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A Study on the Evacuation Performance According to Variation in Remoteness between Exit Stairways in Tall Buildings

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Abstract The purpose of this study is to examine the influence of remoteness between exit stairways on evacuation performance. Firstly, we reviewed the design regulations of the U.S., the U.K., and South Korea, in relation to remoteness between Exit stairways. Secondly, evacuation simulation was implemented, in order to evaluate the adequacy of each standard. Eight tall buildings in South Korea were selected for the simulation. Evacuation performance was assessed for different remote distances between Exit stairways. Lastly, this research analyses the evacuation simulation data statistically in relation to the effect of remoteness on evacuation time. We found that as the distance between two exit stairways increases, the total evacuation time and average evacuation time for evacuees decreases. There was no statistical influence between the maximum travel distance of the evacuee and the remoteness between two exit stairways, but there was a significant effect on the average travel distance of the evacuees. In addition, the results from the optimal point showed that the L_ratio had the highest evacuation time at 0.44, while the D_ratio had the highest evacuation time at 0.38.

Keywords: remoteness, exit stairways, performance-based evacuation design, simulation, statistical analysis

1. INTRODUCTION

Contemporary construction technology has induced competition for high-rise buildings worldwide. The Council on Tall Building and Urban Habitat report in 2018 identified the number of buildings higher than 200 m was as high as 143 during that year alone; the number has been constantly increasing from 73 in 2013, 104 in 2014, 115 in 2015, 130 in 2016, and 147 in 2017, which was the highest on record (CTBUH, 2018). Such a trend is expected to persist, due to high-rise buildings functioning as symbolic demonstration of each country and city's competitiveness.

However, from a disaster managerial perspective, the increase of high-rise buildings means increased risk in the case of disaster outbreak, and in turn, greater loss of life and property. Major countries and cities have thus adopted the Performance-Based Design (hereafter PBD), in order to mitigate the potential danger caused by tall buildings.

The PBD is intended to evaluate and predict the safety of a certain architectural design, with the application of a specific disaster scenario. It integrates user characteristics, number of users and their locations, room size, furniture, and combustible materials and their characteristics, as well as the origin of a fire, its ventilation, initially ignited item, and its location and assess evacuation. Simulation is performed on computers for the quantitative analysis of safety. PBD allows a scientific and logical design in accordance with adequate performance and design standards; however, its methodologies and procedures vary by country or city.

Tall buildings require people to take long vertical routes in order to reach either evacuation area or ground levels. Evacuees could bottleneck effect at the evacuation stairways or elevators, which would aggravate the evacuation process. In this sense, evacuation stairways and elevators are crucial performance-based design factors, and they require adequate amount of consideration for PBD. Design aspects for evacuation stairways include the width of stairs and doors, location of stairs, and maximum walk distance to them, all of which affect evacuation performance.

Among other factors, remoteness is considered one of the

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major components for the assessment of evacuation stairways design in various countries. The concept of remoteness originates from one of the evacuation principles of the insurance of two-way evacuation routes, which means allowing something to move or work in two opposite directions.

The concept of out-of-the-way originates from one of the two-way evacuation insurance's evacuation principles, which means allowing something to move or operate in two directions.

Many countries apply their own standard for calculating the remoteness distances. And it is not possible to deter-mine how much such regulation affect evacuation performance. So minimal regulations are applied conservatively, and it is impossible to measure by how much safety could be compromised.

The aim of this research is to examine the impact of remoteness between evacuation stairways on evacuation performance. And the change in evacuation time and travel distance was compared as the distance between the two evacuation stairways changed for the evacuation performance. And the regulations related remoteness were verified

The research was designed in three stages. Firstly, we reviewed the regulations of the U.S., the U.K., and South Korea, in relation to remoteness between evacuation stairways. Secondly, evacuation simulation was implemented, in order to evaluate the adequacy of each standard. Eight tall buildings in South Korea were selected for the simulation. With the setting of standard levels for each building, evacuation performance was assessed for different remote distances between two exit stairways. Lastly, this research analyses the evacuation simulation data statistically in relation to the effect of remoteness on evacuation time. Based on the result, we suggest effective stairway planning methods that accord with the implications from comparison of the different systems of each country.

2. LITERATURE REVIEW

2.1 Evacuation regulations on remoteness

For comparison and analysis of the standards on remoteness within domestic and foreign evacuation regulations, we checked out the standards of the U.S., the U.K., and South Korea, where performance-based evacuation design is actively practiced.

