Redesign of Koningin Julianaplein

EGRESS AS PART OF FIRE SAFETY IN HIGH-RISE BUILDINGS

REDESIGN OF KONINGIN JULIANAPLEIN | YANG SUN
EGRESS AS PART OF FIRE SAFETY IN HIGH-RISE BUILDINGS

MASTER OF SCIENCE THESIS

Yang Sun

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Abstract
ABSTRACT

The process of evacuating some large high-rise buildings may take upwards of several hours. One question that needs to be asked, however, is whether it is feasible and desirable to completely evacuate the high-rise building in fires. This research seeks to remedy this problem by proposing one or more efficient egress plan(s) for high-rise buildings. Investigation into a number of Dutch projects, international fire codes and state-of-the-art literature laid the foundation for this study. Four egress plans have been presented from a worldwide perspective for a specific certain building: Koningin Julianaplein in The Hague, the Netherlands. At least ten egress possibilities have been presented with respect to different fire scenarios. Assessment results of all egress possibilities suggest that partial evacuation appears to be the most appropriate strategy for Koningin Julianaplein, which results in a reduction in egress time by as much as 50% (defend-in-place) and 43% (relocation). While for office towers under relatively high occupant loading, phased evacuation has positive effect on the egress efficiency in comparison with traditional simultaneous evacuation.

Key words: high-rise building, building fires, egress, evacuation, fire safety
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INTRODUCTION
1.1 General Introduction

As with other domains, building industry is progressing with each passing day. The number of high-rise buildings is growing increasingly around the world. They turn out to be important landmarks for some certain geographical areas. High-rise buildings solve the problem of demanding space. In addition, residents living on the higher floors could have a better view over the city. As it is far from the street level, the noise level can be lower. Unfortunately, tall buildings gave rise to problems at the same time. First of all, they pose particular design challenges for structural and geotechnical engineers. Secondly, transporting all building components to such a height is an interesting logistic challenge for the contractor. More importantly, means of egress in emergency situations such as fire became an essential issue for tall buildings. Since fires can occur anytime and anywhere, building fires are closely related to our daily life. Sometimes occupants are unable to arrive at the ground level in time as a result of the long vertical distance. A large number of pedestrians merge at some intersections that may lead to congestion, and delay the egress progress. However, prolonged exposure to heat and smoke may result in incapacitation or death. Consequently, the topic of egress from high-rise fires should be brought to the forefront.

With the aim of developing a well-organized egress plan, this research focuses on the integration of various vertical egress approaches and strategies. The emphasis is given to reduce the total egress time without endangering human life. Throughout this study, egress time is used to refer to the required safe egress time (RSET), which encompasses the time from fire ignition, detection to notification, from notification until the occupants decide to take actions, and the time from the start of evacuation until complete to a safe area. A considerable amount of literature are studied and from which, we abstract the egress design essentials to build a model and calculate the theoretical egress time for a specific tower. The principal purpose of combining numerous egress possibilities is to compare egress time, study the merging behavior, determine fire-protection requirements and obtain assessing data for the assessment of all egress plans.

This chapter begins by an introduction of high-rise fires. The rest of the thesis has been organized in the following way. Chapter 2 delineates the thesis goal, research approach and constraints. It will then go on to case study of three Dutch high-rise projects and globally literature study in chapter 3 and 4. Chapter 5 deals with the redesign of a specific project and evaluation of all possible egress plans. Each plan consists of egress strategies, vertical egress approach options, egress time calculation, required fire protection system et cetera. Next, an explicit assessment of different plans is given by comparing their beneficial, applicability and efficiency. Lastly, recommendations turn to target egress design for future high-rise projects, as well as suggestions for the building users.

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1 Vertical egress approach: In the thesis, vertical egress approaches represent the vertical transportation facilities that people can use during evacuation, e.g. stairs and elevators.
2 Egress strategy: The evacuation progress on the basis of the egress starting time.
1.2 CHARACTERISTICS OF HIGH-RISE FIRES

1.2.1 FIRE AND SMOKE SPREAD

High-rise building creates the cumulative effect that in fires, a large number of occupants have to travel great vertical distance to descend. On one hand, smoke and toxic gases from fires, particularly carbon monoxide and hydrogen cyanide, are major agents leading to casualties (9). These gases contain both incomplete combustion and combustion toxic products, which becomes mixture with the surrounding air. Lack of oxygen and high temperature jeopardizes people’s health during egress. On the other hand, solid particles in the smoke have light-shielding effect. In the early stage of a fire, smoke layers reduce visibility and thereby turns into hindrance to evacuation (9). Once the fire-protection measures are not taken properly, stairwells and other shafts will act as a chimney. Flame and plumes rise from burning articles, and smoke may extend to fill the vertical channels and reaches untenable conditions. This is the case particularly in hotels, libraries and dwellings where lots of combustibles are present. The smoke spread horizontally at a speed of $0.3m/s$ at the initial stage of a fire, and it increases to $0.5~3m/s$ with the fire development. While inside the shaft, smoke spread even faster which ranges from $3m/s$ to $4m/s$ (115). As a consequence, the top floors will be influenced seriously due to this phenomenon.

![Figure 1: Burning temperature; Causes of fatalities in building fires](image)

In addition to smoke, occupants expose to heat by conduction, convection and radiation at the same time. The fire burning temperature is illustrated in Figure 1. It can be found that people must be evacuated before flash-over\(^3\). Preliminary work on the relation between flame temperature and life safety reported that exposure to less than $120^\circ C$ in dry air causes skin burns (7). In practice, casualties were mainly caused by heat and irritant gases, rather than structural collapsing (100). Reasonable egress design should ensure that people on the critical and surrounding areas are able to move to places of safety before they are threatened by the heat and smoke.

---

\(^3\) Flash-over: The stage in the development of a fire in an enclosure, all combustible materials will suddenly ignite and a complete involvement of the whole enclosure in the fire, characterized by a sudden (explosive) propagation of the fire. The temperature will rise to at least $500^\circ C$. (100)
1.2.2 **COMPARTMENTATION**

Before talking about egress, it is necessary here to clarify exactly what is meant by compartmentation. In fire safety engineering, the structure is divided into different fire compartments. Generally speaking, they are enclosures that protect the occupants against fire hazards (131). One fire compartment is comprised of single or multiple rooms, which contains ideally no more than three floors in low-rise buildings and not more than one floor in high-rise and basements (9). Fire compartments are completely surrounded with fire-resistant construction on all sides, including partition walls, floors, ceilings and all the openings. A fire must be compartmentalized, and these enclosing elements prevent the flames from spreading to other spaces within a certain time period.

As we have known the danger of smoke diffusion, smoke compartments shall be introduced, commonly referred to sub-compartment. A number of fires involving uncompartmented buildings have drawn attention to the absence of subdivision (9). Floor plan and horizontal walking distance are the main factors to determine whether the smoke compartments are requisite. This horizontal travel distance is normally measured from the most remote point to the center of the staircase doorway, or other exits that may enter another fire compartment. Particularly when people have to travel through a very slender corridor, it is recommended to place some smoke barriers on the route. These barriers subdivide the space into isolated smoke compartments so as to create a refuge area on each side of the barrier, and thus reduce the travel distance to another compartment.

![Figure 2: Sketch of sub-compartment with smoke barrier](image)

To summarize, safety is evaluated by considering the use of spaces encountered along the route and the degree of protection provided by fire barriers. Compartmentation is a measure of passive fire protection, and it is the premise of egress design.
1.2.3 FIRE EGRESS

The term fire egress has come to be used to refer to the path or the act of exiting the structure during a fire. The main purpose of providing a means of egress is to ensure safe evacuation of all occupants (or the occupants in the most affected floor) to a place of safety within a reasonable period of time. A structure must meet the egress standards in local or national norms. With respect to high-rise buildings, on the one hand, the floor area is larger and total travel distance is longer. It even takes hours for people to travel down to the street level in some skyscrapers. Even so, it does not mean spaces other than ground floor are unsafe. In tall buildings, occupants are considered safe when they arrive at another compartment. This can be the nearest enclosed stairway, an adjacent smoke compartment, refuge floor, as well as the exterior balcony. On the other hand, the crowd becomes larger and larger as time goes on. When people are unfamiliar with the floor layout, it would be difficult to find the appropriate egress route. Despite that the environment is well known, it is still problematic to follow the way once the light shielding property of smoke obstructs evacuees’ view, or the lighting system has been destroyed.

In terms of high-rise buildings, previous study from Dr. Marja-Liisa Siikonen pointed out the relation between fire egress time, building functions, population and the number of floors (Figure 3), which gives a general impression on high-rise egress (32).

![Figure 3: Simulated egress time from KONE](#)

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4 KONE Corporation: A Finnish escalator and elevator company.
1.2.4 INVOLVEMENT OF FIRE DEPARTMENT

High-rise buildings may possess a variety of safety measures. New high-rise buildings are likely to have active fire protection features, such as automatic sprinklers, smoke and fire detection system and passive features like compartmentation. Since many variables may happen in fire-incident, sometimes these measures do not provide guarantee of safety (4). It would be advantageous to determine the particular requirements for the involvement of fire department.

After the fire department arrived at the site, they first discover the exact location of the fire and find their way to access the fire floor. Fire control panel is usually installed on the ground floor that helps the firemen to identify the situation inside the building. Normally, fire department arrives at one level below the fire floor by fire-service access elevator and approaches the fire floor using stairs. Their work is to extinguish and keep the fire under control, as well as rescue people in the meanwhile (Figure 4). The higher the building becomes, the more difficult is access for firefighting. Sometimes when the vertical travel distance is too remote, the fire department is also in charge of lessen the necessity to evacuate all occupants. In some countries where more and more tall buildings were constructed, not everybody is requested to leave the building during emergency, particularly when life safety systems are properly installed. Statistics show that once people reach a refuge floor and see the fire fighters, they will be psychologically relieved and more confident of their personal safety (4).

![Figure 4: Role of fire department](image)

Supposing that fire occurs on the building facade, to achieve the maximum vertical reach for rescue operations is hard. Especially today, when curtain-wall constructions are used more often, fire spreading to the floor above should be stopped at the perimeter of the floor. As the incident shown in Figure 5, a fire broke out in the 42-story Polat tower, Istanbul, Turkey. One of the fire suppression problems was the extinguishing water supply. Even helicopter released water to put out the fire. It is tough to suppress the fire on the facade for the reason that pump water to such a height requires extremely high power. Additionally, glass and other parts of the facade falling down endangered the firefighters and people who tried to evacuate the building (125).

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5 Fire floor: The floor where fire occurs.
1.3 Fire Damage

Fire damage can be generalized from three aspects: detriment of occupants' life safety, structural damage and loss of properties. Even though overall incident statistics show that the percentage of injuries and property losses associated with fires in high-rise buildings are small (4), everybody hopes to minimize the damage.

Obviously, heat and smoke migration in high-rise buildings is the primary threat to life. Most of the fire deaths occur in dwellings (9). Toxic emissions from the fires have negative influence on the environment, leading to extensive damage to human safety. On the other side, fire damages the building components although structural damage normally plays a minor role (100). But after extinguish the fire, parts of the building were probably water damaged. The cost of repairing or rebuilding the structure brings about the third aspect - the economic losses. It includes the material and properties losses, and extinguishing cost et cetera. High-rise fires will suffer more losses because of the large amounts of stuff and equipment. Many companies go bankrupt after a fire because the production process was halted, and thereupon they lose the market (100).

To sum up, a great deal of factors that affect the fire and smoke spreading in a high-rise building, therefore the level of damage sustained in random. No matter how severe the fire damages, life safety must be the primary concern, and hence fire and building codes require both passive and active fire protection systems to minimize the fire damage.
Figure 5: 152 meter high Polat Tower fire, Istanbul, Turkey, 17 July 2012
2

RESEARCH QUESTION AND APPROACH
2.1 INTRODUCTION

Fire safety encompasses diverse aspects such as design of fire-resistant structure, means of egress, fire protection installation, control of smoke and combustion products, human behavior, risk management and so on. It is essential to define the main research focus, research approach on how to tackle the problem, and the thesis constraints in the beginning.

2.2 RESEARCH QUESTION

The overall subject of this thesis is fire safety in high-rise buildings, specifically focusing on egress plans for Koningin Julianaplein in The Hague, the Netherlands. High-rise design shall meet the requirements of building codes as well as fire codes. Since all requirements in the Dutch norm Bouwbesluit are meant for buildings up to 70 meters, high-rise fire safety design is relatively flexible. Once the client requires a skyscraper, fire safety specialists shall ensure an equivalent level of safety as other low-rise buildings (Dutch: gelijkwaardigheid). It prompts the research question of this design project:

In the event of a fire, how to evacuate efficiently inside a high-rise building?

Effectiveness is measured by:

- Whether the occupants can get to a safe place within a limited time period before the structure or parts of it collapse;
- Whether it is necessary to evacuate the entire building, compare the results of full building evacuation and partial evacuation by summarizing the efficiency of each strategy;
- Whether the route is easy to recognize and access, meanwhile, whether the route is harmful for human’s health; this is achieved by introducing fire or smoke compartments;
- Whether the egress plan is economical or not;

The current amount of knowledge and experience in the Netherlands on the topic of egress plan is mainly based on simultaneous full evacuation using stairs alone. There is always room for improvements and many things could be investigated at the moment.

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6 Bouwbesluit: Dutch Building Decree, the latest version is Bouwbesluit 2012.
2.3 Thesis Objective

This research project is conducted as the graduation project for the Master program in Building Engineering, Civil Engineering of Delft University of Technology. The project is commissioned by DGMR Bouw B.V. The overall objective of this thesis is investigating the state-of-the-art egress options for high-rise building fires by compiling available publications from a global perspective. The main focus of this study is centered on proposing egress plans for a Dutch tower, and presents recommendations for future high-rise development. One or more egress plans for Koningin Julianaplein based on different strategies will be proposed to answer the research question. An egress plan should consist of:

- Egress strategy
- Routing
- Egress time
- Vertical egress approaches
- Required fire protection system

Chapter 4.2 describes the difference between each strategy. The egress plans made in this thesis therefore are not completely according to present regulations, but are based on the relevant literature and worldwide fire safety legislation. The main goals of the thesis are:

- To gather researches around the world, summarize and integrate these design approaches;
- To build a model to calculate the theoretical egress time of a certain high-rise building by combining the knowledge gained from literatures and regulations;
- To propose several egress plans for a certain high-rise building in the event of fire;
- To assess all egress plans and evaluate the efficiency and applicability, and draw conclusions on the implementation of these plans;
- To give recommendations for the future high-rise design in the Netherlands on the topic of egress from fire;


2.4 **RESEARCH APPROACH**

To be able to achieve the main objectives of this project and answer the aforementioned research question, there are steps that have to be systematically taken. First of all, apart from the technical part, when we think about the subsequent occurrences upon a fire alarm, people will normally encounter the following questions. Each question prompts one or more egress issue(s) that can be deliberate further.

