Optimized Exit Location Planning in an Underground Mega Mall
Based on Mathematical Model of Algorithm

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Abstract
Multipurpose buildings that have an underground mega mall require distinguished functional considerations compared to small conventional underground spaces. Thus, this study starts with an assumption that architects' knowledge and personal decisions may not be reliable and valid in a massive multipurpose underground mall, because it is beyond general sense in terms of size and function. Especially, when considering safety issues, an architect's personal subjective decisions should be evaluated with scientific and objective criteria. Therefore, the intention of this study is to present an emergency exit and staircase planning method based on a mathematical model of optimized algorithm. The fundamental notions of the mathematical model and optimized algorithm that this study has developed for architectural planning, practically adapted the theoretical and mechanical principal that has been used in the field of industrial engineering for many decades. Consequently, the developed algorithm was able to prove that it could indicate the most efficient exit/staircase location for a certain space and assign it based on quantitative analysis.

Keywords: emergency exit; mathematical algorithm; underground mega mall; planning methodology

1. Introduction
1.1 Research Background and Intention
The recent tendency of massive multipurpose architectural composition is a relatively new phenomenon and, thereby, demands many unconventional architectural planning considerations. The COEX Center in Korea, the Midtown in Japan and the Tseung Kwan O in Hong Kong clearly represent unique aspects in architectural planning in a multipurpose functional mega space. Moreover, these mega spaces have large underground commercial malls that have very complex arcades and shopping spaces for an undetermined number of general visitors, which clearly require distinguished functional considerations compared to small conventional underground spaces. Therefore, a spatial planning based on an architect's personal artistic experience and speculating ideas should be evaluated with scientific and objective criteria. Especially, when it comes to safety issues such as emergency exits and stairs, an architect's personal subjective decisions may create some unexpected pedestrian dynamics that can result in fatal blockages or a deadlock situation that may lead to serious casualties.

An analysis of the fire department in Korea, over the last five years shows a clear increase in fire damage not only in residential facilities, but also in commercial buildings. Moreover, in 2010, 39% of all the fire breakouts took place in non-residential facilities (16,388 cases), which is a relatively high ratio compared to other western countries. It also shows that while there were 34,844 cases of fire breakouts in 2010, this increased to 41,862 cases. This is more than a 20% increase and the amount of damage sharply increased by more than 75.6%. Also, data showed that while 11.6% of all the fire breakouts took place in underground facilities, their casualty ratio was 20.8%, which clearly states that underground fire breakouts are more life threatening than regular situations.

Therefore, the intention of this study is to present an emergency exit and staircase planning method based on a mathematical model of optimized algorithm. The developed algorithm will be applied to a well-known underground commercial mall in Seoul, Korea and a simulation comparison between the existing plan and the modified plan will be conducted to prove its reliability and effectiveness in a fire escape event. Consequently, this study will reveal the problematic emergency issues of conventional planning methods that have relied heavily on an architect's speculative recognition.

1.2 Research Method
This research is a simulation study on one of the biggest underground commercial malls, the Central Park, located under the Central City Complex (Note
In general, architectural planning deals with spatial fragments. In other words, the user's activity plays a very important key role in any fire evacuation event. On the other hand, according to Helbing (2001), individual pedestrians have their own unique walking characteristics in terms of speed, aim and destination etc. Yet, when it comes to crowd movement it becomes strikingly easy to predict some regularity in its flow. In regard to group movement, empirical research based on naturalistic observation, photographs and motion pictures since the 1950’s has come to the common conclusion that crowds have a tendency of choosing a straight route with the shortest distance to their aimed destination. Also, facts that influence behavior including any decision making in a certain situation has been guided by so-called ‘social fields’ and/or ‘social force’. According to Helbing, individuals have a tendency to make a right turn, walk on the right side and so on. He also claims that pedestrians keep some type of invisible distance in order to maintain a personal domain even under a tense situation with low density in order to respect an individual’s conceptual territory and thus avoid any unnecessary.
physical contact. However, some of his findings are contrary and exactly the opposite when it comes to the behavioral patterns of Koreans. They have a tendency to turn left, and are less sensitive to personal interactions with strangers even under a low density situation. In other words, many simulation programs may not adequately represent an appropriate reality due to the cultural and social differences. Furthermore, most of the architectural simulation programs only perform under a given situation and do not suggest any creative solutions.