Table 1. Regulations on Remoteness in each Country

South Korea	Preliminary Disaster Impact Assessment and Consultation Guidelines	Appendix 4.2 ② Minimum Walking Distance to Exit Stairways by Floor	At least 1/3 of the longitudinal dimension of the building at the exit stairways, exit accesses, or exit discharges
	Seoul Performance-based Design Assessment Guideline	Chapter.10 Appropriateness of Evacuation Planning	It must be separated by at least 1/2 the longitudinal dimension of the building
U.K.	Fire Safety Approved Document B. Buildings other than Dwellinghouses (Volume2)	B1 3.11 Planning of Exits in a Central Core	Exits are remote from one another, and so that no two exits are approached from the same lift hall, common lobby, or undivided corridor, or linked by any of these.
U.S.	International Building Code (IBC)	403 High-Rise Buildings 403.5.1 Remoteness of Interior Exit Stairways.	Interior exit stairways shall be separated by a distance of not less than 30 feet (9144 mm) or not less than 1/4 of the length of the maximum overall diagonal dimension of the building
	National Fire Protection Association (NFPA) 101 Life Safety Code	7. Means of Egress 7.5. Arrangement of Means of Egress.	two exits, exit accesses, or exit discharges required, they shall be located at a distance from one another of not less than 1/2 the length of the maximum overall diagonal dimension of the building

2.1.1 United States

International Building Code (IBC[1]) 403 High-Rise Buildings - 403.5.1 Remoteness of Interior Exit Stairways.

The International building code (IBC) has provisions for evacuation planning for each type of building. The criteria for high-rise buildings are clearly presented as SECTION 403 HIGH-RISE BULIDINGS. Also, the standard regarding the remoteness is first specified in 403.5 Means of Progress and Evaluation.

Check the remoteness content – It is required that interior exit stairways shall be separated by a distance of not less than 30 feet (9144 mm) or not less than one-fourth of the length of the maximum overall diagonal dimension of the building or area to be served, whichever is less. The distance shall be measured in a straight line between the nearest points of the enclosure surrounding the interior exit stairways.

National Fire Protection Association (NFPA[2]) 101 Life Safety Code - 7.5. Arrangement of Means of Egress.

NFPA 101 is a set of regulations regarding evacuation safety that started as the Building Exit Code, and has been continuously developed, and is currently being followed in various states. In other words, it covers a wide range of measures regarding how to plan and maintain buildings so that occupants could evacuate safely. Moreover, it delineates human safety related measures differently by each usage, making it more detailed and concrete than IBC regarding evacuation safety.

In chapter 7. Means of Egress, it sets out many standards for evacuation, and regarding the standards for remoteness: Where two exits, exit accesses, or exit discharges are required, they shall be located at a distance from one another of not less than one-

[1] The International Building Code (IBC) is a model building code developed by the International Code Council (ICC). It has been adopted for use as a base code standard by most jurisdictions in the United States. In addition, each local government has a separate set of regulations that are more detailed. However, there is not much difference within the framework of the IBC with regard to the regulations on evacuation facilities.

[2] The National Fire Protection Association (NFPA) is a trade association of United States, albeit with some international members, that creates and maintains private, copyrighted standards and codes for usage and adoption by local governments. It has more than 300 consensus codes and standards to minimize the impact and potential of fire and other hazards.

half the length of the maxitabmum overall diagonal dimension of the building or area to be served, measured in a straight line between the nearest edge of the exits, exit accesses, or exit discharges.

2.1.2 United Kingdom

Fire Safety - Approved Document B. – B1 3.11 Planning of Exits in a Central Core

The evacuation-related regulations in UK concentrate on life safety in the case of fire, like the life safety codes in the U.S. These are stipulated in the government-enacted Building Act and British Standards (BS). Detailed and concrete regulations are covered in the Approved Document in the Building Regulation, and the legislated evacuation methods in buildings are obliged to satisfy the British Standards.

For the 14 approval documents, specific detailed design standards (British Standard Code: BS code) are given for each part. Approved Document B related to Fire Safety (Part B) is operated in two separate building types: Dwellinghouses (volume 1), and Buildings other than dwellinghouses (volume 2).

Regulations concerning the evacuation of the occupants in Buildings other than dwellinghouses (volume 2) are dealt with in Section B1, where the separation of exits is referred to. The content is as follows: Buildings with more than one exit in a central core should be planned so that storey exits are remote from one another, and so that no two exits are approached from the same lift hall, common lobby, or undivided corridor, or linked by any of these.