![Diagram showing questions related to a fire alarm]

**Figure 6: Questions related to a fire alarm**

The research is composed of three phases based on these questions. **In the first phase**, the major task is to understand the Dutch design method in fire safety engineering from all related aspects, and have an overall impression on egress requirements for high-rise buildings. **Phase two** concentrates on literature and case studies so as to find an appropriate way to design means of egress. Literature studies focus on synthesizing international references in order to find out new possibilities and developments in the field of egress design. After, several egress plans will be created for a specific tower. Followed by the assessment and recommendation for the future high-rise designs, which will be the **last phase**.

It should be noted that the most essential part of this study is the calculation model of theoretical egress time. A number of underlying theories have been formulated to build this model. Before establishing the model, it is beneficial to review all the input, for they are the basis that the model is derived.

- Building function and occupant load
- Architectural design of the building
- Dimension of pedestrian evacuation routes
- Different egress strategies

Additionally, it is also important to know that all questions described in Figure 6 will be answered, but without emphasizing on dealing with human behavior upon the fire alarm. In
fact, time for individual decision making is of great importance in an emergency situation, but then it is beyond the scope of this study. Figure 7 below depicts how all abovementioned research aspects are transformed to thesis chapters through this design approach.

**Figure 7: Research approach**
2.5 CONSTRAINTS

Figure 8: Fire safety engineering

Fire safety engineering is an integration of all relevant topics demonstrated in Figure 8. Though we will focus on egress from fire in high-rise buildings, there are still numerous design aspects one can take into account. The expected time frame for this thesis project is 9 months (April to December, 2012). To undertake this research, it is necessary therefore to state the constraints and keep the project manageable.

- The thesis mainly focuses on buildings above 70 meters;
- This research do not study multiple fire events;
- Means of egress by elevators is taken into account, but the technical detail in the lift industry is not the concentration;
- Fire suppression installation system will be mentioned if necessary. Neither is there calculation on the extinguishing water pressure, nor the placement of fire hydrants;
- Egress from parking garage and underground is not investigated;
- Construction techniques of fireproof structures are not the main concern;
- Choice of the egress route is determined by the individual occupant, which will not be considered particularly.
- This study deals with traditional fire scenario caused by burning combustibles. Fire and building collapse caused by bomb or terrorist attacks is not included.
3
DUTCH FIRE SAFETY DESIGN


3.1 INTRODUCTION

To be able to have an explicit understanding of the Dutch way of design, this chapter aims at studying the overall aspects regarding fire safety, and gains the background for further research. A brief overview of some fundamental legal design requirements in the Netherlands is presented, which can facilitate a comprehensive understanding of the three projects provided by DGMR. Basically, the first several sections are synthesized from Bouwbesluit, NEN norms and SBR\(^7\) high-rise guideline. Following this, these technical requirements in fire codes have been employed to the three previous high-rise projects.

3.2 LEGAL DESIGN REQUIREMENTS

3.2.1 BOUWBesLUIT REQUIREMENTS

The Dutch building code Bouwbesluit is the basis of all building designs. The current version Bouwbesluit 2012 has been implemented since 1\(^{st}\) April 2012. While considering the design period of the three projects (all before 2012), this section deals with both Bouwbesluit 2012 and Bouwbesluit 2003, the original clauses in Dutch can be found in Appendix B.

3.2.1.1 General

A structure which is constructed with occupiable floor above 70 meters, or lower than 8 meters beneath the measuring level, should be designed to be fireproof. The following requirements shall apply with the scope of the master plan:

1) A building is designed to have structural components that ensure the resistance against fire for a reasonable period, and the building can be searchable by the fire department without any risk of collapsing;
2) A building is designed to provide fire-protection measures to the vertical escaping route;
3) A building is designed to reduce the occurrence of a fire hazardous situation sufficiently;
4) A building is designed in such a way that fire will not be developed rapidly;
5) A building is designed in such a way that the fire spread can be sufficiently limited;
6) A building is designed in such a way that the rapid development of smoke can be sufficiently limited;
7) A building is designed in such a way that the smoke from fire cannot propagate to another (different) part of the structure within a short time, so that occupants can reach the adjacent area by means of safe escaping routes;
8) A building is designed in such a way that occupants can leave the smoke compartment and sub fire compartment safely and fast enough;

\( ^7\)SBR: Stichting Bouwresearch, brandveiligheid in hoge gebouwen, the high-rise directive in the Netherlands.
9) A building is designed with adequate escape routes so that another safe area can be reached in case of fire;
10) A building shall be equipped with smoke proof escaping routes, so that occupants can escape safely and quickly during fire;
11) A building is designed in such a way that people can be saved and fire can be extinguished;
12) A building shall be equipped with firefighting facilities so that fire can be extinguished within a reasonable time period.

3.2.1.2 Occupancy Class

Occupancy class (Dutch: bezettingsgraadklasse) is the rate of usable areas in a building. It is an essential design factor in fire safety engineering of Bouwbesluit 2003, which was used in the three previous projects in the thesis. However, the latest Bouwbesluit 2012 has made some changes on this issue. As the following three projects were designed in light of Bouwbesluit 2003, new provisions in Bouwbesluit 2012 are not discussed. Table 1 presents the calculation method of occupancy class from Bouwbesluit 2003.

Table 1: Calculation method of occupancy class in Bouwbesluit 2003

<table>
<thead>
<tr>
<th>Class</th>
<th>Occupancy rate (Dutch: Bezettingsgraad)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Usable area per person (m²)⁸</td>
</tr>
<tr>
<td>B1</td>
<td>0.8 &lt; area ≤ 2</td>
</tr>
<tr>
<td>B2</td>
<td>2 &lt; area ≤ 5</td>
</tr>
<tr>
<td>B3</td>
<td>5 &lt; area ≤ 12</td>
</tr>
<tr>
<td>B4</td>
<td>12 &lt; area ≤ 30</td>
</tr>
<tr>
<td>B5</td>
<td>area &gt; 30</td>
</tr>
</tbody>
</table>

3.2.1.3 Capacity Check

Capacity check encompasses the opening direction, width, flow capacity of the door, as well as the storage and flow capacity of the staircases. From which, we can identify the number of people queuing and merging at some intersections, more importantly, adjustment can be made to rectify the unsatisfactory egress facilities.

Storage Capacity

In the latest Bouwbesluit 2012, the new requirements for stair treads are:
- When stair tread width > 1.1 m, tread rise > 0.17 m, the maximum storage capacity on the tread is width × 0.9 persons / m / tread
- When stair tread width < 1.1 m, the maximum storage capacity on the tread is width × 0.5 persons / m / tread

⁸ Usable area per person: including occupied room and transportation area, structural areas not included. (Dutch: In m² gebruiksoppervlakte per person)
⁹ Occupied floor area per person: effective areas, transportation areas are not included, structural areas not included. (Dutch: In m² vloeroppervlakte verblijfsgebied per person)
The maximum storage capacity for floors and landing (platform) is \( 4 \text{ persons} / \text{m}^2 \).

**Flow capacity**

An example provided by DGMR is given below. Capacity check is a requirement in the Dutch regulation, while it is not a necessity in every country. The required door width in Bouwbesluit 2003 is calculated by the number of occupants divided by \( 135 \text{ persons} / \text{m} \), and the minimum requirement of the door width is 0.85m. For example, \( 170 \div 135 = 1.26m \), then the required door width is larger than 1.26m. While for compartment 2: \( 27 \div 135 = 0.2m \), since door width of 0.2m is not reasonable, and the minimum required value is 0.85m, the required door width should be 0.85m.

Table 2: Flow capacity check

<table>
<thead>
<tr>
<th>Floor</th>
<th>Compartment</th>
<th>Total floor area</th>
<th>Max number of users</th>
<th>Exit</th>
<th>Door width and rotation direction of the door</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Number of users</td>
</tr>
<tr>
<td>23</td>
<td>Compartment 1</td>
<td>1003m²</td>
<td>340</td>
<td>Door 1</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Door 2</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>Compartment 2</td>
<td>533m²</td>
<td>107</td>
<td>Door 3</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Door 4</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Door 5</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Door 6</td>
<td>27</td>
</tr>
</tbody>
</table>

### 3.2.2 NEN6702 REQUIREMENTS

NEN6702 Principle: 'The main load-bearing structure during a fire is that part of the structure leads to collapse of a construction':

a. Fire compartment is not in the same location as the location of fire, not including residential function;

b. In the case that the fire happens in the (sub) fire compartment or part of the (sub) fire compartment, ensures that the preservation of non-directly adjacent sub fire compartment and non-directly adjacent other compartment;

c. In the case that the fire is a part of the (sub) fire compartment, which comprises more than 3 floors, ensures that the preservation of the areas that are not directly to the fire location boundaries, but in the (sub) compartment are located, this may be assumed of the collapse of the most unfavorable location of the fire compartment in a combination of three floors.
3.2.3 SBR REQUIREMENTS

3.2.3.1 General

- Time for occupants to walk through smoke: maximum 30 seconds
- After the alarm, people should reach a safe place within 60 seconds
- For the crowd, the waiting time of the occupants cannot be longer than 30 seconds
- During evacuation, the descent time is designed as 60 seconds per floor
- Each segment higher than 50 meters, 90 seconds is added to the evacuation clearance time in high-rise buildings
- Theoretical maximum evacuation time depends on the evacuation concept

3.2.3.2 Egress Concepts

Four egress concepts (Dutch: ontruimingsconcepten) are addressed according to SBR, which are particularly applied for buildings higher than 70 meters. The choice of egress concept is made dependent on the theoretical clearance time and the function of the building. For the theoretical egress time calculation, we assume a 7-minute period as the occupants’ pre-movement time in SBR, which involves the fire detection time, alarming time and decision-making time.

Concept A

Concept A represents a full evacuation within 30 minutes. It is widely applicable and usually adopted for buildings with moderately low occupancy level. Statements below provide the requirements within egress concept A.

- Total egress time $\leq 23$ min;
- Time for the occupants to descend one floor height: $\leq 1$ min
- The waiting time should be: $\leq 30$ s

![Figure 9: Concept A (SBR)]
Concept B

Concept B represents a full evacuation between 30 and 60 minutes. Statements below provide the requirements within egress concept B.

- $23 \text{ min} < \text{Total egress time} \leq 53 \text{ min}$
- Time for the occupants to descend one floor height: $\leq 1 \text{ min}$
- The waiting time should be: $\leq 30 \text{ s}$

![Figure 10: Concept B (SBR)](image)

Concept C

Concept C is generally applied as a step-by-step evacuation, which contains two phases. After the fire discover and alerting, the emergency zone must be evacuated within 10 minutes. People egress from emergency zone through fire and smoke free escaping routes to a gathering zone outside the building, or are guided to the ground floor, or to the floor beneath. After 30 minutes, if necessary, all users will be alerted and start a complete evacuation. The fire department is operating within 22 to 30 minutes. Statements below provide the requirements within egress concept C.

- Egress time for the emergency zone $\leq 10 \text{ min}$
- Egress time for the remaining occupants $\leq 30 \text{ min}$
- Time for the occupants to descend one floor height: $> 1 \text{ min}$
- The waiting time should be: $> 30 \text{ s}$
- Extra door width to meet the requirement of the sufficient flow capacity.

![Figure 11: Concept C (SBR)](image)
**Concept D**

Concept D is not applied frequently, which represents a partial evacuation. Statements below provide the requirements within egress concept D.

- Egress time for the emergency zone $\leq 10$ min;
- The rest of the building does not evacuate.

It should be noted that concept C and D are seldom applied. Defend-in-place strategy is not recommended in the Netherlands, although it could be argued for high-rise apartment buildings.

### 3.2.3.3 Theoretical Total Egress Time

In this section, an example from the latest SBR guideline on the theoretical egress time calculation is provided, which is applied as a reference for actual projects. Following are the description of the relevant steps.

- Step 1: Calculate the number of occupants per floor
- Step 2: The distribution of all users on all the available steps inside the staircase
- Step 3: Calculate the available storage capacity
- Step 4: Total egress time calculation
- Step 5: Check the required time for one floor to descend

**Example**

![Diagram of the example office building](image1)

**BUILDING INFORMATION**

- Floor dimension: $30 \times 35 \text{ m}$
- The highest occupied level: $141.5 \text{ m}$
- Number of floors: 40
- Floor-to-floor height, ground floor: 5 m
- Floor-to-floor height, other floors: 3.5 m
- Number of staircases: 2 staircases
- Widths of the staircases: 1.20 m

**STEP 1: CALCULATE THE NUMBER OF OCCUPANTS PER FLOOR**

<table>
<thead>
<tr>
<th>Usable area</th>
<th>1000 m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupy class B4</td>
<td>12 persons/m²</td>
</tr>
<tr>
<td>Maximum number of persons</td>
<td>83</td>
</tr>
</tbody>
</table>

**STEP 2: THE DISTRIBUTION OF ALL USERS ON ALL THE AVAILABLE STEPS INSIDE THE STAIRCASE**

Number of users in the building: \(40 \times 78 = 3480\)

Number of person per staircase: \(3480 \div 2 = 1740\)

**STEP 3: CHECK THE AVAILABLE STORAGE CAPACITY**

Maximum 4 persons / m² on the platform; 0.9 persons / m / step in Bouwbesluit 2003;

Platform surface per stair: \(2 \times 12.0 \times 2.7 = 6.48 \text{ m}^2\)

Persons on platform per stair: \(6.48 \text{ m}^2 \times 4 \text{ person} / \text{ m}^2 = 25.92 \approx 25 \text{ persons}\)

Persons on the stair: \(0.9 \times 12.0 \times 19 = 20.52 \approx 20 \text{ persons}\)

Total number of persons of the two stairs: \(2 \times (25 + 20) = 90 \text{ persons}\)

Consequently, the capacity of the two staircases is 87 persons.