2.2 Evacuation Simulation

The most widely used evacuation simulation program in Korea is called the Simulex (Note 2), which was developed by a virtual company in England. It enables an architect to simulate an occupant's behavior in an event of a building evacuation within a 2D floor plan. Also, it can define the population by age and gender, and take into account factors which may include: walking speed, body type, and the time that it takes to respond to a fire alarm. However, there are limitations; it only provides a view of how the population evacuates within a given floor plan as it happens and monitors the number of people left in the building at a certain time in order to predict how long it will take for all the occupants to reach the exits. Consequently, it only shows whether the given floor plan meets or exceeds the acceptable evacuation criteria in a timely manner. In other words, the Simulex is a kind of Post Occupancy Evaluation (POE) tool that only indicates safety based on time in a limited and passive manner. A common limitation of this simulation program and other simulation programs is that unfortunately, it is not able to suggest architectural solutions from a planning point of view. Therefore, this study used the Simulex evacuation simulation only as a tool in order to make a comparison between the existing underground floor plan of the Central Park and the modified floor plan based on the mathematical algorithm that this research developed.

2.3 The Mathematical Model and Optimized Algorithm

The fundamental notions of the mathematical model and optimized algorithm that this study has developed for architectural planning, practically adapted the theoretical and mechanical principal that has been used in the field of industrial engineering for many decades. The basic interest of optimized facilities planning in the field of industrial engineering is to locate necessary industrial equipment and machines to maximize mass production in a short period of time. In other words, the main interest is to find the most efficient machinery set up and/or distribution that can promote a modulus of production line flow of essential raw materials to shorten the manufacturing process based on a scientific algorithm.

To apply this basic notion into architectural terms, the developed mathematical model of this study considered industrial equipment and machinery distribution as locating emergency exits and stairs and raw material's manufacturing flow as the pedestrian evacuation movement, since it has a common factor, which is the shortest distance. To accomplish this adaption, it was necessary to identify the number of emergency exits/stairs in the underground mall and its' shortest distance with various spaces. The shortest distance between various spatial fragments and emergency exits/stairs are indicated as 'Arc' and the number of occupants for each spatial fragment are indicated as 'Node' for the formula. Over a number of decades, a sufficient number of studies (Seneviratne & Morrall 1985, Borges & Timmermans 1986, Bovy & Stern 1990 etc.) have been conducted and claim that individuals in general have a tendency to choose the most direct and shortest route for their destination, therefore it would be reasonable to consider the shortest distance (Arc) as the most important variable in an emergency evacuation. Furthermore, corridor width and crowd movement of panicked occupants were also taken into account when developing the mathematical algorithm to modify the locations and/or orientations of emergency exits and stairs quantitatively. Unlike the Simulex or other simulation software that can only be used after a fixed plan, this developed algorithm has the advantage to being used during the early stages of an architectural schematic plan based only on brief spatial locations.

3. Framework of the Analysis

3.1 Site: Underground Mega Mall - Central Park

Table 1. Architectural Condition of the Central Park

| Central Park (2000) | Location | Size       |
|--------------------|----------|------------|
| Seocho-Gu Banpodong| 19-5 Central City B1, Seoul, Korea. | 36,860.65m² |

Composition: Shopping mall, movie theater complex, mega bookstore, music shop, banks, subway connections, shopping center, the Fountain Central Plaza etc.

The site for the algorithm analysis and the Simulex simulation is an underground mega mall, called the Central Park, and it is located under the multi-purpose complex, called the Central City in Seoul, Korea. The Central Park is connected with the subway lines 3, 7 and 9 and it has one of the highest number of unspecified daily visitors in Seoul. The underground facility, the Central Park, is a multi-purpose shopping complex that has a central intermediate area called the Fountain Plaza. It provides connections to a basement area of a shopping center, a mega bookstore, a movie theater complex, food courts and so on. Since the Central Park has such a vast area with a variety of spaces, its underground pedestrian circulation is not always interconnected and, therefore, it is
required to consider a separate evacuation strategy for spatial sections. Likewise, it has only a few limited connections between the Central Park and the basement area of the hotel. Moreover, it is not even for general visitors and, thereby, the basement area of the hotel was not included for this analysis.