2.1.3 South Korea

Preliminary Disaster Impact Assessment and Consultation Guidelines – Appendix 4.2 ② Minimum walking distance to evacuation stairways by floor

Codes related to Evacuation in Korea are divided into building and fire/disaster acts. The Building Codes and Fire Service Act have until recently only focused on low and multi-storey buildings. In order to supplement laws with regards to high-rise buildings, the 'Special Act on Management of Disasters in Super High-Rise Buildings and Complex Buildings with Underground Connections' was established in 2012.

Since then, based on these acts, the Ministry of Public Safety and Security developed the 'Preliminary Disaster Impact Assessment and Consultation Guidelines', which suggests examination guidelines and detailed assessment standards, in order to preliminarily examine various factors related to disaster impacts in high-rise buildings, and apply them flexibly during the building planning process.

However, the guidelines are used in reference to domestic and overseas evacuation performance standards. Thus, the content of the remoteness between evacuation stairways is the same as the IBC standard.

Seoul Performance-based Design Assessment Guideline – Chapter 10. Appropriateness of Evacuation Planning

The city of Seoul has established, and is currently carrying out its own performance-based evaluation guidelines, based on the 'Act on Fire Prevention and Installation, Maintenance, and Safety Control of Fire-fighting Systems' and 'Standards and Methods of Performance-based design for fire-fighting facilities', which put relatively more emphasis on performances.

The guideline is its approval guideline developed by the Seoul Metropolitan Government to ensure the safety performance of large-scale buildings against disasters. Therefore, detailed regulation for performance design is provided for each section. The section of evacuation planning is also presented, and the regulation for remoteness between evacuation stairways is given as follows: If two or more evacuation stairways are installed, the direct election at each entrance to the evacuation stairways must be separated by at least one-half the longitudinal dimension of the building.

The regulations on remoteness in each country differ slightly. Further, the regulation does not even mention how much effect the criteria have on evacuation performance. In particular, in Korea, it can create confusion in the planning of high-rise buildings by using both overseas and domestic standards.

2.2 Previous studies

Few prior studies have been conducted regarding the influence of changes in remoteness between evacuation stairways for the purpose of this study on evacuation performance. However, the importance of remoteness is mentioned in some of the papers.

Bukowski (2009) mentioned that most tall buildings are designed with a core area that contains the elevators, stairs, and shafts in which the utilities run vertically through the building. The core usually serves as the building's spine, and often plays a significant role in the structural system. The remoteness is intended to ensure that no single incident can block access to both stairs. Buildings are required to have at least two, independent exits, separated by a minimum distance.

Also, Watts (1996) mentioned the measure of exit remoteness has no obvious relationship to emergency egress. Nor does it relate to the common path of travel that codes allow. In his papers, the angle of exit remoteness provides a logical determination of the appropriate separation of exits as a measure of safe egress. It is flexible and readily adaptable to occupancy-oriented variations. In the absence of better scientific evidence, it is important that life safety criteria be logical and intuitive.

Kim(2017) analysed the status of evacuation stairways for public library buildings and proposed measures to improve the standards for the installation of evacuation stairways considering the separation distances. The distance between stairways was changed and the evacuation performance (evacuation time) was reviewed using simulation. The results showed that the type of central layout evacuation time was increased. However, the results are judged to be somewhat unreliable by changing the layout of the stairs at any location only once in the application of the regulations.

Therefore, this study analysed the regulations of each country and adjusted the distance variation more subdivided, as considering the significance and limitations of the previous studies. Thus, by comparing and reviewing the simulation results according to each regulation, there is a distinction from previous studies in presenting improved standards for more effective evacuation.

3. METHODS

3.1 Building Data

In order to analyse the influence of evacuation performance according to remoteness variation between evacuation stairways, which is the purpose of this study, eight tall buildings in Korea were selected to perform an evacuation simulation analysis.

The criteria for selecting buildings were the office buildings built in metro city like Seoul, where tall buildings are concentrated. They were basically selected common office buildings with the type with a central core. And most office buildings were planned as open plans, which allow flexible application of variations in remoteness for simulation. In addition, the building's plane type was divided into two general types: square and rectangle, which are common forms of tall buildings. Also we selected buildings with similar floor area and gross area so that they can be compared.