**STEP 4: TOTAL EGRESS TIME CALCULATION**

In this method, egress time is the time required from the moment that all users begin to evacuate (after the alarm) until everyone get out of the building. According to ABR guideline, we should pay attention to four times that have the most impact on the total evacuation. Different speeds and the flow capacity for the egress time calculation are given as Table 4.

| Speed on the floor, without hindrance | 1.6 m/s |
| Speed on the floor, maximum number of persons | 0.37 m/s |
| Speed on the stair, without hindrance | 0.8 m/s |
| Speed on the stair, maximum number of persons | 0.32 m/s |
| Flow rate capacity | 128 persons/s/m |
a. The first person egress from the floor to the outside of the building
\[ 3 + 1.6 + 11\div 0.8 = 16\text{s} \]
b. The time that all other persons need to get to the exit of the ground floor
\[ 1740 \div \left[1.28 \times (1.2 - 0.3)\right] = 1510\text{s} \]
c. Every 50m height should add 90s
\[ 2 \times 90 = 180\text{s} \]
d. The last person get to the outside
\[ 11 \div 0.37 = 30\text{s} \]
Thus, total egress time is the sum of four aforementioned results, which is:
\[ 16 + 1510 + 180 + 30 = 1736 \text{s} = 28.9\text{min} \]

**STEP 5: CHECK THE REQUIRED TIME FOR ONE FLOOR TO DESCEND**
Assume 60s to reach the subjacent floor, waiting time \(< 30\text{s}\)
Number of persons per floor: 87
Number of persons per staircase: 44
Time for descending one floor: 
\[ 44 \div \left[128 \times (1.2 - 0.3)\right] = 38\text{s} < 1\text{min} \]

**CONCLUSION**
The theoretical egress time is 28.9 minutes. The criteria are met for egress. Egress concept A is applied. No waiting time occurred in more than 30 seconds. This approach is applied based on SBR guideline, which helps the designer to grasp the overall egress time of a building.
3.3 CASE STUDIES OF THREE PROJECTS

With the aim of having a general understanding of fire safety engineering in the Netherlands, three high-rise projects provided by DGMR have been examined, namely, Koningin Julianaplein in The Hague city center, Hoog aan de Maas and Coolsingeltoren in Rotterdam. For each project a brief introduction is given in the beginning, and emphases are put on the aspects with regard to fire compartments, structural fire resistance, fire-resistant rating, egress routes and the theoretical egress time. All projects were provided and consulted by DGMR based on Bouwbesluit 2003 and SBR guideline 2005.

3.3.1 COOLSINGELTOREN, ROTTERDAM

![Coolsingeltoren, Rotterdam]

Figure 14: Coolsingeltoren, Rotterdam

Introduction

Coolsingeltoren is located adjacent to the street Coolsingel, Kruiskade and Stadhuisplein in Rotterdam. It is mainly an office building combined with some commercial spaces, theater and an underground parking garage. The architectural design was accomplished by Atelier d’Architecture Christian de Portzamparc, France, and building physics, fire safety and facade technology consultant was DGMR. According to the Dutch design factors we described in chapter 3.2.12, we can distinguish the following occupancy class:

- Office: B4
- Restaurant and conference room (1st, 2nd floors): gathering function, B3
- Call center (19th floor): office function, B3
- Shops: retail function, B3
- Bicycle storage: B4

There will be maximum 100 persons per floor in Coolsingeltoren. 1st, 2nd, 19th floors are exceptional, which has 180 people each. The parking garage contains 600 places for cars, and 4 floors in total. Thus, there will be a maximum of 150 cars and 300 people per floor (1 car - 2 persons). The entire tower is composed of 36 floors with a bicycle shed at -1st floor,
the Luxor Theater, a low-rise office building at the side of the City Hall (Dutch: Stadhuisplein), an atrium, some shopping spaces on the ground floor, and an underground parking garage with 4 floors. The highest occupied floor is the 36th floor. Both passenger elevators and escalators are applied in this tower. Construction materials regarding fire-protection property are listed below:

- Main load bearing structure: concrete, steel
- Roof structure: concrete, steel
- Roofing: Bituminous, non-flammable roof
- Facade construction: interior finishing (non-combustible), insulation (non-combustible), exterior finishing (glass and non-combustible cladding)
- Interior walls: stone, concrete, partition walls
- Floor: construction material (concrete), insulation (non-combustible materials)
- Ceiling: concrete or non-combustible ceilings
- Stairs: concrete

**Egress concept**

Egress time of high-rise buildings higher than 70m should comply with the additional high-rise fire safety directive SBR as well. According to different requirements, as has been stated, there are four egress concepts in the Netherlands (Chapter 4.1.6). Since the building is not intended for sleeping, and the highest residential area: 100m and 150m respectively, Coolsingeltoren applies Concept A.

**Structural fire protection**

The fire resistance time of the main structure in Coolsingeltoren must under the requirements of Bouwbesluit 2003 of at least 120 minutes. On the basis of SBR, there is no possibility to reduce it. 120 minutes' requirement is not only for the Coolsingeltoren but also for the part of supporting structure beneath the tower and the construction components in the adjacent compartment extend the part of the main structure of the tower. The fire-resistant time of the main building components is demonstrated in Table 5.

**Table 5: Fire resistance time of the main structure in Coolsingeltoren**

<table>
<thead>
<tr>
<th>Building components</th>
<th>Requirement (min)</th>
<th>Fire resistance of the main structure (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Coolsingeltoren</td>
</tr>
<tr>
<td>Coolsingeltoren</td>
<td>120</td>
<td>-</td>
</tr>
<tr>
<td>Luxor theater</td>
<td>90 #</td>
<td>-</td>
</tr>
<tr>
<td>Offices Stadhuisplein</td>
<td>90 #</td>
<td>120</td>
</tr>
<tr>
<td>Commercial areas</td>
<td>90 #</td>
<td>120</td>
</tr>
<tr>
<td>Parking garage</td>
<td>?</td>
<td>120</td>
</tr>
</tbody>
</table>

Attention:

# Reduction of 30 minutes possible on the basis of permanent fire load < 500 MJ/m² and implementation of sprinkler installation all over the building.
Apart from the requirements of the building components, constructional fire safety should also meet certain standards. The construction of vertical shafts is normally 60 minutes fire resistance and protected from the adjacent compartments. As additional requirement in SBR, every 50 meters in the vertical direction shall be sealed with 60 minutes fire resistance separations. The elevator shaft (including the elevator door) should be 60 minutes fire resistance as well. The internal separation between the fire compartments should be 60 minutes fire resistant. All penetrations must be sealed to ensure the requirement of fire resistance, and fire dampers are installed if necessary. Doors in such partitions must be self-closing.

**Fire compartments**

In principle, the size of the fire compartments must in accordance with the rules applicable in Bouwbesluit, which means the maximum area of compartment is 1000m². Technical spaces larger than 50m² form another fire compartment.

**Safe egress**

Egress design of offices in Coolsingeltoren is based on the occupancy of 100 persons per floor, and the occupancy class of B4. The maximum walking distance to an entrance of a smoke compartment in the classified situation is therefore up to 45m. If the offices are used as working function only (they are not further subdivided into residential areas), Dutch regulation stipulates that the maximum walking distance is 30m. For the exceptional floors (1st, 2nd and 19th) when the maximum total population is 180 people, the maximum walking distance is 30m.

![Figure 15: Egress design example in Coolsingeltoren](image-url)
Each standard office floor of Coolsingeltoren was divided into two smoke compartments. Two independent escaping routes per floor are available for each of the two stairways in the scissors staircases.

Egress plan should contain more than two egress routes for the occupants. The smoke compartment on the south (rectangular shape) leads the single egress route through the smoke compartment on the north side to one of the two staircases in the scissors staircases. The other egress route leads the occupants to the elevator lobby in the other stairway of the scissors staircases through a 30 minutes fire resistance protected corridor.

For the smoke compartment on the north side (triangular shape) directly connect to the escape stair in scissors stairs. The other egress route leads to the other stairs in the scissors staircases through the 30 minute fire resistant protected corridor. From the first floor staircase 1 in a 60 minutes fire resistance porch, and two independent escaping routes provided (60 minutes fire resistance separated from each other). One route goes through the reception of Robeco, the other around the core to the 90 minutes fire resistance protected staircase 2 which directly comes out. This endures that even in a fire occurs at the reception in Robeco, there is still a safe egress through stair 1 can be guaranteed. Stair 2 on the 1st floor leads to a 90 minutes fire protected stairway that leads directly to the adjacent site.

As stated from egress concept A in SBR guideline, it must be determined whether the total egress time is less than 15 minutes or not. If necessary, a longer clearance time of up to 20 minutes\textsuperscript{10} or 30 minutes\textsuperscript{11} is still allowed. According to Bouwbesluit, the egress time is determined using a flow capacity of 45 persons per meter width of the step per minute.

\textsuperscript{10} 20 minutes: with the help of a pressurisation system.

\textsuperscript{11} 30 minutes: with the help of safety staircase.
3.3.2 Koningin Julianaplein, The Hague

Introduction

Koningin Julianaplein is mixed-use tower situated at the square in front of the Hague central station, close to the New Babylon tower and Rijnstraat. Four towers altogether composed Koningin Julianaplein, two containing a total of 179 apartments and two larger office towers. Apart from offices and dwellings, the multi-functional towers also consist of restaurant, auditorium, retailing, conference spaces, bicycle and car parks. The architectural design was done by OMA, Rotterdam, and building physics and fire safety consultant was DGMR. According to the Dutch design factors we described in chapter 3.3.1.2, we can distinguish the following occupancy class:

- Office: B3 (20%) and B4 (80%)
- Restaurant and conference floor (22th floor) in the office tower: B3
- Auditoria in the office tower: gathering function, B1
- Commercial spaces: retail and gathering function, B1/B2/B3
- Storage room and bicycle storage: B4
- Bicycle shop: retail function, B3
- Parking garage: B4

In consultation with the client (City of The Hague/Multi Vastgoed, Gouda/NS Vastgoed, Utrecht), 80% of the tower applies B4 occupancy class, while 20% applies B3.

Two residential towers with 26 floors meet and merge from the 20th floor, forming a continuous curving structure. Office tower had 20 floors each, and connected from the 18th and the 19th floor. Retail spaces are adjacent to the OV-terminal with two levels. Below ground, there will be four levels of public car parking, including space for 6,000 bicycles on top. During the design stage, these towers were marked as tower 1, 2, 3 and 4, which is illustrated in Figure 14.
Egress as Part of Fire Safety in High-rise Buildings

Figure 17: Koningin Julianaplein - Tower 1, 2, 3 and 4

The highest occupied area in tower 1 and 2 (office towers) is the 22nd floor with the height of 81 m above ground. While for tower 3 and 4 (residential towers), the 26th floor is the highest, at a height of 81 m as well. The parking garage was placed at approximately 12.15 m beneath the street level, which is the lowest -4th floor.

Structural fire protection

For the four towers, the fire resistant time of the main load bearing structure must be at least 120 minutes based on Bouwbesluit 2003. If automatic sprinkler system is applied, SBR indicates that a reduction of 30 minutes can be possible when the permanent fire load is lower than 500MJ/m² and meanwhile the building should be fully sprinklered. This requirement shall be not only applied to the main towers, but also for the portion that directly beneath them. In the vertical direction, the fire compartment in the office towers goes no more than one floor. According to NEN6068, each dwelling forms a separate fire compartment. The summary of the structural fire safety requirements is demonstrated in Table 6.

Table 6: Fire resistance time of the main structure in Koningin Julianaplein

<table>
<thead>
<tr>
<th>Building components</th>
<th>Requirement (min)</th>
<th>Fire resistance of the main structure (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Office tower 1 &amp; 2</td>
</tr>
<tr>
<td>Office tower 1 &amp; 2</td>
<td>120 #</td>
<td>-</td>
</tr>
<tr>
<td>Residential tower 3 &amp; 4</td>
<td>120</td>
<td>-</td>
</tr>
<tr>
<td>Parking garage</td>
<td>120</td>
<td>120 #</td>
</tr>
<tr>
<td>Retail areas</td>
<td>30</td>
<td>-</td>
</tr>
</tbody>
</table>

Attention:

# Reduction of 30 minutes possible on the basis of permanent fire load \(<500MJ/m²\) and implementation of sprinkler installation all over the building

The internal separation between the fire compartments should be 60 minutes fire resistant. Penetrations through fire compartment must be sealed, and installed with fire dampers if necessary. Doors in such partitions must be self-closing.
Safe egress

The SBR guideline specifies that in an office for example, the evacuation usually start 2 minutes after the early warning in reality. In residential buildings, it takes even longer. The maximum descending time for one floor is 1 minute. In addition, the required time for all people to enter the staircase should be less than 30 seconds.

OFFICE TOWERS

According to calculation from DGMR, the theoretical clearance time for stairway 1 in tower 1 is up to 11:53 and 12:01 for stairway 2. However, the 15th floor is an exception because of the auditorium. Attention should be paid to the storage capacity. Calculation by DGMR demonstrates that the maximum theoretical egress time for stairway 1 and 2 is 20:45 and 20:40, respectively. According to egress concept A, the maximum allowed theoretical egress time is 23 minutes. The two office towers therefore conform to egress concept A in SBR.

RESIDENTIAL TOWERS

In the residential towers, calculation was on the basis of 3 persons per dwelling. The total designate number of occupants is 284 in tower 3 and 286 in tower 4. Calculation from DGMR indicated that in tower 3, the free walk egress time is 5:35 (5:44 in tower 4). When taking hindrance into account, for instance congestion or any other accidents that prolong the egress time, the theoretical egress time was extended to 13:22. But this is a conservative assumption, since the occupant density in these towers is quite low, the actual egress time is closer to the calculated result without hindrance. The average egress time based on the duration exceeds to 9:29. Based on the above, the theoretical clearance time of tower 3 is 9:29. According to egress concept A, the maximum allowed theoretical egress time is 23 minutes. The two residential towers therefore conform to egress concept A in SBR.

Horizontal travel distance

As has been stated, egress concept A has been applied in all the towers. For the residential egress design, the maximum walking distance from the access of a corridor to an entrance of the dwelling must not exceed 15 meters. This requirement can be met everywhere in the residential towers.

The occupancy class for office tower is B4. The maximum walking distance is 45m. For B3 class, the distance can be up to 30m. Two egress routes shall be available for all dwellings in the residential tower. There should be two separate egress routes and at least two exits on the ground floor.

Fire compartment

The size of fire compartments in buildings higher than 70 m must in principle comply with the rules applicable to them from the Bouwbesluit 2003. This means that the size of a fire

\[\text{11:53 represents 11 minutes and 53 seconds (mm:ss), the following times are all expressed in this way.}\]
compartments is up to 1000m². Preferably, each floor is thereby considered as a separate compartment. Technical areas greater than 50m² must be in a separate compartment.