3.2 Occupants Fixation Method

Regarding the number of occupants for the analyzed area, this study considered the actual number of potential visitors for a worst-case scenario, rather than relying on daily average usage. To obtain the necessary data, on Saturday and Sunday during the peak times of 1 to 3pm, a direct naturalistic observation was conducted by 3 observers who counted the number of occupants every 30 minutes.\(^{(3)}\) In the case of corridors and intermediating areas, the average number of occupants was considered by certain sections. Similarly, also for an oversized area such as the mega bookstore, the B1 shopping center and the food court, the average number of visitors within a certain square area was counted and multiplied to represent the actual area and visitors. Finally, the number of patrons for the movie theater relied solely on the data that was given by the company.

3.3 Analysis based on the Mathematical Model and Optimized Algorithm

In order to determine the preprocessing step to convert the engineering optimized algorithm for an architectural analysis, the following process was taken:

First of all, this study classified and organized the spatial compositional fragments of the Central Park and identified the number of occupants (Node) for each facility. Second, the shortest direct distance (Arc) between spatial fragments were measured. The notion of the 'shortest direct distance' was continuously stressed as being the most important variable during an evacuation process. An experiment conducted by Bovy & Stern in Jerusalem in 1991, revealed that 2/3 of all the participants choose the shortest direct route to arrive at a certain destination.\(^{(15)}\) The specific meaning of the shortest direct distance is the distance between the center points of two spaces in a practical sense. After the center point of each space was identified, the shortest distance between spaces was measured as shown in Fig.2. and then the actual number of occupants for each space was assigned. Thereafter, a pattern recognition qualitative variable on whether to assign emergency exits or stairs for each functional space or not was determined. Finally, possible variables that can emerge during an evacuation situation such as crowd movement, walking speed, bottleneck phenomena etc. were taken into account in developing optimized algorithm. More specific preprocessing steps will be explained in the next section.

4. Algorithm Analysis and Findings

This section will present a detailed method and process of using a mathematical model to find the optimized exits and staircase locations within the Central Park which will eventually minimize the necessary evacuation time in a fire event. Also, this section will show the comparison analysis between the existing plan and the modified plan based on the developed algorithm.

4.1 Mathematical Conversion

The notations and parameters to analyze the Central Park are as follows;

\[w_i: \text{Number of occupant in facility } i, i=1,2,\ldots,N\]
\[N: \text{Number of facilities in the Central Park } N=53\]
\[S_i: \text{Space required (m}^2\text{) for facility}\]
\[d_{ij}: \text{Distance between facilities } i \text{ and } j\]
\[t_{ij}: \text{Evacuation time for facility } i \text{ to exit nearby facility } j\]
\[M: \text{Arbitrary Large Number}\]

The following variables are the decision variables for the mathematical model

\[Y: \text{An emergency exit is necessary to be located near facility } j: \text{ if yes = 1, no=0}\]
\[X_{ij}: \text{Occupants in facility } i \text{ need to use an emergency exit near facility } j: \text{ if yes 1, no=0}\]
Parameters, $w_i$, $s$, and $d_i$ are as given in Table 2. The mathematical model is developed based on the above considerations and qualitative decisions are as follows: 

\[
\text{Minimize } \sum_{i=1}^{N} \sum_{j=1}^{N} w_{ij} X_{ij} 
\]

s.t. 

1. \[ \sum_{j=1}^{N} X_{ij} = 1, \ \forall i \] 
2. \[ \sum_{i=1}^{N} Y_{ij} = u \] 
3. \[ \sum_{i=1}^{N} X_{ij} \leq MY_{ij}, \ \forall j \] 
4. \[ X_{ij} \in \{0,1\}, \ \forall i, j \] 
5. \[ Y_{ij} \in \{0,1\}, \ \forall j \] 

The objective function is a formula to minimize the total time from each facility to the assigned exit. According to research on crowd movement, the density (number of occupants/m²) - $\nu$ and the crowd's moving speed - $\nu$ can be integrated by a linear regression equation as follows.\(^{160}\) 

\[ \nu = 0.978 - 0.191 \rho \]