And the buildings were selected with two exit stairways, preferably in the form of a typical office floor plan, and in order to be reasonable in the statistical analysis. Buildings with three or more evacuation stairways were excluded from this study, due to difficulties in modifying the cores for the variation of remoteness between each evacuation stairways.

Basic information and drawing data were collected for the 8 selected buildings. Table 2 summarizes the information relating to the buildings. Based on the drawings of each building, the remoteness between two exit stairways was changed, and the distance was manipulated by at least 10 m in 5 m intervals.

And then 83 planes have been made by organizing the reference floor plan of the 8 buildings. Based on this, the

Table 2. Summary of Buildings.

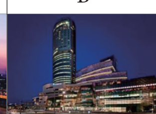
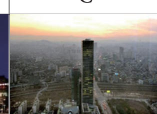
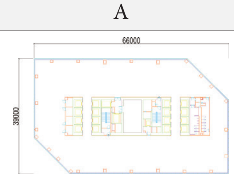
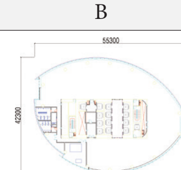
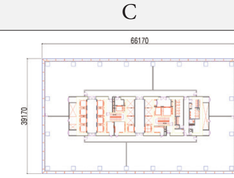
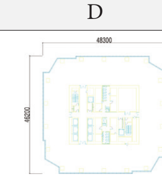
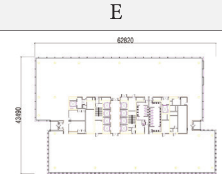
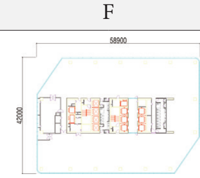
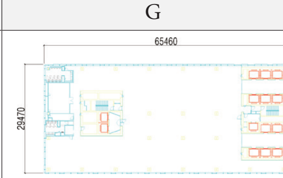
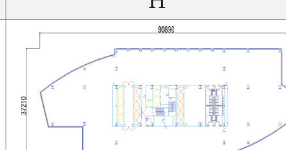
	A	B	C	D	E	F	G	H
Building								
Constructed	2012	2011	2013	2013	2008	2016	2000	1992
Location	Seoul	Seoul	Seoul	Busan	Seoul	Seoul	Seoul	Seoul
Main Use	Office	Mixed Use	Office	Office	Office	Mixed Use	Office	Office
Height (m, floor)	284 (55F)	189 (51F)	245 (50F)	289 (63F)	200 (44F)	185 (39F)	148 (33F)	176 (42F)
Gross Floor Area (m2)	130,944	229,988	168,506	197,869	196,561	219,385	83,801	91,315
Typical Floor Area (m2)	42F	25F	25F	49F	37F	26F	18F	30F
	2,329.91	1,474.66	2,320.62	1,572.93	2,538.25	1,546.79	1,827.92	2,823.79

Table 3. Typical Floor Plans and Input data for Simulation

Classification		A		B		C		D	
Typical Floor Plan									
L.D	D.D	66.00 m	76.66 m	55.30 m	69.62 m	66.17 m	76.90 m	48.30 m	46.20 m
DTS	MWD	21.41m	38.64 m	27.33 m	29.65 m	22.71 m	42.20 m	19.38 m	30.65 m
O.N	W.S	210	1.19 m/s	146	1.19 m/s	214	1.19 m/s	170	1.19 m/s
Classification		E		F		G		H	
Typical Floor Plan									
L.D	D.D	62.82 m	78.71 m	58.90 m	70.06 m	65.46 m	71.79 m	90.89 m	98.21
DTS	MWD	19.55 m	38.73 m	15.34 m	40.57 m	34.60 m	29.92 m	7.86	55.22 m
O.N	W.S	220	1.19 m/s	193	1.19 m/s	153	1.19 m/s	251	1.19 m/s

L.D: Longitudinal dimension , D.D: Diagonal dimension , DTS: Distance between Two Staircases , MWD: Maximum Walking Distance , O.N: Occupant Number , W.S: Walking Speed separation distance ratio for diagonal and longitudinal dimension were calculated according to the regulation regarding remoteness for each country.

If the remoteness distance within the core was maximized, the center of the core was divided so that an open space was created in the center, keeping the public area of the entire core identical.

3.2 Evacuation simulation

This research deals with evacuation simulation, in order to measure influences in evacuation time in accordance with changes in remoteness.