Figure 18: Fire compartment example in Koningin Julianaplein
3.3.3 **HOOG AAN DE MAAS, ROTTERDAM**

![Figure 19: Hoog aan de Maas, Rotterdam](image)

**Introduction**

Hoog aan de Maas is designed above an existing building near Boompjes street along the Nieuwe Maas River. The huge columns are situated between the Terwenakker and Scheepmakershaven. The panoramic facade faces the river. It is an office building with two residential floors at the top (the 20th and 21st floor). The architectural design was done by 01-10 Architecten B.V. in Rotterdam, and DGMR was in charge of the building physics and fire safety consultation. According to the Dutch design factors we described in chapter 3.3.1.2, we can distinguish the following occupancy class:

- Office: B4
- Residential: 20th and 21st floor. Residential is calculated as maximum 30 occupants per dwelling, which is determined by the worst-case situation.
- Bicycle storage: B4
- Storage room: B4

In Hoog aan de Maas, the highest occupied area is 71.2m (21st floor) over the level of Boompjes. Since the ground floor is 2.4m beneath this level, the highest occupied level is 73.6m.
Structural fire protection
Under the requirements of Bouwbesluit 2003, the fire resistant time of the main load bearing structure in Hoog aan de Maas shall be at least 120 minutes. Each floor forms a separate fire compartment. Since Hoog aan de Maas is a unique project, which would be constructed on an existing structure, the floors above serve as part of the load-bearing structure. DGMR suggested that after 60 minutes’ igniting, the failure of one upper floor may not lead to the collapse of the floors below and/or the steel load-bearing structure. With the condition that the failure of an upper floor will not lead to progressive collapse, the fire resistant time for the main structure was reduced to 60 minutes.

Egress concept
The theoretical egress time calculation corresponds with egress concept A in SBR. As a result, the entire building should be vacated within 30 minutes after the outbreak of a fire. All occupants shall evacuate simultaneously.

The following example of Figure 17 illustrates the standard office floor (from the 12th to 19th floor) in Hoog aan de Maas. Each floor has been divided into two smoke compartments. Owing to the 30 minutes fire-resistant screen in the elevator hall, two independent egress routes are available in order to access the two stairways in the scissors staircase. In this example, attention should be paid to the following locations:

1. Fire compartment should be surrounded by 60 minutes fire resistant enclosure on all sides. In this case, fire compartment was regarded as an elevator hall. According to NEN-EN 1364 part 4, the door of the elevator hall shall meet the standard of B60 and R30 at the same time (60 minutes fire resistance and 30 minutes smoke resistance).
2. 30 minutes fire resistant wall should be added in between the two stairways.
(3) 30 minutes smoke resistant screen.

(4) According to NEN 6075, the big fire compartment was divided into three smoke compartments (sub-fire compartment). The partition should be fire and smoke resistant. And the required smoke resistant time is 30 minutes. This partition reduced the travel distance for SC-1 occupants, and ensures the safety of these people.

(5) As same as (4).

Fire compartment

The design size of fire compartment in high-rise buildings is up to 1000m². The two residential floors locate on top of the building, which is around 70m above ground. Each floor forms a separate fire compartment, which is also the sub fire compartment of every dwelling. Office floors in Hoog aan de Maas is equipped with automatic sprinkler system. Sprinkler installation for residential areas is omitted since the requirement for sprinklered dwelling building is 100m high.

WBDBO: Resistance of fire spread through compartment and through wall. (Dutch: Weerstand bij Branddoorslag en Brandoverslag)
3.4 SYNTHESIS AND CONCLUSION

This chapter begins with a description of fire safety design in the Netherlands. We recited three high-rise projects which were designed according to the legal requirements in Dutch building code Bouwbesluit 2003/2012, SBR guideline 2005 and relevant NEN norms. Lastly, to conclude this chapter, a synthesis and a review upon the three projects with respect to the Dutch fire safety design are going to be presented.

3.4.1 SYNTHESIS

In the Netherlands, buildings higher than 70 meters are generally classified into three categories: 70m-100m, 100m-150m and above 150m. Building height is one of the bases of selecting an appropriate egress concept. As has been mentioned, Coolsingeltoren, Koningin Julianaplein and Hoog aan de Maas has 36, 26, and 21 floors each, with the height of 156m, 87.6m and 78m, respectively. All the three projects applied egress concept A, simultaneous full evacuation, according to SBR.

SBR egress concepts

Even though four egress concepts are presented within SBR, in the Netherlands phased evacuation and stay-in-place are seldom adopted, which stand for concept C and D. A summary of egress concept A, B and C is given in Figure 22.
Most of the Dutch projects apply concepts A and B relating to full evacuation simultaneous evacuation so that all occupants eventually leave the building using stairs. One of the reasons for this is that the number of high-rise buildings in the Netherlands is fewer in comparison with some Asian countries and the United States. Typical Dutch residential houses do not exceed 5 floors (Figure 23), while apartment buildings are around 10 to 15 floors. Most high-rise buildings are constructed in big cities like The Hague and Rotterdam (Figure 24).

![Figure 23: Typical Dutch dwellings (left); apartment buildings in Delft (right)](image)

![Figure 24: Skyline of Rotterdam](image)

Indeed, full evacuation is the safest tactic with respect to low-rise and uncomplicated buildings. There is room to improve and combine various concepts and vertical egress facilities in the modern high-rise projects. Correlated subjects with respect to different egress strategies from an international viewpoint will be elaborated further in chapter 4.

**Compartments and travel distance**

The structure should be divided into different fire compartments with a maximum area of circa 1000m² each. In case of fire, all occupants on the fire floor leave their room using the unblocked exit(s) to reach the adjacent compartment, usually within dozens of seconds or one minute. The construction of fire compartments should meet certain standards so as to limit the spread of fire. Mostly, high-rise buildings contain larger compartments, which lead to longer horizontal travel distance. On account of the life safety, separate the fire compartments with smoke proof partitions or additional exits are requisite in some cases.

Bouwbesluit 2012 regulates the time for people to reach the stairwell door within one minute, and the maximum walking distance inside one compartment shall not exceed 30
Egress as Part of Fire Safety in High-rise Buildings

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meters. Few exceptions like parking garages or other places with lower occupancy, design of travel distance can be prolonged to 45 meters. Automatic sprinkler systems can reasonably be expected as guarantee of providing sufficient protection to evacuating occupants. Attention should be drawn to the two egress directions inside a building, both horizontal and vertical, and transformed into well-designed fire protected routing.

**Table 7: Egress directions**

<table>
<thead>
<tr>
<th>Horizontal egress</th>
<th>Vertical egress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside the room</td>
<td>In the stairwell</td>
</tr>
<tr>
<td>On each floor</td>
<td>In the elevator</td>
</tr>
<tr>
<td></td>
<td>Or other vertical passes</td>
</tr>
</tbody>
</table>

Furthermore, the direction of traffic relates to the number of users per floor, the quantity of available emergency stairwells, and the floor directly exposed to fire. In the Netherlands, much attention is paid on the vertical egress and the time of the last person passing the ground floor exit.

**Structural requirements**

Similar to the load bearing structure, fire compartments shall remain integrity within a requisite time period during a fire. This time period allows occupants to escape, as well as the fire department to rescue people and extinguish the fire. Compartment boundaries are the crucial components that could ensure egress safety, which must be thereby sealed. The structural elements of a compartment would only be affected if a fire grew into flashover. Concluded from the abovementioned projects, the general structural fire-resistant time is summarized in Table 8.

**Table 8: Fire resistance time of the structure**

<table>
<thead>
<tr>
<th>Building components</th>
<th>Fire-resistant time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main load bearing structure</td>
<td>120</td>
</tr>
<tr>
<td>Shafts</td>
<td>60</td>
</tr>
<tr>
<td>Smoke proof separations</td>
<td>30</td>
</tr>
<tr>
<td>Fire separations</td>
<td>60</td>
</tr>
</tbody>
</table>

Egress routes are closely linked to human safety. Sometimes the level of the fire protection increases along with the height of the building. In terms of vertical egress, staircases are shielded from compartments by generally 60 minutes fire-resistant walls and self-closing doors. Depending on the situation, additional sluices and pressurization system can be necessary in evacuation stairs.

All components should be certified for each specific requirement before applied. The broad use of the structural fire-resistant rating is sometimes equated with the time that the element can withstand in fires. The fire resistance period was achieved by the standard fire test (follow the standard temperature-time curve in ISO or other national norms). It should be noted that, for instance 60-minute period, cannot be linked directly to a structural failure after 60 minutes. Fire-resistant level of a structural component must be much higher than
Whenever the structure will collapse is depended upon numerous parameters, which encompasses the environment, the condition of the construction (new or old), available burning material and so on. As a matter of fact, the fire tests are intended to evaluate the duration for the element retains its structural integrity, measure the transmission of heat, hot gases through the test specimen, and radiation at the unexposed side of the specimen. Fire test ends until the structure collapse or there is break based on different fire codes. 30 minutes intervals are normally used on account of the uniform standards.

3.4.2 CONCLUSION

To sum up, the three projects demonstrated in this chapter helped us to comprehend the Dutch egress design method. Through working in DGMR, we summarized the general step-by-step fire safety design procedures in the Netherlands:

1) Obtain information from the architect: such as floor plan, building height, number of floors, dimensions of the building elements, the functions of the building, number of expected occupants et cetera;
2) Analyze the structure: from the point of view of civil engineering, involving separate main structure and non-load-bearing structure;
3) Analyze the construction materials, and make sure that they are not combustible or they can fulfill the Dutch standard;
4) Divide fire compartments: depend on the allowable compartment area, travel distance, building function in light of national codes;
5) Analyze how the fire spreads and calculate the heat flux from the flames;
6) Propose egress plan(s): determine the reasonable routing, travel distance, structural fire resistance and calculate theoretical egress time;
7) Check the flow and storage capacity for doors, corridors, staircases and other fire exits, and adjust the unsatisfactory ones;
8) Determine fire safety installations: for example, sprinkler system, fire damper, smoke detector, alarm and communication system et cetera;
9) Approach plan for the fire department, provide the routes for finding the fire location;
10) Conclusion and advice for the client.

Currently, it is not recommended to use elevator during evacuation in the Netherlands. For one thing, elevator shaft can be a vertical chimney in some extreme cases, and special protection measures must be applied. For another, elevator-assisted evacuation can be a waste of time due to the height of most Dutch buildings. People would rather leave the building by stairs than spend much time on waiting for the elevator. Many investigations have been done in order to make much safer and efficient egress plans. The following chapters will develop different kinds of egress strategies with integrated vertical egress methods. Furthermore, whether the egress concept is apposite relates to the number of floors, the height of the building, occupancy class, construction requirement, floor layout and fire installation system et cetera. For future design, we should consider all these factors with a broader and integral look.
4

WORLDWIDE FIRE SAFETY DESIGN
4.1 INTRODUCTION

In reality, not all the countries have the same prescriptions for a given issue. As we have discussed the Dutch fire safety design, this chapter examines the basic egress concepts from the global point of view. Fire safety design will be substantiated by case studies of some well-known towers. Attention will be drawn to means of egress, vertical egress methods, different types of egress strategies, fire drills and two high-rise fire examples. This is then followed by a brief review of the fire codes and standards from various countries. To end with, some other essential design issues regarding egress design are presented.

4.1.1 MEANS OF EGRESS

Egress composes of various spaces. All these spaces are connected by doors, corridors and traffic areas. Means of egress consists of an exit access, a common use of corridor leading to the exit, the exit itself and exit discharge such as doors or protected corridors leading to the outside \(7\). Generally speaking, a great deal of relevant issues has impact on means of egress, which can be categorized into two groups: architectural and human factors. This topic can be best treated under the key aspects listed below.

Architectural factors

The Geography of the Structure has critical impact on means of egress, such as the building height, number of floors, floor layout, net occupiable area, the arrangement of exits, as well as the interior decoration, emergency lighting et cetera. All building elements shall meet the certain dimension standard to ensure the egress safety. Most aspects are determined by the Occupant Load, which is the total number of people expected to be in the building, or on a certain floor. Depending on the function of each floor, occupant load varies from parking garage (very low) to theater (relatively higher), which is also the design basis of the dimensions of transportation and circulation. Occupant load can be either provided by the client, or calculated by fire specialists according to different occupancies.

Human factors

Apart from the architectural and engineering features, Human Behavior is another primary concern in pedestrian safety. The issue has grown in importance in light of recent egress research. Upon an alarm, occupants' response, travel speed, ability to navigate and make decision have significant effects on the total egress time. However, it is a complicated issue since individuals' reaction varies from age, gender, characteristics and the fire situation. In addition to that, Environmental Factors highly correlate with the behavior of occupants. Heat, irritant, toxicity, and the smoke density would be obstacles during evacuation, which emphasized the role of fire-prevention and smoke extraction system.
4.1.2 Design Principles

It is possible to design skyscrapers with large dimension and insure adequate safety at the same time. Summarized from the three previous Dutch projects and literature (7), a number of egress design principles are explained in this section. Comprehending the underlying principles facilitate the fire safety engineers to achieve a better design.

Safety

The primary concern within egress design is human safety for both the building users and the fire fighters. Occupants should be able to move away from a fire to any locations that are relatively safe. Leaving the building seems to be the safest way. But in high-rise buildings, it is also possible to relocate at an unaffected space depends on the fire situation and local legislation. On the other hand, the safety of fire fighters and other emergency first responder personnel need to be considered. Statistical data indicates that on average 40,270 fire fighters were injured during fire ground operations in the United States annually from 2003 through 2006 (78). After all, the prerequisite of ensuring human safety is that the structure needs to remain intact in fires and assure a certain fire-resistant period.

Escape routes

In spite of the building height, most buildings should provide at least two well-defined escape routes. The escape route encompasses corridors, ramps, stairs and other circulations inside the building. If one route is blocked by flames or smoke, at least evacuees can escape via the other one. Each of them shall be protected and terminate outside the building. In particular for high-rise buildings, multiple and protected escape routes are of great importance. Meanwhile, confusing elements along the route must be avoided so that they can remain intact, unambiguous and unobstructed. Otherwise a large number of occupants will be stuck at the fire floor once they cannot pass through, and leading to uncertain risk.

Escape distance

Well-designed vertical and horizontal travel distances contribute to the egress efficiency in fires. Limited escape distance could avoid exposing occupants to smoke and other unnecessary hazard. In case of a high-rise fire, the smoke temperature can be extremely hot and reaches 1300°C. Egress under such high temperature leads to seriously harm to evacuees14.

In short, the above-mentioned principles are the design basis. Occupants should be able to escape or to be rescued from fire in its early stage (14), which is the essence of fire egress. In addition to that, egress design has to be integrated with building installation system, which controls the fire spread, limit the fire area and provide a better condition in egress.

4.2 EGRESS STRATEGIES

It is necessary here to clarify exactly what is meant by egress strategies in this research, which may be defined as the evacuation process on the basis of evacuation starting time. It is basically a plan to get out of a situation. The entire population can either start their evacuation altogether at once or step-by-step. Sometimes egress strategies can be categorized into the population of evacuees as well (Table 9). This section gives an overview about different types of egress strategies that can be employed in our further research.

Table 9: Different types of egress strategies

<table>
<thead>
<tr>
<th>By the time occupants start to evacuate</th>
<th>By the population of evacuees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simultaneous evacuation</td>
<td>Total evacuation</td>
</tr>
<tr>
<td>Phased evacuation</td>
<td>Partial evacuation</td>
</tr>
</tbody>
</table>

4.2.1 SIMULTANEOUS EVACUATION

Simultaneous evacuation strategy aims to evacuate all the people at the same. The egress process is single staged initiated by the sounding of the alarm over the fire warning system, which is activated simultaneously on each floor. Evacuation of the entire building is the simplest strategy to implement [18].