Therefore, if we assume that occupants in facility $i$ and $j$ are using the same exit to evacuate, then the density of evacuating crowds can be considered and its evacuating speed can be calculated as follows: 

\[ v_{ij} = 0.978 - 0.191 \rho_{ij} \]

The objective function shows that if occupants in facility $i$ are using an exit near facility $j$ ($X_{ij} = 1$), then occupants in facility $j$ can manage themselves to make a direct evacuation ($d_j = 0$). However, occupants in facility $i$ will need extra time ($t_{ij}$) to arrive in a safe area. The total amount of time that it takes for an evacuation can be calculated with the number of occupants in facility $i$ multiplied by the necessary evacuation time; therefore, more occupants will obviously need more time to complete the whole evacuation process.

The evaluation was conducted with a computer (Intel(R) Core 2 Duo CPU 3.16 GHz, 3.25 GB RAM) that can engage with Microsoft Visual Studio 2005 C++ and an optimization software ILOG CPLEX 11.0 simultaneously. The mathematical process to assign emergency exits for the Central Park is as shown in Table 3.

Consequently, the mean modification plan between the algorithm analysis and realistic issues such as architectural code, circulation, connections between facilities etc., is suggested as shown in Fig.3. The algorithm analysis suggested putting in an exit for every movie theater separately and assigning only one exit for the whole basement area of the shopping center. However, the basement area of the shopping center cannot be considered as an independent facility.
Table 3. Optimized Distribution of Emergency Exits

| Optimized exit location | Algorithm Value | Assigned Occupant       |
|------------------------|----------------|-------------------------|
| Y1 = 1 (Food Court)    | $X_{1,1} = 1$  | Food Court Occupants    |
| Y2 = 1 (Ticket Box)    | $X_{2,2} = 1$  | Ticket Box Occupants    |
| Y3 = 1 (Theater 1)     | $X_{3,3} = 1$  | Theater 1 Occupants     |
| Y4 = 1 (Bookstore)     | $X_{4,4} = 1$  | Bookstore Occupants     |
| Y24 = 1 (Corridor 3)   | $X_{24,24} = 1$| Corridor 3, Dunkin Donuts and 3 other shop's Occupants |
| Y28 = 1 (Corridor 3)   | $X_{28,28} = 1$| Corridor 1 and Outback Steak House's Occupants |
| Y40 = 1 (Outback Steak House) | $X_{40,40} = 1$ | Corridor 1 and Outback Steak House's Occupants |

but must be considered as a part of the whole shopping center, which will essentially need vertical circulations within its upper parts. Therefore, major modification for its basement area will not deliver a realistic solution and, therefore, the 5 exits that were assigned to the movie theater complex were ignored and remained in the shopping center's basement area for its vertical connections as it is in the current existing plan.

On the other hand, an exit that was in the northeast corner of the Central Park has been moved to the movie theater complex area as the algorithm suggested. Based on the algorithm for more efficiency, the orientation of an exit was facing to a sub-corridor was changed to the movie theater complex side.

5. The Simulation Analysis

In this section, a comparison analysis between the existing plan and the modified plan of the Central Park was conducted using the Simulex evacuation evaluation software. The same fire event scenario regarding the number and characteristics of occupants, fire conditions etc. were applied to estimate the total time of evacuation. Eventually, the comparison analysis revealed that the emergency exit/staircase plan based on the mathematical model of optimized algorithm escalated the reliability and validity in evacuation safety issues.

5.1 Simulation Conditions

For the analysis, occupant type was defined as 20% male, 30% female, 15% children and 10% elderly. Also, the occupant's physical condition and standard followed the data provided by the Korean Agency for Technology and Standards. The result of the comparison simulation is presented in Figs. 4 and 5. It shows that the modified plan based on the mathematical model of optimized algorithm showed its reliability and validity in emergency exit/staircases planning by an approximate 10% improvement in overall time. (Note 4)