Evacuation simulation makes possible the prediction of evacuation time of occupants in buildings in the case of fire, and evaluation of how infrastructure or evacuation process-related improvement can contribute to reducing evacuation delay. As such, evacuation simulation is often used in performance-based evacuation design, such as predicting specific locations that could be potentially congested during the process of evacuation. Pathfinder 2018 egress modelling software was used in order to conduct simulations on the aforementioned 8 buildings.

Developed by Thunderhead Engineering in the US, Pathfinder is an agent-based egress simulator. Pathfinder's simulation model takes advantage of advances in agent-based approaches to movement modelling that make it possible to capture more complex behaviour and interactions between occupants.

It expresses motions of occupants in SFPE and Steering modes. In SFPE mode, simulations are conducted based on the measuring system proposed by the Society of Fire Protection Engineers (SFPE). This mode is rooted in algorithms in which the walking velocity is determined by the occupancy density of the living space, while flow is set by the width of exits.

On the other hand, steering mode is capable of curve running, and is based on algorithms that react to environment changes. To put it plainly, steering mode allows the agents to react to changes in the environment while evacuating along the intended paths in the process of egress. Moreover, each agent maintains selected paths that connect its position to the target area. Diverse factors, such as bumping into other individuals, could result in deviating from the selected paths; nevertheless, the agents react, to get back to the original paths.

As such, simulations were conducted based on Steering Mode in this research, which reflects more realistic movement of the occupants. The number of occupants was computed based on the occupant density standard of 8 m^2/person as stated in the domestic regulations, which was multiplied by the area of the selected floor of each building. Also walking speed is set to 1.19m/s which is the average walking speed in an emergency.

Furthermore, occupants were assigned uniformly across the entire space, in order to prevent them from concentrating on certain two exit stairways, and the original position of occupants remained the same throughout the simulation, so that the location of the occupants would not affect the evacuation performance, even when the remoteness changes. Moreover, although the shape of the core changes in accordance with the change in remoteness between two exit stairways, areas for exclusive use and common use spaces remain constant.

Above these, architectural design factors that would affect walking time or speed, such as elevator usage, exit width, staircase dimensions, were omitted in this study as it only concerns the relation between remoteness and evacuation time.

The 83 data such as building data(gross area, floor area, longitudinal dimension, diagonal dimension, distance between stairways), the ratio by remoteness regulation(ratio by diagonal dimension, ratio by longitudinal dimension), evacuation time(total, average), and travel distance(total, average) were obtained.

3.3 Statistical analysis

For the purpose of this study, statistical analysis was conducted with the results data obtained from the evacuation simulation, to examine the extent to which the variation of remoteness between the two exit stairways affected the evacuation time. All statistical analyses were performed with the software R 3.5.1. Table 4 shows each variable.

While studying evacuation, evacuation time is generally used as a dependent variable to assess the evacuation performance. Evacuation time is considered more important than any other factor, because the spread of flames and smoke in the fire can threaten many people's lives, and the spread time is limited. Also, different components of evacuation time have to be well understood. These include evacuation time, Required Safe Egress Time (RSET), Available Safe Egress Time (ASET), and Total Evacuation Time (TET) (Candy and Chow, 2006).

In this study, the evacuation time obtained through simulation was used as a dependent variable, and the unit of time was set to seconds. Evacuation time was measured as the total evacuation time for all evacuees completed, and the average evacuation time for all evacuees.

The remoteness between the two exit stairways was set as the independent variable, to analyze the effect on the evacuation time. The remoteness was changed by setting the minimum distance of 10 m, which is the minimum standard for the US and the UK, and intervals in 5 m.

In addition, based on the codes for the design of evacuation performance in Korea and the U.S., the D_ratio was named as the ratio of remoteness to the diagonal dimension of the building based on the U.S. codes. The L_ratio was named as the ratio of remoteness to the longitudinal dimension of the building based on the Korean standards.

The calculation of the appropriate number of exits of a floor depends on the size of the floor or the total distance of the path. Notake, Ebihara and Yashiro (2001) stated that the number of exits on the floor influences the average travel distance, and it is recommended that the exits be separated on the floor to minimize the expected average travel distance.

Therefore, it was selected as a control variable to see how much the average and maximum travel distance of evacuees spread evenly in the floors affected the evacuation time. In addition, the size of a floor is closely related to the number of occupants, which greatly affects the evacuation time. Therefore, the Area was set as the control variable to hold the other independent variable, and to check the effect of one independent variable on the dependent variable.