4.2.2 PHASED EVACUATION

As the name implies, phased evacuation is implemented in the time sequence, which is based on keeping a large number of occupants in place and moving those directly impacted by the fire. It allows occupants on the fire floor and the most affected floors evacuate at once. If there is no alarm signal, remaining occupants may not even be immediately aware that a fire event occurred. While the rest of the building could either exit later or stay, provided that the fire is kept under control.

4.2.3 RELOCATION

Since a great deal of incidents will be somewhat localized, sometimes vacate the entire building is unnecessary. Relocation is only conducted in where a fire is located and its adjacent zone by fire department or the rescue team. They will lead the occupants to a floor from which they can be safely sheltered from the fire.
4.2.4 PROTECTION-IN-PLACE

Different from the relocation strategy, the emergency egress takes place only in the affected zone in a protection-in-place strategy, which means only the fire floor are requested to leave the building. As a result, protection-in-place strategy typically relies on a combination of active and passive fire-protection features to ensure safety. Besides, this strategy is also called stay-in-place or defend-in-place.

4.3 VERTICAL EGRESS APPROACHES

In this research, the term ‘vertical egress approaches’ tends to be used to refer to the vertical means of egress apparatus. The conventional awareness with regard to evacuation implies 'In case of fire, do not use the elevators'. Nevertheless, instead of egress by stairs only, there are more types of egress approaches today. Some combinations can be much efficient in a fire egress. This section is intended to discuss different possibilities in fire egress.

4.3.1 STAIRCASE

Traveling through stairway is the most common vertical egress method. To guarantee adequate flow and storage capacity, stairway width and size of the landing shall be designed in accordance with the occupant load and local regulations. The elevated height and total building evacuation of all occupants result in an extensive queuing before discharge in the staircases (18). There can be significant delays and crowding in the stairs for simultaneous full evacuation (10). Consequently the dimension of stairwell should have a required capacity that all occupants could egress at the same time. Emergency staircase typically forms a fire-protected enclosure separated from the main building by self-closing fire doors. With the purpose of smoke prevention, most emergency staircases are equipped with smoke prevented lobby. In high-rise buildings, pressurization and smoke extraction system is also necessary.

Figure 25: Smoke protected staircases without natural ventilation
The staircase route shall be adequately illuminated at all times to ensure safety, and extra measures can be taken. Figure 26 illustrates the emergency stairs with illuminated lighting strips.

![Figure 26: Emergency stairs with illuminated lighting strips](image)

In addition to escape via enclosed stairwell, another possibility is stairs that leading to outdoor platforms or balconies. No matter what kind of stair is used, it shall be free from all obstruction at any time.

### 4.3.2 Elevator

Elevators can be generally grouped in two divisions according to the users: fire service and passengers (building users). Since the 1980s, elevator has been designated to be used by firefighters during firefighting operation in many countries. Today, most elevators can be switched to ‘fire service mode’ that allows fire fighters to approach the fire floor. In terms of skyscrapers, elevator egress may be the only option for some elderly or people on wheelchairs. Meanwhile, it is compulsory to take extra protection measures as long as the elevator serves during fires. In order to speed up fire evacuation, modifications to current building and fire codes such as the application of elevators has gained considerable attention in recent years around the world (4). As a result, the concept of an emergency elevator evacuation system (EEES) is developed. This system indicates that emergency elevators should include the

> When incorporating elevators into fire evacuation it is important to exploit their strengths while protecting their weaknesses. The typical design metric for elevators in a modern high rise commercial building is to provide sufficient car capacity and speed to be capable of moving 10% of the total population of the building in 5 minutes during peak times at the start and end of the work day.

> Elevators are most efficient when operating in shuttle mode (avoiding time needed for accelerating and decelerating smoothly). Further, it makes sense to use the elevators to move those with the longest distance to go, first (23).
protection from heat, flame, smoke, water, overhang of elevator machine room equipment, and loss of electrical power (105). Chapter 4.6.8 will elaborate this topic further.

4.3.3 **HELICOPTER**

Helipad is a landing area or platform for helicopters, which can be placed on top of skyscrapers so as to rescue people in emergency situations. For example, the MGM Grand fire\textsuperscript{15}, which will be discussed specifically in chapter 4.4.4, approximately 1000 people were rescued by helicopter from the roof and balconies of the MGM Grand. More than 300 people on the rooftop were rescued. Since hundreds of hotel guests were trapped on the upper floors at that time, helicopters were the only way to rescue the guests. The total evacuation of the building took nearly four hours.

Besides, not only is helipad a way of egress, but also used for leisure. Burj Al Arab converted its helipad into a tennis court in preparation for the 2005 Dubai Championships.

![Helicopter pad on Burj Al Arab](image)

*Figure 27: Helicopter pad on Burj Al Arab*

\textsuperscript{15} MGM Grand fire: A fire broke out in MGM Grand Hotel, Nevada, USA 1980. It killed 85 people and lead to more than 700 injuries.
4.3.4 ESCAPE CHUTE

Escape chute can be applied from high areas that provide a relatively rapid means of emergency evacuation \((139)\). Occupants can use to reach the safe exterior location in fires. Typically, escape chute is a flexible cylindrical device made of fire-resistant fabric or netting \((138)\). It offers fireproof and high temperature-proof at the same time \((107)\). Presently, escape chute became an accepted alternative means of emergency evacuation from high-rise buildings and industrial plant.

![Figure 28: Sliding in the escape chute](image)

Chutes can be designed with single or multiple entries. Sometimes one chute serves many floors and occupants can gain access to the chute at each floor. The chute can be installed in segment at each floor level inside a fire-protected shaft, one segment of chute per floor, from the top to the ground floor on the same vertical line. There are no mechanical devices used to deploy chutes. Since it requires little instruction, deploying the chute can be quick and easy as stated below \((143)\):

- Open the escape chute door;
- Take several steps forward, crouch down and place your lower legs into the chute;
- Push your body forward to enter the chute system;
- Egress is accomplished by sliding down the chute.

![Figure 29: Speed up and slow down the escape chute (1), activation of a chute (2, 3)](image)

Evacuees can adjust the speed by increase and relax the pressure \((1107)\). Experiments show that escape chute can bring evacuee more safety and escape efficiency \((107)\). It can be of a permanent device with no length and height constraints \((133)\). At present, the longest one in use is 165m at the Nation Tower, Bangkok, Thailand.
4.3.5 Abseiling

Abseiling evacuation plan for towers takes place outside along the cable. It is the process of sliding down a rope under controlled conditions [141]. However, it can be considered as an option but not very common. Also, evacuees must ensure that they buckled the rope in a proper way. Another problem for high-rise egress is the high wind speed at the upper floors, especially in the Netherlands. Wind load on facades can higher the risk and involving more potential difficulties.

Figure 30: Abseiling evacuation

Sometimes people go abseiling for entertainment or donation to charity. Some towers provide this activity such as the Euromast tower in Rotterdam (the Netherlands), Guy’s and St Thomas’ Hospital in London and Spinnaker tower in Portsmouth (the United Kingdom) et cetera.

Figure 31: Abseiling AMP building in Sydney, Australia
4.4 Case Studies

4.4.1 Petronas Twin Towers

The Petronas twin towers were designed in accordance with a combination of the United States and British standards (87). The two towers jointed at the 41st and 42nd floors by a skybridge, shown in Figure 33. Both towers have a reinforced concrete core. There are 10 escalators and 29 double-deck high speed passenger elevators in each tower. Besides, both towers were equipped with fire-fighter elevators (92).

- Number of floors: 88
- Height: 452m
- Length of the skybridge: 58.4m
- Height of the skybridge (41st floor) from street level: 170m
- Stairs: 765 flights
- Functions: office,
- Total built-up area: 395,000m²
- Weight per tower: 300,000t
- Two annexes: 186,000m²
- Usable area: 213,750m² per tower
- Start of project planning: 1992
- Official opening: 1999

Egress route

At least two means of egress routes have been provided for each floor. The skybridge connecting the two Petronas towers serves as a horizontal transfer of occupants between the towers in a fire condition. With the aim of reducing the egress time during an emergency situation, occupants in the affected tower underneath the skybridge are designed to reach the level of exit discharge by stairs. People locate at or above the skybridge travel down to the bridge by stairs, then cross the bridge and relocate to the other unaffected tower. Further egress can be done by passenger elevators and stairs.
Egress plans
As we can see from Figure 34, the typical floor plan has three stairwells (red marks). The occupant loads on the upper floors decrease with height. Engineers proposed three egress plans for Petronas twin towers in case of fire.

Figure 34: Typical floor plan of Petronas twin towers

Figure 35 illustrates egress plan I. Presuming that the 66th floor catches on fire:

- Occupants from one floor above and one floor below are required to leave and re-enter the building to the temporary refuge floor respectively (TRF: the 62nd and 63rd floor). These occupants will then remain on alert and await further instruction;
- Occupants from two levels above and two levels below the fire floor (the 68th and 64th floor) will be alerted via announcements and prepare for escaping. If the fire department is able to control the fire, all clear instructions from the Central Fire Command Room will be issued and the occupants will be allowed to return to their floors via stairs and the passenger elevators.

However, if the fire cannot be contained, full evacuation is needed. The skybridge connecting the two towers serves as an integral part of the building's egress design, which leads to the egress plan II. Each tower was divided into four evacuating zones, and the egress process for each zone is described as follows:

- Low zone (Ground floor to the 37F): go down to the concourse by stairs, exit and assemble at the KLCC park;
- Middle zone (40F to 60F): down the stairwells to the 41st floor, across over the skybridge, use shuttle lifts to reach the ground floor, exit and assemble at KLCC park;
- High zone (61F to 77F): down the stairwells to the 42nd floor, cross over the skybridge, use shuttle lifts
to Mezzanine, exit and assemble at KLCC park:
- Top zone (78°F to 86°F): similar to high zone evacuation.

Figure 36: KLCC Park

Since the aforementioned egress plans were all related to the skybridge, in plan III consideration should be given to the unworkability of the skybridge. Thus, occupants from 40F to 60F need to get down to the 41st floor by stairways and use the shuttle lifts to reach the grade. Both high zone and top zone walk down to the 42nd floor via stairs, and as well as the middle zone, they transit to the shuttle lift under the skybridge.

Shortly after the 9/11 event, Petronas Twin Towers received a bomb thread forcing an evacuation of the building. However, it took longer than expected. Experts responded by designing and implementing a new escape plan using the lifts that halved the evacuation time to 20 minutes. Therefore in the new egress design of the towers, 76 fire elevators will be applied in the event of a fire (33).

Summary
Partial evacuation and full evacuation strategy are both concerned in Petronas Twin Towers. The application of full evacuation depends on whether the fire can be extinguished. Traveling from more than 80 levels down to the ground is exhausted, and people might get injured during fleeing. The enclosed elevator shaft should be unaffected in the twin towers. As a result, the three egress plans combined the using of stairs and elevators. People under the skybridge (41st floor) use the shuttle lifts in the annexes. The objective of giving different alarms in different areas is to keep pedestrians in their original locations for a certain amount of time, and avoid arrivals at the merging areas simultaneously. Beside, in high-rise buildings, considerations will also be given to occupants’ movement and dispersion once they leave the building. Occupants in the Petronas Twin Towers are distributed to the nearest park, but not re-enter the building.

Figure 37: Egress plan 2
4.4.2 **TAIPEI 101 TOWER**

![Taipei 101 Tower](image)

- Number of floors: 101 floors above ground, 5 floors underground
- Height: 509m
- Highest occupied floor: 438m
- Office area: 198,347m²
- Retail area: 77,033m²
- Parking garage: 83,000m² for more than 1,800 vehicles
- Sky lobbies: 35F, 36F, 59F, 60F
- Construction started: 1999
- Completion: 2004

Multi-function makes the Taipei 101 a vertical city. Every day it attracts 10,000 to 40,000 people working or visiting. The building consists of the tower and podium above. The tower is for office usage (9F to 84F); the podium is a shopping mall, which filled with boutique stores.

**Fire protection**

In Taipei 101, firewalls, shutters and protective wall fillings divide building into discrete fire zones. Automatic sprinkler system is equipped on all floors throughout the building. Each floor has fire hydrants and fire extinguishers. Foam fire extinguishers are installed in the parking garage.

Mechanical floors locate in every 8 floors. Each mechanical floor has two fireproof refuge rooms (Figure 39), which are connected by an outdoor balcony, except for the refuge rooms on 25th floor. Office floors and the main escape routes are protected by smoke exhaust system. Lifts for the fire department serve from the basement to the top floor (l35).

There are 50 escalators in the tower, 27 single-deck and 34 double-deck. Layout of the vertical transportation system is shown in Figure 40. Two emergency elevators are applied as means of egress in higher floors, and two emergency staircases with automatic smoke extraction system.

![Fire protection system](image)
**Egress route**

In the layout of the tower, pressurized corridors on two sides of each floor and pressurized staircases provide the major emergency evacuation routes for the occupants. People can also use elevator to escape. Fire service elevators are provided from the basement to the top floor. Furthermore, an outdoor refuge platform and a safety refuge space exist on the engine floor (89).

**Egress time**

Preliminary investigation in 2010 was undertaken by the Council on Tall Buildings and Urban Habitat (CTBUH), the original traditional evacuation plan for Taipei 101 is by means of staircase. An evacuation drill conducted before the building neared completion resulted in an egress time of about 2 hours. With the intention of figuring out whether the time can be reduced, Taipei Fire Department ran another drill incorporating the elevators. The evacuation time was limited to 57 minutes, which became the egress plan used when the building opened (33).

**Summary**

The tower has 101 floors above ground. Sometimes full evacuation it is not efficient. As a result, people can be relocated to some refuge areas like Taipei 101 tower. The refuge floors locate at about 15 floors interval, which used as the sky lobbies.

As indicated from Taipei 101 fire drill, the total egress time reduced by half when elevators were integrated. Additionally, when an emergency takes place, stairs used on lower floors and elevators used on higher floors can greatly shorten the time of escaping (104).

![Figure 40: Vertical transportation](image)
4.4.3 Shanghai World Financial Center

- Height: Architectural 492m, occupied 474m, observatory 474m
- Number of floors: 101 above ground, 3 underground
- Number of Elevators: 91
- Top Elevator Speed: 10 m/s
- Tower GFA: 381,600m²
- Units/Rooms: 300
- Function: hotel, office
- Start of Construction: 1997
- Completion: 2008

Shanghai World Financial Center (SWFC) is a mixed-use skyscraper, comprising of offices, hotels, conference rooms and shopping malls. The observation deck was regarded as the highest in the world in 2008, which offers views from 474 meters above ground (137).

