a theoretical one-step random
movement is made and the resulting matrix shows the probability of the
number of occupants in each space after one random movement. The
detailed explanation of ERAM theory and methodology is beyond the
scope of this paper, and can be found in Choi et al. (2003).
4 An elevator cannot be considered as a separate space on each floor
because the elevator vehicle arbitrarily jumps from one floor to another
floor and the users move within a single vehicle, or a space, without
stopping at each floor in their vertical movement.
5 How much of a weight should be given is a very tricky issue. A
number 0.5 surely lacks any empirical or theoretical supports. In this
paper, the hall and elevator connection is liberally set to 0.5 (less than
normal 1) because there is a ‘resistance’ between the two. A further
research is needed for the provision of specific weight on this issue.
6 The number of people surveyed on the B1 floor is bigger than others
because there is an exit from the subway on the B1 floor and there are
many people coming to the building.
7 Here, the passage count is deduced from the tracking survey.