Table 4. Independent / Dependent / Control Variables.

Variables	Measurement Method
FL_Area	Area of typical floor in each buildings (㎡)
Remoteness	Distance between exit stairways (m, Over 10 m , Intervals of 5 m)
L_length	Longitudinal dimension of the building (m)
D_length	Maximum overall diagonal dimension of the building (m)
L_ratio	The ratio of remoteness to the longitudinal dimension of the building
D_ratio	The ratio of remoteness to the diagonal dimension of the building
ET_Total	Total evacuation time (s)
ET_Aver	Average evacuation time (s)
TD_Max	Maximum travel distance of Evacuees (m)
TD_Aver	Average travel distance of Evacuees (m)

4. RESULTS

4.1 Descriptive statistic

A total of 83 Data samples acquired from the simulation in the 8 buildings was collected. Table 5 summarizes the descriptive statistics, and describes the prominent features of the data.

For the evacuation time, the dependent variable, the mean of the total evacuation time was 107.62 s and the mean of the average evacuation time was 54.55, which is half the former. The average evacuation time exhibits a distribution congregated more around the median, compared to that of the total evacuation time.

This is because decisions made by each individual agent lead to switching to another route or the bottleneck phenomenon at two exit stairways, which results in the increase in ET_Total, the time measured for the last evacuee to fully evacuate; the values are thus widely distributed. On the other hand, ET_Aver indicates the mean for all the evacuees to evacuate, and is less dispersed.

The dependent variables comprise the L_ratio and D_ratio. As mentioned earlier, they are measurements of the ratio of remoteness in accordance to the longitudinal dimension and diagonal dimension of a building.

The max value of the L_ratio is 1.04; the dimension can be higher than the longitudinal dimension of the building, because remoteness between two exit stairways can be measured diagonally, which can result in higher than 1.00. By contrast, the D_ratio measures the diagonal dimension of the building; the remoteness cannot have values higher than those of the diagonal dimension of the building, and thus cannot exceed 1.00.

The maximum travel distance has a mean value of twice the average travel distance, and the maximum value is almost three times. The maximum travel distance is a measure of the travel distance of the longest traveled evacuees. If a path change occurs due to decision making or bottlenecks in agents, the maximum travel distance is measured high in the simulation. Because of this, the maximum travel distance data was inconsistent in each simulation result. Therefore, the standard deviation value (11.23) of the maximum travel distance was relatively higher than the average travel distance value (3.40).

Another controlled variable is Area, which has different values in each of the eight buildings; it has a higher standard deviation value (293.10 m2), because the range of variable value is wide, and thus has much difference between the mean value and the observed values.

Table 5. Descriptive Statistics.

Statistic	N	Mean	St. Dev.	Min	Max
ET_Total	83	107.62	19.37	72.70	142.30
ET_Aver	83	54.55	9.65	37.00	73.00
L_ratio	83	0.53	0.24	0.11	1.04
D_ratio	83	0.48	0.22	0.10	0.98
TD_Max	83	53.00	11.23	36.10	90.30
TD_Aver	83	24.89	3.40	15.90	34.40
FL_Area	83	1,611.05	293.10	1,168.08	2,004.89

4.2 Correlation Analysis

The changes in the variables were examined, in order to determine the correlation between them. When the variables show changes in the same direction, this signifies a positive correlation; when they change in the opposite direction, they have a negative correlation.

The Pearson's correlation (R^2) has a range of (0.1 to 1.0). The value of 1.0 for its coefficient indicates a perfect positive relationship, while (0.4 to 0.7) is moderate positive, and (0.1 to 0.4) is weak positive.

The graph exhibits numerous significant correlations between the independent and dependent variables; they all have positive relationships. In the case of ET_Total, it has a strong positive correlation with Area, and TD_Total has the same with TD_Aver.

The L_ratio has a strong positive relationship with the D_ratio, and a weak one with TD_Aver. ET_Aver also shows a positive correlation with TD_Total, TD_Aver, and area.

The stronger the correlation, the more probable it is that multicollinearity exists. A correlation higher than 0.8 between explanatory variables is usually translated as collinearity.

Table 6. Correlation Analysis.