Fire protection

Anti-smoke system was installed in SWFC, which prevents smoke propagating to the refuge floors. Sprinklers, smoke detectors, smoke exhaust ducts, and emergency public address speakers were equipped in compliance with the national and local fire codes.

Egress method

Originally, the two panorama elevators running on the diagonal corners of the SWFC were designed to provide express service only to the observation deck at the top. However, they were modified to stop at each of the fireproof refuge floors for egress during fire. Occupants can be relocated to sky lobbies which serve as refuge floors. As can be seen from Figure 42, the furthest vertical distance an occupant needs to travel in the stairs is 25 floors. In addition, those who are not
capable to reach a refuge floor by stairs would be picked up by a fire-fighter driving interior elevator.

Figure 42: Elevator plan and sky lobbies in SWFC

**Egress experiments**

Table 10 demonstrated the floor information and building height. Three egress experiments in SWFC took place in January, 2010 (48).

**Table 10: Heights and functions of different floor intervals**

<table>
<thead>
<tr>
<th>Floor interval</th>
<th>Height (m)</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>101 - 89</td>
<td>77.25</td>
<td>Hotel and sightseeing</td>
</tr>
<tr>
<td>89 - 78</td>
<td>54.25</td>
<td></td>
</tr>
<tr>
<td>78 - 66</td>
<td>50.4</td>
<td>Business office</td>
</tr>
<tr>
<td>66 - 54</td>
<td>50.7</td>
<td></td>
</tr>
<tr>
<td>54 - 42</td>
<td>476</td>
<td></td>
</tr>
<tr>
<td>42 - 30</td>
<td>50.7</td>
<td></td>
</tr>
<tr>
<td>30 - 18</td>
<td>52.8</td>
<td></td>
</tr>
<tr>
<td>18 - 6</td>
<td>50.6</td>
<td></td>
</tr>
<tr>
<td>6 - ground floor</td>
<td>27.6</td>
<td>Shopping mall and conference rooms</td>
</tr>
</tbody>
</table>
Egress as Part of Fire Safety in High-rise Buildings

1st experiment: free movement

All participants were initially placed on 101st floor. They moved into the stairs at 120s intervals. Results of the experiment indicate that it takes about 30 min for the evacuee to move down to the ground floor. The vertical moving speed of the evacuee was about 0.28 m/s. Figure 44 and 45 illustrate the results.

Table II: Information about the participants in Experiment 1

<table>
<thead>
<tr>
<th>Participant</th>
<th>Participant 2</th>
<th>Participant 3</th>
<th>Participant 4</th>
<th>Participant 5</th>
<th>Participant 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>62</td>
<td>21</td>
<td>43</td>
<td>26</td>
<td>24</td>
</tr>
<tr>
<td>Gender</td>
<td>Male</td>
<td>Female</td>
<td>Female</td>
<td>Male</td>
<td>Male</td>
</tr>
</tbody>
</table>

Note: In the subfigure (a), the red arrows represent the evacuation path for the evacuees after moving out of one staircase into another one. (b) The way evacuees move from each regular floor into the corresponding staircase and then down to the refuge floor where they have to change staircase. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Figure 45: Mean vertical speed for each participant

2nd experiment: mass evacuation

The second experiment shows the human behavior during evacuation process. 177 occupants took part in the second experiment. Participants were mainly young people. All of them were asked to wait in the selected lobbies of staircase 1 as shown in Figure 43 on the 12th to the 17th floor. 30 people on each floor, except 16th and 17th floor. There are 12 and 45 people, respectively.

When they came to the refuge floor, they would be directed to the selected staircase by following the guide arrows on the floor. The mean speed along their movement direction was about 0.62 m/s. When the density in the stairwell was low, evacuees can move freely, thus the one who wanted to escape as fast as possible can overtake others. However, evacuees have to slow down and queue with the increase of the occupant density in the stairways. When they egress from one staircase into another staircase on the refuge floor, their mean speed is approximately 0.9 m/s. Overtaking phenomena is observed frequently on the refuge floor.

Figure 46: Composition of participants in the office levels of SWFC
3rd experiment: mixed strategies of evacuation

Sometimes evacuation by stairs alone may be highly inefficient in tall buildings. Accordingly lifts can be used to evacuate pedestrian for different refuge floors in this experiment. 10 evacuees on each of the 41 stand on the 65th floor were instructed to first move down to the refuge floors 30 and 54, respectively. When the evacuees came to the refuge floor, they left the staircase and went to the lift room. After entering into the lift room, one half of the evacuees took the lift to egress down to the ground floor. While the others waited there during the above process until the lift came up to the refuge over again.

<table>
<thead>
<tr>
<th>Actions</th>
<th>Time (mm:ss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participants departure from the 41F at</td>
<td>0</td>
</tr>
<tr>
<td>Participants arrive at the 30F at</td>
<td>2:37</td>
</tr>
<tr>
<td>Lift button at the 30F been pressed at</td>
<td>4:04</td>
</tr>
<tr>
<td>The lift arrives at the time of</td>
<td>8:35</td>
</tr>
<tr>
<td>Half of the participants enters the lift</td>
<td>8:39</td>
</tr>
<tr>
<td>Lift door closes at the time of</td>
<td>8:41</td>
</tr>
<tr>
<td>Lift arrives at the ground floor</td>
<td>9:25</td>
</tr>
<tr>
<td>Lift button at the 30F been pressed again at</td>
<td>10:00</td>
</tr>
<tr>
<td>Lift arrives at the 30F again at</td>
<td>10:38</td>
</tr>
<tr>
<td>The other half participants enters the lift</td>
<td>10:40</td>
</tr>
<tr>
<td>Lift door closes at the time of</td>
<td>10:43</td>
</tr>
<tr>
<td>Life arrives at the ground floor again at</td>
<td>11:30</td>
</tr>
</tbody>
</table>

Table 13: Time feature of lift evacuation for SE-2

<table>
<thead>
<tr>
<th>Actions</th>
<th>Time (mm:ss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participants departure from the 65F at</td>
<td>0</td>
</tr>
<tr>
<td>Participants arrive at the 54F at</td>
<td>1:49</td>
</tr>
<tr>
<td>Lift button at the 54F been pressed at</td>
<td>2:16</td>
</tr>
<tr>
<td>The lift arrives at the time of</td>
<td>5:00</td>
</tr>
<tr>
<td>Half of the participants enters the lift</td>
<td>5:04</td>
</tr>
<tr>
<td>Lift door closes at the time of</td>
<td>5:14</td>
</tr>
<tr>
<td>Lift arrives at the ground floor</td>
<td>6:05</td>
</tr>
<tr>
<td>Lift button at the 54F been pressed again at</td>
<td>6:51</td>
</tr>
<tr>
<td>Lift arrives at the 54F again at</td>
<td>8:05</td>
</tr>
<tr>
<td>The other half participants enters the lift</td>
<td>8:11</td>
</tr>
<tr>
<td>Lift door closes at the time of</td>
<td>8:15</td>
</tr>
<tr>
<td>Life arrives at the ground floor again at</td>
<td>8:55</td>
</tr>
</tbody>
</table>

Other experiments results

Figure 48 illustrates the transit time from staircase to the refuge area. 40 seconds can be used as a reference in our future design. Relates to the distance and floor area, it is better to control the transit time within 1 minute.
Summary

It can be found that in the first experiment the speed fluctuation was small. In a building with 101 floors, it takes about 30 min to move down to the ground floor when the vertical moving speed was about 0.28 m/s. The second experiment mainly observes the human behavior and travelling speed. Elevators are also used as means of egress in the third experiment. But the occupants must be informed beforehand if they can use elevators, since most people have the preconception that lifts cannot be used during a fire. Thus the application of communication system in Shanghai World Financial Center is necessary. Trained stuff can operate the evacuation elevators and instruct the occupants.

Experiments results show that the mean travel speed on stairs is around 0.6 m/s. Comparing with the Dutch calculation method in SBR, travel speed on stairs is 0.8 m/s without hindrance and 0.32 m/s with maximum evacuees, respectively (Dutch: loopsnelheid over trap, ongehinderd 0.8 m/s; loopsnelheid over trap, maximale bezetting 0.32 m/s). The mean speed on stairs is \( \frac{0.8 + 0.32}{2} = 0.56 \text{ m/s} \). It is very close to the experiments results in SWFC.

Research shows that in China many high-rise buildings were designed with refuge floors, but many occupants do not know where they are and how they can be used. Education is essential to inform the public on the basics of fire development, especially in complex large buildings. Some fire drills and information on egress routes are necessary for an effective evacuation. When full evacuation is not the only considered strategy, further information on how to protect-in-place is necessary.
4.4.4 MGM Grand Hotel

On 21 November, 1980, a fire broke out in MGM Grand Hotel, Nevada, the United States. MGM Grand Hotel was a 23-storey building, built in the early 1970’s. It composed of 21-storey guest rooms, a casino, theatres, convention facilities, arcade, the Deli restaurant, mercantile complex and underground parking garage. The perspective view is illustrated in Figure 50. The high-rise part was of fire-resistive construction while the lower portion consisted of both protected and unprotected non-combustible materials. Most interior partitions were made of gypsum board on steel studs including enclosures around the means of egress (98). The hotel was partially sprinkler-protected, while there was no sprinkler system in the main casino.

MGM Grand fire, 1980

The fire started in the electrical wiring over a delicatessen at the east end of the casino (10). Materials burned near the fountains in the front entrance. Following full involvement of the Deli restaurant, the fire spread rapidly throughout the high-rise complex. Smoke also rose through the high-rise via stairways, seismic joints, elevators and ventilation systems. During the fire, the heating, ventilation, and air-conditioning (HVAC) system continued operating. Meanwhile, the vertical openings were provided with inadequate protection. The casino and some of the guest rooms were directly infected by fire. Any means of egress from the high-rise tower was impaired because of smoke, and most deaths were caused by smoke. A number of guests had trouble in finding the exits to get downstairs. But when they found the exits, some of the fire doors were locked automatically. Thus, although people can enter the stairwell, they were trapped inside these smoke-filled areas. In addition, the high-rise tower evacuation alarm system did not sound (98). The fire resulted in 85 deaths and more than 700 injuries (128).
Means of egress
As can be seen from the related figures below, the building was divided into four parts in terms of means of egress.

- High-rise hotel rooms
- Top floor of the tower
- Casino level
- Jai alai fronton and lower arcade level

The stairwells were distributed evenly in the hotel building, and their locations are illustrated in Figure 50. Two stairways were designed to serve each of the three wings. Many occupants in the high-rise tower were able to exit the building unassisted down stairways. Others were turned back by smoke and sought refuge in rooms (I.36). In the casino, the travel distances from certain areas to the exits were too long, which exceeded 30.5m in length. Apart from egress by stairs, helicopter pilots evacuated 300 people from the roof of the high-rise tower.

Figure 50: Perspective view from the northeast - MGM Grand Hotel

Figure 51: Elevation (facing north) - MGM Grand Hotel
Figure 52: Cross-section - MGM Grand Hotel

Figure 53: Stair locations - MGM Grand Hotel
Las Vegas Hilton fire

90 days after the devastating MGM Grand fire, an arson fire started at the Las Vegas Hilton. At the time was being retrofitted with modern fire safety equipment. The fire department used the knowledge they had learned from the MGM Grand fire, applied local television networks to notify people to stay in their rooms and not go out to the halls and stairwells. After the incident, many hotels in Las Vegas installed updated fire safety systems. Because of the previous lessons learned, only eight people died in this incident (128).

Summary

In fact, high-rise fires do not happen very often. From MGM Grand fire, we can learn that once the staircases were blocked or occupants have trouble to get down, the use of helicopter can be an additional method for evacuation. Correct and timely instructions by means of mobile phone, combined with aero medical evacuation, increase the survival during high-rise fires accidents (55). Fire doors must be designed properly, both the lock and the opening direction. In some cases they should be locked to prevent fire spread and smoke propagation. But when a large number of doors are locked, more routes should be available in the meantime which ensures that occupants have several choices to egress. It is the transportation logistics.

Alarm signal is an important way to inform the occupants about the fire. Without alarming system, people can only notice the fire when they heard or saw fire apparatus, smelled smoke, or heard people yelling and knocking on doors. It would be a serious delay in the total egress process which leads to much dangerous situation.
4.4.5 World Trade Center

A bomb in a vehicle exploded in the parking garage on the basement level of World Trade Center on 26 February, 1993. It caused heavy fire on B2 basement, confined to 25 to 30 vehicles. The New York City Fire Department brought the fire under control in one and a half hour. Several occupants took hours to make their way out of the darkened buildings. There were not enough lights and instructions, most fire alarm systems were destroyed by the explosion. During the rescue process, they were forced to use the stairs since all elevators were out of service. It took approximately 11 hours to complete the search-and-rescue operation. Building occupants delayed for as long as four hours in tower 1, in tower 2 of three hours. In the evacuation of the towers following the terrorist bombing, it was estimated that the egress time for occupants on the top floor was at least 1.5 to 3 hours.

Although this incident did not bring about directly regulation change, researchers published some main findings which can be concluded:

- Fire safety training should not only confined to fire department, occupants should also get sufficient information and take part in the fire drill;
- Guidance and the exit route markings is important;
- Since nearly all communication system was destroyed, the only way for occupants to contact the fire department was telephones. Some occupants complained about the time for waiting for rescue was too long. This is because of the loss of power to the elevators.
II September, 2001 - Aircraft crash

On Tuesday, 11 September, 2001, an aircraft departed from Boston crashed into the northern facade of the WTC tower 1. There were 5000-7000 occupants in each tower at the time the first attack, around 8:45 in the morning. At 9:03 a.m., another hijacked flight crashed into the south side of the south tower of the World Trade Center.

In the north tower, the aircraft penetrated the core and destroyed all three stair shafts at the floors of impact. There was no vertical route for them to egress. None of the occupants located above the attack in tower 1 survived. But 99% of those located below the impact point were able to escape. Many occupants remained in place and waited for the fire department to initiate an evacuation. The second aircraft destroyed two stair shafts. Fortunately, elevators were successful for evacuate from tower 2. Each tower has three enclosed stairways located in the core. Two stairways discharge on to the mezzanine level in the atrium/lobby area of the respective tower.

All the towers did have the necessary structural fire proof materials. However, building codes do not require building design to consider aircraft impacts. The situation regarding to the fire alarm system were similar with the 1993 bomb explosion. They were almost destroyed and fewer than 14% of the survivors hear the alarm, fewer than 5% were able to use the alarm as a cue to escape.

This event of September 11th demonstrates that even in fully sprinklered buildings, events such as explosions may disable sprinkler systems and produce serious unanticipated smoke spread and life safety system failure.
**Announcement system**

In 1993, no announcements were made to the building occupants, because the communication system located in the basement had been destroyed by the bomb blast. The occupants had been trained to go to the voice annunciator in an emergency and await further instructions.