5.2 Comparison Analysis and Findings

Reducing evacuation time under any fire event has a direct decrease in casualties. As was witnessed in an airline fire breakout in 2007 at the Naha Airport, in Okinawa, Japan, passengers were able to evacuate within one minute without any loss of life, to which a report claimed that it may have killed all 165 passengers if there was only a 30 second delay. Likewise, efforts and strategies that can reduce seconds in an early stage of an evacuation process are extremely important in saving valuable lives. The Simulex comparison analysis showed a 44.8 second difference in the total evacuation process between the existing plan and the modified plan, which is more than a 10% improvement that ultimately supports the reliability and validity of the mathematical model of optimized algorithm. The Simulex simulation visualizes the early stages of the evacuation situation in Figs. 5 and 6., which starts to show the difference due to the replacement of an exit from the north-east steak house area to the highly dense part of the plan, which is the south-west movie theater section. In re-orienting an exit that was facing toward a sub-corridor area to the movie theater 8, it showed an improvement to be more efficient for shoppers in the mall.

As a result, a major modification was carried out with one exit/staircase, and one minor change was made for a core area in the shopping center, which switched its elevators and staircase position for easier access from the Central Park's main corridor rather than from the shopping center side. As directed by the algorithm for more efficiency, the orientation of an exit that was facing to a sub-corridor was changed to the movie theater complex side.
of more than 30 seconds in the evacuation process for that certain area. Also, Figs.7. and 8. are starting to show a major difference, especially in the south-west movie theater area by showing a more efficient status. As a result, the existing plan at the movie theater section took more than 120 seconds to evacuate than the modified one.

6. Discussion and Conclusion
A visitor's comprehension of a mediocre space depends heavily on their experience and activity in utilizing a certain spatial area and, in this case, conceptualizing its physical boundaries and functionality might be well defined. Therefore, even if a building plan was designed based on an architects' personal artistic experience and speculative notions, it would not create a problematic planning issue as long as a common spatial sense can be shared between an architect and general users. This study, however, started with the assumption that architects' knowledge and personal decisions may not be reliable and valid in a massive multipurpose underground mall, since it is a relatively new building composition which is beyond general sense in terms of size and function. Especially, when it comes to safety issues such as emergency exits and staircases, this study came to the conclusion that the challenging new scientific planning method can improve an overall evacuation process in a more efficient way. In other words, a more elaborated scientific planning method seemed extremely important to reduce time at the early stage of an evacuation process which has a direct effect on its casualties.

The basic notion of a facility planning method in the field of industrial engineering was practically adapted and reengineered architecturally to locate emergency exits and staircases. Afterward, Simulex simulation evaluation identified approximately 10% improvement in the total evacuation process. In terms of the early stage of an evacuation process, there is a high possibility that a certain building floor will be ravaged after only around 10 minutes from the first fire ignition and will make the whole evacuation process more chaotic. Actually, considering 2-3 minutes retardation time for realizing a fire situation, speculating for exits and taking actions, a 10% improvement can play a critical role in saving lives. Above all, the mathematical model for optimized algorithm in locating fire exits and stairs proved its potential and reliability especially in the most crowded movie theater complex area by reducing evacuation time from 442.2 seconds to 305 seconds, which is more than a 30% improvement in efficiency.

Consequently, the developed algorithm was able to prove that it could indicate the most efficient exit/staircase location for a certain space and assign it based on quantitative analysis. On the other hand, the limitation is that it cannot exactly pin point the most appropriate spot for an exit/staircase yet and can only suggest in brief section areas. Therefore, emergency planning in general still has to rely on an
architect's knowledge and qualitative decision for locating the exact position of exits and staircases, but the significance of this study is that the developed algorithm showed a great potential as a sub-tool in making the final decision, which will always be an architect's own share.

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Notes

1) The site area of the Central City is approximately 126,700 m², which is similar to Roppongi Hills (110,000 m²) in Japan. Also, it is a building known for one of the biggest first floor area in Korea.

2) http://www.firemodelsurvey.com/EgressModels.html, This website briefly introduces and updates dynamic characteristics and evaluation methods on widely used evacuation simulation software including the Simulex.

3) According to Park's research in 2009, 'Study on Characteristics of Walking Environment by Factors of Physical in Mediation Space of Mixed Use Complex', the highest pedestrian rate of 30% has been witnessed during weekends between 1-3 pm at the Central Park.

4) It was estimated that 442.2 seconds was taken to evacuate from the existing plan and 397.4 seconds for the modified plan based on the algorithm, which showed 44.8 seconds differences.

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