	ET_Total	ET_Aver	L_ratio	D_ratio	TD_Max	TD_Aver	FL_Area
ET_Total	1						
ET_Aver	0.98***	1					
L_ratio	-0.03	-0.10	1				
D_ratio	-0.05	-0.13	0.97***	1			
TD_Max	0.44*	0.43*	-0.04	-0.08	1		
TD_Aver	0.54*	0.58*	0.33*	0.28	0.45*	1	
FL_Area	0.84**	0.81**	-0.05	-0.02	0.42*	0.39*	1

*** P < 0.001 , ** P < 0.05 , * P < 0.10

4.3 Multiple Regression Analysis

A multiple analysis was conducted to sort out factors that affect evacuees' total and average evacuation time. In this analysis, the D_ratio, L_ratio, Area, TD_Total, and TD_Aver were independent variables and control variables, along with the variation in the distance between the two exit stairways. In addition, a total of six models were set with total evacuation time and average evacuation time set as dependent variables.

Table 7. Description of Models.

Model	D. V	I. V	Remark
Model 1	ET_Total	L_ratio	
Model 2	ET_Aver	L_ratio	
Model 3	ET_Total	D_ratio	
Model 4	ET_Aver	D_ratio	
Model 5	ET_Total	L_ratio, L_ratio2	Add Quadratic Terms
Model 6	ET_Total	D_ratio, D_ratio2	Add Quadratic Terms

Models 1 – 4 had different L_ratio and D_ratio applied, in order to examine their impact on the total evacuation time and average evacuation time. Models 5 and 6 were measured with additional quadratic terms as an independent variable, in order to find the optimal point at each ratio. When introducing the quadratic terms, the centering method was adopted, to avoid multi collinearity. The modified R^2 for regression ranged (76.3 to 79.3) %, which is fairly high for a determination coefficient.

In regression, ET_Total was influenced by TD_Aver and D_ratio (5 %), and ET_aver by TD_Aver, L_ratio, and D_ratio, all at 1 %.

The average evacuation time showed -8.027 s in accordance with the L_ratio; the total evacuation time reduced each -11.152 s with the decrease in D_ratio, and the average was -10.518 s. This means the evacuation time decreases as the separation distance between the evacuation stairways increases. In particular, the D_ratio and L_ratio both had a significant influence on the average evacuation time, and the time reduction was found to be slightly greater in the D_ratio.

Models 1–4 were affected by TD_Aver. This is explained by the fact that TD_Aver shows more stable a distribution than that of TD_Total; when the evacuee changes from the original choice of an exit stairway to a different one, the maximum travel distance heavily affects TD_Total, compared to TD_Aver that is defined by the average of distances of all the evacuees.

The total and average evacuation times are affected by the average travel distance, but not by the maximum travel distance. This means that the size of a space affects travel distance as well as evacuation time, but not the total evacuation time; on the other hand, the average distance affects the evacuation time.

Models 5 and 6 are the multiple regressions with the squared quadratic terms of L_ratio and D_ratio, in order to determine the validity of each country's standards for remoteness, and to compute the optimal point. In the case of the dependent variable at its maximum value, the evacuation time is the highest with L_ratio ≈0.44 for Model 5, as well as with D_Ratio ≈0.38 for Model 6.

Table 8. Multiple Regression Statistics Result of Simulation

Estimate p Value	Model 1 ET_Total	Model 2 ET_Aver	Model 3 ET_Total	Model 4 ET_Aver	Model 5 ET_Total	Model 6 ET_Total
(Intercept)	-6.632	-3.217	-5.792	-2.56	-25.007**	-24.778**
	0.438	0.436	0.492	0.521	0.034	0.026
L_ratio	-7.131	-8.027***			43.016*	
	0.144	0.001			0.06	
D_ratio			-11.152**	-10.518***		47.658**
			0.033	0.000		0.042
TD_Max	0.007	-0.031	-0.016	-0.048	-0.033	-0.074
	0.951	0.572	0.888	0.374	0.766	0.504
TD_Aver	1.657***	1.148***	1.716***	1.159***	2.192***	2.252***
	0.000	0.000	0.000	0.000	0.000	0.000
FL_Area	0.047***	0.022***	0.048***	0.022***	0.046***	0.046***
	0.000	0.000	0.000	0.000	0.000	0.000
L_ratio2					-48.708**	
					0.026	
D_ratio2						-62.859**
						0.011
N	83	83	83	83	83	83
R2	0.763	0.777	0.771	0.793	0.778	0.789
adj R2	0.751	0.766	0.759	0.782	0.764	0.776
VIF(mean)[3]	1.393	1.393	1.362	1.362	1.535	1.474

***p < 0.001 , ** p < 0.05 , * P < 0.10

[3] Centering was used to solve the common causes of multicollinearity during the insertion of the quadratic terms.