On September 11th, 2001, announcements were made over bullhorns and voice communication systems. In tower 2, sometime during the 16.5 minutes that separated the two attacks, a message came to tell people that an airplane had hit tower 1, while tower 2 was secure and it was safe for occupants to return or stay in their offices. It should be stressed that the message content was perfectly correct at the time it was made. It is estimated that tower 2 announcement was issued at approximately 9:00 a.m., as the majority of survivors claimed they heard it just a couple of minutes before tower 2 was struck, which occurred at 9:03 a.m. One survivor from the 103rd floor of tower 2 describes that he had reached the 70th floor when he heard the announcement and decided with his colleagues to continue walking down. He had descended another 3 floors to the 67th, when the second airplane hit the tower. Of the 60 survivors in tower 2 who mentioned hearing the announcement, 53 decided to disregard the instruction and continue their evacuation, while 7 people decided to turn back but didn’t have time to go far before their tower was hit (15).

**Post 9.11 changes regarding egress**

The qualitative data also suggested that, after a decision to evacuate was made, many persons stopped to attend to last-minute activities (e.g. making telephone calls, shutting down computers, or gathering up personal items). Deciding which route to take might have delayed evacuation progress for others. Progress was reportedly slowed for some persons as a consequence of poor physical condition or inadequate footwear (e.g. high-heeled shoes or 'flip-flops'). Some persons also delayed their progress to stop and assist others (39).

After 11 September terrorist attack, ASCE, NIST, ICC and FEMA recommended many changes in the design codes (91). These code changes will produce buildings to improve the resistance of extreme loads. Current policy on credible hazards has risen, so they should be re-evaluated. The protection against fire damage of building elements should be increased. But it will result in higher the building cost.

NIST recommendations:
- Maximize the remoteness of egress components (stairs, elevators, exits) without negatively impacting the average travel distance. Maintain the functional integrity and survivability of egress components in a manner that becomes intuitive to building occupants.

---

17 ASCE: American Society of Civil Engineers.
NIST: National Institute of Standards and Technology
ICC: International Code Council
FEMA: Federal Emergency Management Agency
• Enforce available provisions in building codes to ensure that egress and sprinkler requirements are met by existing buildings.
• Improve building occupants' preparedness of evacuation in case of building emergency.
• Design tall buildings to accommodate timely full building evacuation of occupants when required. Stairwell capacity and stair discharge door width should be adequate to accommodate counter flow due to emergency access by responders.
• Evaluate current and next generation evacuation technologies, including protected/hardened elevators, exterior escape devices, and stairwell descent devices.

**ICC Code modification:**

• Clarification of multiple requirements related to egress widths.
• Clarifies egress stair and corridor width requirements, and the requirements means of emergency voice communication.
• Requires evacuation plans for all occupants, consistent across all jurisdictions.
• Requires occupants' evacuation elevator activation upon fire alarm activation.

In the aftermath of the collapse of the towers at the World Trade Center in 2001, however, there are real questions as to whether occupants would be willing to remain in place over an extended period of time, especially if they see fire and smoke in their building. It is essential to learn more about the general public's perception of their level of safety in high-rise buildings (17). Despite the impact of airplanes into each tower at high speed, the towers did not immediately collapse. The time prior to collapse provided most of those below the crash floors time to escape (91).

**Summary**

Evacuation plan shall be kept with current. Just like the aftermath of some fire incidents, government and fire specialists took measures to adjust the regulations and develop evacuation strategies, do research in new egress approaches and improve the fire-protection methods.
4.5 Legislation and Standards

This chapter gives an account of the recent internationally-orientated research in the field of fire legislation and standards. As references and fundamentals for our further research, fire regulations from some typical countries have been chosen from different continents. Indeed, there is no internationally definition about the height of high-rise buildings. Hence each section begins by the building classification or definition about high-rise in that country. It will then go on to the different structural fire-protection measures such as the fire resistance rating or the fire installation systems. Another major issue is examined on the subject of compartmentalization and means of egress according to various fire regulations.

4.5.1 The United States

In the United States, fire safety design complies with the International Building Code (IBC) and National Fire Protection Association (NFPA) standards. The United States stipulates that the definition of high-rise is buildings with occupied floors 22.86m (75 feet) or higher above the lowest level of fire department access (Figure 56).

![Figure 56: High-rise definition in the United States](image)

4.5.1.1 Structural Fire-protection

*NFPA 220 Standard on Types of Building Construction* and *NFPA 5000 Building Construction and Safety Code* regulate five construction types according to different kinds of construction materials. The following paragraphs were quoted from NFPA 220 4.3 (page. 220-6 to 220-8). As can be seen from Table 14, different construction types have impact on the fire resistant properties.
- **Type I (442 or 332) and Type II (222, III or 000):** Construction shall be those types in which the fire walls, structural elements, walls, arches, floors and roofs are of approved noncombustible or limited-combustible materials.

- **Type III (211 or 200):** Construction shall be that type in which exterior walls and structural elements that are portions of exterior walls are of approved noncombustible or limited-combustible materials, and in which fire walls, interior structural elements, walls, arches, floors and roofs are entirely or partially of wood of smaller dimensions than required for Type IV construction or are approved combustible materials.

- **Type IV (2HH):** Construction shall be that type in which fire walls, exterior walls, and interior bearing walls and structural elements that are portions of such walls are approved noncombustible or limited-combustible materials. Other interior structural elements, arches, concealed spaces and shall be solid or laminated wood without concealed spaces and shall comply with the allowable dimensions of the following requirements.

- **Type V (Ill or 000):** Construction shall be that type in which structural elements, walls, arches, floors, and roofs are entirely or partially of wood or other approved materials.

### Table 14: Fire resistance rating from Type I though Type V construction (hour)\(^\text{18}\)

<table>
<thead>
<tr>
<th></th>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
<th>Type IV</th>
<th>Type V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>442</td>
<td>332</td>
<td>222</td>
<td>III</td>
<td>000</td>
</tr>
</tbody>
</table>

**Exterior Bearing Walls**

| Supporting more than one floor, columns, or other bearing walls | 4 | 3 | 2 | 1 | 0\(^\text{b}\) | 2 | 2 | 2 | 1 | 0\(^\text{b}\) |
| Supporting one floor only                                      | 4 | 3 | 2 | 1 | 0\(^\text{b}\) | 2 | 2 | 2 | 1 | 0\(^\text{b}\) |
| Supporting a roof only                                        | 4 | 3 | 1 | 1 | 0\(^\text{b}\) | 2 | 2 | 2 | 1 | 0\(^\text{b}\) |

**Interior Bearing Walls**

| Supporting more than one floor, columns, or other bearing walls | 4 | 3 | 2 | 1 | 0 | 1 | 0 | 2 | 1 | 0 |
| Supporting one floor only                                      | 3 | 2 | 2 | 1 | 0 | 1 | 0 | 1 | 1 | 0 |
| Supporting a roof only                                        | 3 | 2 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 |

**Columns**

| Supporting more than one floor, columns, or other bearing walls | 4 | 3 | 2 | 1 | 0 | 1 | 0 | H | 1 | 0 |
| Supporting one floor only                                      | 3 | 2 | 2 | 1 | 0 | 1 | 0 | H | 1 | 0 |
| Supporting a roof only                                        | 3 | 2 | 1 | 1 | 0 | 1 | 0 | H | 1 | 0 |

**Beams, Girders, Trusses, and Arches**

| Supporting more than one floor, columns, or other bearing walls | 4 | 3 | 2 | 1 | 0 | 1 | 0 | H | 1 | 0 |
| Supporting one floor only                                      | 2 | 2 | 2 | 1 | 0 | 1 | 0 | H | 1 | 0 |
| Supporting a roof only                                        | 2 | 2 | 1 | 1 | 0 | 1 | 0 | H | 1 | 0 |

**Floor-Ceiling Assemblies**

| Floor-Ceiling Assemblies | 2 | 2 | 2 | 1 | 0 | 1 | 0 | H | 1 | 0 |

**Roof-Ceiling Assemblies**

| Roof-Ceiling Assemblies | 2 | 15 | 1 | 1 | 0 | 1 | 0 | H | 1 | 0 |

**Interior Nonbearing Walls**

| Interior Nonbearing Walls | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Exterior Nonbearing Walls**\(^\text{2}\)

\(^{18}\) Quoted from NFPA 220: Table 4.11 (page 220-6)
Attention:
- H: heavy timber members
  - exterior walls shall have a fire resistance rating based on relevant tables in NFPA whichever is greater;
  - exterior walls shall be based on relevant tables in NFPA whichever is greater;
  - exterior non-bearing walls shall be constructed of non-combustible materials, limited-combustible materials or materials as follow: Fire-retardant-treated wood shall be permitted in exterior nonbearing walls when such walls are not required to have fire resistance ratings; exterior nonbearing walls tested in accordance with and meeting the conditions of acceptance of NFPA 285 Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Non-Load-Bearing Wall Assemblies Containing Combustible Components shall be permitted. Exterior nonbearing walls tested in accordance with, and meeting the conditions of acceptance of, NFPA 285 shall be permitted.

4.5.1.2 Fire Safety Installation

IBC has tended to focus on the fire safety installation and egress safety. High-rise buildings must have elevator lobbies or pressurized elevator shafts so that smoke cannot migrate up through elevator shafts. This helps to keep both enclosed and unenclosed elevator lobbies safe, and provides the areas for people to wait for assistance. Buildings with occupied floors above 36.6m (120 feet) or higher above the lowest level of fire service access, are demanded to have fire-fighting elevators. IBC allows reduction in egress widths for buildings provided with automatic sprinkler protection.

Furthermore, egress requirements vary for different occupancy. NFPA101 Life Safety Code addresses all types of occupancies, with requirements for egress, features of fire protection, sprinkler systems, alarms, emergency lighting, smoke barriers, and special hazard protection. It standardizes that high-rise buildings shall be protected throughout by an approved, supervised automatic sprinkler system. A sprinkler control valve and a water flow device shall be provided for each floor. More than one means of egress is required in a building. The loss of any one means of egress leaves not less than 50% available of the required capacity. All of the transportation facilities shall have a sufficient width and capacity.
4.5.2 CHINA

As everyone knows, the density of population in China is high even though the national land is huge. Owing to the high demand for residential properties in some crowded cities, designers are pushing the limit of building height gradually. This section is mainly concluded from GB50045-95 Code for Fire Protection Design of Tall Buildings, GB50016-2006 Code of Design on Building Fire Protection and Prevention and GB 50352-2005 Code for design of civil buildings.

GB50045-95 presents that tall buildings are assorted into two groups. In contrast with the United States, the principle of classification is not only based on construction materials, but also the height and the function of the building.

Table 15: Tall building classification in China

<table>
<thead>
<tr>
<th>Function</th>
<th>Class I</th>
<th>Class II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>Residential buildings with more than 19 floors</td>
<td>Residential buildings with 10 to 18 floors</td>
</tr>
<tr>
<td></td>
<td>1. Hospital</td>
<td>1. Except the commercial, exhibition, finance, and telecommunication buildings in Class I</td>
</tr>
<tr>
<td></td>
<td>2. Commercial, exhibition, finance, telecommunication buildings which is higher than 50m, or any occupied floor area larger than 1000m² of the part higher than 24m</td>
<td>2. Local/town postal, precaution or preparedness against natural calamities center, radio and broadcasting building, electric power building</td>
</tr>
<tr>
<td></td>
<td>3. Commercial mixed with residential building which is higher than 50m, or any occupied floor area larger than 1500m² of the part higher than 24m</td>
<td>3. School building, hotel, archives building, scientific research building and office building which are lower than 50m</td>
</tr>
<tr>
<td>Public/Others</td>
<td>4. National or provincial radio and broadcasting building</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5. National or provincial electric power building</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6. Provincial postal building</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7. Library with more than 1 million books</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8. School building, hotel, archives building, scientific research building and office building which are higher than 50m</td>
<td></td>
</tr>
</tbody>
</table>

4.5.2.1 Structural Fire-protection

Table 16 provides the minimum fire protection requirements for tall buildings in China, which is divided into two grades. High-rise buildings of Class I should be no less than Grade 1 in Table 16, and Class II should be no less than Grade 2. Underground levels shall apply Grade 1. In line with the tests in GB8624-2006 Classification for Burning Behavior of Building Materials and Products, combustible properties and fire resistant time of all the components in the building cannot be less than Table 16.
Table 16: Fire resistance grade and fire resistance time

<table>
<thead>
<tr>
<th>Name of the components</th>
<th>Fire resistance time (hour)</th>
<th>Fire resistance grade</th>
<th>Grade 1</th>
<th>Grade 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wall</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fireproof wall</td>
<td></td>
<td></td>
<td>NC 3.00</td>
<td>NC 3.00</td>
</tr>
<tr>
<td>Load bearing wall, fire compartments wall, wall of the stair well, wall of the elevator shaft, separation wall between different neighbors</td>
<td></td>
<td></td>
<td>NC 2.00</td>
<td>NC 2.00</td>
</tr>
<tr>
<td>Non-load bearing exterior wall,</td>
<td></td>
<td></td>
<td>NC 1.00</td>
<td>NC 1.00</td>
</tr>
<tr>
<td>Partition wall</td>
<td></td>
<td></td>
<td>NC 0.75</td>
<td>NC 0.50</td>
</tr>
<tr>
<td><strong>Column</strong></td>
<td></td>
<td></td>
<td>NC 3.00</td>
<td>NC 2.50</td>
</tr>
<tr>
<td><strong>Beam</strong></td>
<td></td>
<td></td>
<td>NC 2.00</td>
<td>NC 1.50</td>
</tr>
<tr>
<td>Floor, evacuation staircase, load bearing components on the roof</td>
<td></td>
<td></td>
<td>NC 1.50</td>
<td>NC 1.00</td>
</tr>
<tr>
<td>Suspended ceiling</td>
<td></td>
<td></td>
<td>NC 0.25</td>
<td>DC 0.25</td>
</tr>
</tbody>
</table>

Attention:
- NC: non-combustible components (The substance cannot burn, e.g. concrete, bricks, metal, stone etc.).
- DC: difficult combustible components (The substance is hard to burn, e.g. bituminous concrete etc.).
- Scissors stairs should have at least 1 hour fire resistant separation wall. Each staircase should have its own pressurization system.

4.5.2.2 Means of Egress

As far as we know, the egress strategy is not regulated as a fixed clause in Chinese fire regulations. The way of how to evacuate the building relates to the egress plan made by engineers, the property management company, and the fire department. According to numerous available egress plans, we can summarize that the most widely used strategy is simultaneous egress, while phased evacuation strategy can be applied in skyscrapers as well. Fire-fighting elevator is required according to the floor area provided in Table 17.