4.4 Conclusion

We have demonstrated the influence on evacuation performance according to remoteness variation between two exit stairways. Evacuation simulation was performed to review the standards for remoteness, which were presented differently in many countries, and to look at the standards that were appropriate. In addition, statistical analysis was conducted with the resulting data obtained from the simulations.

In conclusion, we would like to state the following 3 points:

1) As the distance between two exit stairways increases, the total evacuation time and average evacuation time for evacuees decreases. As we looked at the simulations, if the distance is short, a bottleneck occurs for a long time when evacuations begin that is concentrated on each stairway at the early time, as the two exit stairways are assembled and located at the center of the floor. This is considered to affect the total evacuation time and average evacuation time. Evacuation time is related to the duration of bottlenecks. Bottlenecks are a phenomenon of stagnation in front of exits, which greatly affects evacuation time because of the reduced walking speed of evacuees, due to clashes between those who fail to do so in the case of congestion.

   In addition, when bottlenecks occur at the first selected evacuation stairway, the number of evacuees moving to the other stairway changes. On the other hand, the number of evacuees changing their evacuation routes decreases as remoteness increases. This is also considered to have some effect on evacuation time. Therefore, it is important to plan beyond a certain distance in space planning, so that the evacuees can make two-way evacuations of appropriate numbers. This means that the standard for remoteness by each country is appropriate. Further studies are needed to find an optimal location on the two exit stairways.

2) There was no statistical influence between the maximum travel distance of the evacuee and the remoteness between two exit stairways, but there was a significant effect on the average travel distance of the evacuees. The maximum travel distance is measured by an evacuee who has move the longest travel distance among the evacuees in the simulations. Therefore, the results of maximum travel distance depend largely on the decision of a single agent in each simulation, such as the increased travel distance by changing or detouring from the evacuation route due to bottlenecks. However, the average travel distance tends to be constant, because all evacuees have averaged the distance travelled, and can be found to be relatively closely related to the evacuation time. Therefore, it is considered that the average travel distance can be used as a major factor in the evaluation of evacuation performance. In addition, standards for maximum distance from each floor and means of evacuation are given in most countries, and it is deemed that an evaluation of evacuation safety performance will be required, considering the average travel distance travelled by all evacuees.

3) In terms of suitability for each country's remoteness standards, L_ratio, the Korean standard using longitudinal dimension, and D_ratio, the U.S. standard using diagonal dimension, both showed that the evacuation time decreased as the ratio increased. This is due to the reduced evacuation time as the distance increases. In general, the ratio variation of D_ratio is relatively smaller than that of the L_ratio, because the diagonal dimension of the building is longer than the longitudinal dimension. This results in a large D_ratio reduction in evacuation time when the ratio is equal. In addition, the results from the optimal point show that the L_ratio had the highest evacuation time at 0.44 and the D_ratio had the highest evacuation time at 0.38. In Korea, where the standard of the L_ratio is applied, it is deemed reasonable, because it is consistent with the optimal point derived, and requires remoteness of more than one-half (0.5) of the longitude dimension of the building. For the US with the D_ratio, it is deemed necessary to reinforce the standard, since it applies more than a quarter (0.25) of the reference in the high-rise, which is lower than the optimum point. However, although this is a significant statistical result, it is likely that when the variables not considered in this study are included, other results will be produced, which requires further studies.

Even though this study suggested implications for the applicable remoteness standards for each country by the analysis of standards, simulation, and statistical analysis through the evacuation performance for the variation remoteness between evacuation stairways, the following limitations exist:

First, the simulation performed has the feature of basically evacuating to the nearest exit, assuming that evacuees are familiar with their building. In addition, in a real emergency situation, the choice of the exit stairway is made on its own judgment, so bottlenecks may cause a lopsided crowd to stay on one stairway, rather than seek another. Therefore, it has its limitations as a research using simulation.

Next, since the simulation was performed by setting up an open plan to control the impact factors of the occupants' location, further studies are needed on the evacuation performance of layout by floor in reality. Future work will focus on the unfamiliar and complex spaces, and the behavior and response of evacuees according to environmental changes.

Nevertheless, this study is meaningful, in that the effects of evacuation performance have been verified as the remoteness variation in tall buildings. The study is also worthwhile, in that it has given some implications for the different standards application of remoteness from each country.

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