Table 17: The relation between floor area and the required fire lift

<table>
<thead>
<tr>
<th>Floor area</th>
<th>Number of fire lift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor area &lt; 1500 m²</td>
<td>1</td>
</tr>
<tr>
<td>1500 m² &lt; floor area &lt; 4500 m²</td>
<td>2</td>
</tr>
<tr>
<td>Floor area &gt; 4500 m²</td>
<td>3</td>
</tr>
</tbody>
</table>

In Hong Kong, refuge floors are required for high-rise buildings at intervals not fewer than 20 stories. Refuge areas are required to be 50% open on two sides; these openings are generally protected by water curtains. The occupants of the fire floor and floors immediately above and below it should use the exit stairs to descend at least a few floors below the fire floor. Then they can re-enter the occupied space on those safe floors to await further instructions. Moreover, refuge floor is required when the total building height exceeds 100 meter in the mainland of China. The distance between the first to the second refuge floor should not be more than 15 floors.
4.5.2.3 Fire Compartment

The maximum compartment area for high-rise buildings in China is demonstrated in Table 18. Every fire compartment should have at least two exits in high-rise buildings.

Table 18: Maximum area of single fire compartment

<table>
<thead>
<tr>
<th>High-rise classifications</th>
<th>Maximum fire compartment area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I</td>
<td>1000 $m^2$</td>
</tr>
<tr>
<td>Class II</td>
<td>1500 $m^2$</td>
</tr>
<tr>
<td>Basement</td>
<td>500 $m^2$</td>
</tr>
</tbody>
</table>

Attention:
- If there is automatic sprinkler system in the garage, the maximum fire compartment area can be doubled.
- Electric buildings of Class I can be 150% of the values listed above.

4.5.3 SINGAPORE

At present, with the continuous growth of population and the limited land space of the city-state Singapore, there has been a sharp increase in the number of skyscrapers since 2000. Singapore has over 4300 completed high-rises, and there are 59 skyscrapers that rise higher than 140 meters (134). In general, buildings are sorted into three categories with regard to number of total floors.

Table 19: Building types in Singapore

<table>
<thead>
<tr>
<th>Building types</th>
<th>Number of floors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-rise building</td>
<td>Below 8 floors</td>
</tr>
<tr>
<td>Middle-rise building</td>
<td>Between 8 to 30 floors</td>
</tr>
<tr>
<td>High-rise building</td>
<td>Between 30 to 40 floors</td>
</tr>
<tr>
<td>Super high-rise building</td>
<td>More than 40 floors</td>
</tr>
</tbody>
</table>

4.5.3.1 Structural Fire-protection

The structural fire resistant property is influenced by the building height, floor area, building function, and other factors. It is apparent from Table 20 that any separating wall shall have fire resistance of not less than 1 hour in Singapore.

Table 20: Minimum periods of fire resistance

<table>
<thead>
<tr>
<th>Purpose group</th>
<th>Maximum dimensions</th>
<th>Minimum period of fire resistance for elements of structure (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Height (m)</td>
<td>Floor area ($m^2$)</td>
</tr>
<tr>
<td>I. Small residential</td>
<td>NL</td>
<td>NL</td>
</tr>
<tr>
<td>House having any number of stories</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
II. Other residential Building having any number of stories: Building having any number of stories

<table>
<thead>
<tr>
<th>Building Type</th>
<th>NL</th>
<th>28</th>
<th>3,000</th>
<th>1/2</th>
<th>1</th>
<th>1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over 28</td>
<td>NL</td>
<td>2,000</td>
<td>5,500</td>
<td>1/2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

III. Institutional

<table>
<thead>
<tr>
<th>Building Type</th>
<th>NL</th>
<th>Over 28</th>
<th>2,000</th>
<th>1/2</th>
<th>1</th>
<th>1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL 28</td>
<td>NL</td>
<td>14,000</td>
<td>1/2</td>
<td>1</td>
<td>1/2</td>
<td>2</td>
</tr>
</tbody>
</table>

IV. Office

<table>
<thead>
<tr>
<th>Building Type</th>
<th>NL</th>
<th>Over 28</th>
<th>2,000</th>
<th>1/2</th>
<th>1</th>
<th>1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL 28</td>
<td>NL</td>
<td>7,000</td>
<td>1/2</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

V. Shop

<table>
<thead>
<tr>
<th>Building Type</th>
<th>NL</th>
<th>Over 28</th>
<th>2,000</th>
<th>1/2</th>
<th>1</th>
<th>1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL 28</td>
<td>NL</td>
<td>5,500</td>
<td>1/2</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

VI. Factory

<table>
<thead>
<tr>
<th>Building Type</th>
<th>NL</th>
<th>Over 28</th>
<th>2,000</th>
<th>1/2</th>
<th>1</th>
<th>1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL 28</td>
<td>NL</td>
<td>8,500</td>
<td>1/2</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

VII. Place of public resort

<table>
<thead>
<tr>
<th>Building Type</th>
<th>NL</th>
<th>Over 28</th>
<th>2,000</th>
<th>1/2</th>
<th>1</th>
<th>1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL 28</td>
<td>NL</td>
<td>7,000</td>
<td>1/2</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

VIII. Storage and general

<table>
<thead>
<tr>
<th>Building Type</th>
<th>NL</th>
<th>Over 28</th>
<th>2,000</th>
<th>1/2</th>
<th>1</th>
<th>1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL 28</td>
<td>NL</td>
<td>7,000</td>
<td>1/2</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Attention:

- Cubical extent: the cubical extent of the building or, if the building is divided into compartments, the compartment of which the elements of structure forms part;
- Floor area: the floor area of each story in the building or, if the building is divided into compartments, of each story in the compartment of which the element of structure forms part;
- Height: the height of a building;
- NL: No limit applicable;
- (c) This period is reduced to 2-hours for open-sided buildings which are used solely for car parking.
- This table only demonstrated the standards for buildings higher than 24 meters.

4.5.3.2 Means of Egress

The applicable egress strategy can be different in each category. As we have already known, the number of skyscrapers is large in this country. Full evacuation of the entire population may not be necessary. Therefore we can divide the total egress into phases. Singapore Civil Defense Force office recommended full evacuation for low-rise buildings. Medium-rises and high-rise buildings above 30 floors are recommending a phased evacuation.

The first phase alarm signal is for informing all floors. After the fire-fighting team arrives, they ascertain the location of the fire from the main control panel and use the fire lift to arrive at two stories below the fire floor and proceed to the fire floor via the staircase. The second stage alarm is the signal to commence sequential evacuation. The evacuation announcement shall be made in phases beginning with the fire floor, two floors above and two floors below the fire floor. The rest of the floors will be evacuated on subsequent phases depending on the situation. Notwithstanding the above, a total evacuation of the building may be declared in extreme cases (118). For holding occupants in super high-rise residential buildings, they must be provided with refuge floors every 20 floors. Refuge areas shall be of masonry construction having fire resistance rating not less than 2 hours (119).
They are usually mechanical floors with at least 50% of the floor area configured as an area of refuge. Occupants can wait on the refuge floors for assistance.

In addition to that, emergency elevator shall be designed for the fire department in high-rise buildings. Stairway is the most common means of egress for occupants. Singapore Civil Defense Force also states that ‘When evacuating, do not panic but quickly walk down the staircase by the nearest exit and proceed to the assembly point. Do not use lifts.’ [118].

4.5.3.3 Fire Compartment

In any building which exceeds 24m in habitable height, no compartment shall comprise more than one story for compartments at story level exceeding 24m above average street level, other than a compartment which is within residential maisonette which may comprise two store levels. Table 21 gives the maximum compartment size of buildings in Singapore.

<table>
<thead>
<tr>
<th>Compartments</th>
<th>Maximum floor area</th>
<th>Maximum cubical extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compartment below ground level. No compartment to comprise more than one story.</td>
<td>2000\text{m}^2</td>
<td>7500\text{m}^3</td>
</tr>
<tr>
<td>Compartments between average ground level and a height of 24 m. No compartment to comprise more than 3 stories.</td>
<td>4000\text{m}^2</td>
<td>15000\text{m}^3</td>
</tr>
<tr>
<td>Compartments above a height of 24 m from average ground level. No compartment to comprise more than one story.</td>
<td>2000\text{m}^2</td>
<td>7500\text{m}^3</td>
</tr>
</tbody>
</table>

4.5.4 SWEDEN

In Sweden, there are around 30 buildings that rise higher than 60 meters. Until now, the tallest building in Scandinavia is the Turning Torso building in Malmö, Sweden, which rises 190.5 meters with 57 stories. Since high-rise buildings are not customary in Sweden, there are few details in the building regulations that are specific for tall buildings. This section is based on the Swedish building regulation BBR (Boverkets byggregler 2012).

4.5.4.1 Fire Compartment

Buildings should be divided into fire compartments to the extent that it creates sufficient time for evacuation and restricts the consequences of a fire. To begin with, we need to understand the different definitions with respect to fire safety in Sweden. (Quoted from BFS 2011:26, BBR 19, Chapter 5 Safety in case of fire)

- Article 5:242 Fire compartment: The term fire compartment refers to a part of a building separated from other parts of the building in which a fire, during all or part
of a fire progression, can develop without spreading to other parts of the building or other buildings. The fire compartment shall be separated from the rest of the building, by enclosing walls and building floors to ensure that escape from the building is secured and to ensure that people in adjoining fire compartments or buildings are protected during a fire or parts of a fire progress. (BFS 2011:26).

- Article 5:243 Fire section: The term fire section refers to a part of a building separated from other parts of the building in which a fire can develop without spreading to other parts of the building or other buildings. The fire section shall be separated from the rest of the building by firewalls and building floors or equivalent to ensure that fire spread is restricted within and between buildings. (BFS 2011:26).

- Article 5:247: Escape route and secure location: An escape route shall be an exit to a secure location. An escape route may also be a space in a building which leads from a fire compartment to such an exit.

- Article 5:561: To limit the extensive spread of fire in large buildings, these should be designed with fire compartments, fire sections, fire safety installations or combinations thereof.

<table>
<thead>
<tr>
<th>Protection systems</th>
<th>Maximum size in the fire section for fire load f (MJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f ≥ 800</td>
</tr>
<tr>
<td>No automatic fire alarm or automatic fire suppression system</td>
<td>2500 m²</td>
</tr>
<tr>
<td>Automatic fire alarm</td>
<td>5000 m²</td>
</tr>
<tr>
<td>Automatic water sprinkler system</td>
<td>Unlimited</td>
</tr>
</tbody>
</table>

Attention:
- The net area is determined based on all floors contained in the fire compartment or fire section.
- Quoted from BFS 2011:26, BBR 19, Table 5:561

Each staircase is a separate fire compartment. Each group of elevators is likewise a separate fire compartment. The lift shaft can be placed in the stairway as part of the same fire compartment.
4.5.5 AUSTRALIA

The vast majority of Australian skyscrapers are located in the three eastern states of New South Wales, Queensland, and Victoria. Of Australia's high-rise buildings with a height of over 100m, over 100 are in Sydney, over 70 are in Melbourne, over 50 are in Brisbane, more than 40 are on the Gold Coast, and more than 10 are in Perth (Wikipedia). In Australia, much attention is given to controlling smoke and fire growth. Egress standards were apparently based on overseas standards and concepts (60).

Egress route should be kept as simple as possible. At least two routes shall be provided. Egress exit widths are specified as a function of the type of building, the number of occupants, and the physical capability of the occupants. The number, width, separation and slope of exits need to be appropriate for the safe evacuation of building occupants (11). In terms of egress from large and complex buildings, EWIS (Emergency Warning and Intercommunication System) is applied. The building is divided into multiple evacuation zones. Each zone has its own amplifier and loudspeaker circuit. In response to area-specific signals from the fire detection system, the EWIS automatically controls a zone-by-zone progressive evacuation according to a pre-programmed cascade scheme. Detailed information will not be provided to the occupants, such as evacuation routes or instructions. EWIS only works correctly if the management processes and training are in place. With full evacuation system, EWIS system automatically generates 'rising whoop', with a voice message conveying specific evacuation instructions (11).
4.6 OTHER DESIGN CONSIDERATIONS

4.6.1 OCCUPANT LOAD CALCULATION

According to NFPA101 of the United States, the steps used to determine occupant load can be broken down as follows (58):

i. Determine proper occupant load factor to be used:
   NFPA101 table 7.3.1.2: The American 'occupant load factor' is similar with Australian values. It is not the occupancy class for the entire building. In America, the most commonly used factors are 0.65m²/person and 1.4m²/person. The first one is used for concentrated without fixed seating, while 1.4m²/person is for less concentrated areas without fixed seating.

ii. Determine 'net' or 'gross' floor area
   After determine the occupant load factor, the next step is to determine the areas. And the occupancy classification should be gross area, while the values in table 7.3.1.2 are mostly net values.

iii. Calculated expected occupant load
   Determine the net occupiable area, and divided by the occupant load factor in table 7.3.1.2, then the occupant load is achieved.

iv. Determine egress capacity needed for the calculated occupant load.

Table 23: Capacity factors

<table>
<thead>
<tr>
<th>Area</th>
<th>Stairways (width/person)(mm)</th>
<th>Level components and ramps (width/person)(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board and care</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Health care, sprinklered</td>
<td>7.6</td>
<td>5</td>
</tr>
<tr>
<td>Health care, nonsprinklered</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>High hazard contents</td>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>All others</td>
<td>7.6</td>
<td>5</td>
</tr>
</tbody>
</table>

Once the occupant load is known, the exit widths can be calculated then. The capacity factor is multiplied by the total number of occupants to obtain the exit width.

If the occupants are travelling straight out of the building on the same level (in other words, walking out doors, or walking on ramps and not negotiating stairs to get out) then the code prescribes taking the occupant load and multiplying it by 5mm width per person. Then the number of exits can be calculated. On the other hand, if the occupants are travelling through the staircases to the exits, then 7.5mm width per person can be applied.

The total required egress width of stairs is larger than the total egress width resulting from the calculation, because the side-to-side swaying space of occupants is not considered.

v. Determine minimum width requirements for aisles and aisle access ways located within seating arrangement

vi. Determine minimum number of means of egress, based on occupant load
Most buildings shall have at least two means of egress. Although sometimes a single door is enough according to the calculation, it is still the case that the second door is required.

vii. Determine main entrance/exit requirements
The “main entrance/exit” must be able to handle one-half of the calculated occupant load. The remaining exits provided must be able to handle the remaining 50% of the required egress capacity.

viii. Other considerations and requirements
The calculation is only the minimum widths of the exits based on occupant load. But all areas can have additional occupants. Doors serving more than 50 occupants must swing in the direction of exit travel. Doors serving more than 100 occupants and capable of locking or latching must have approved panic or fire exit hardware.

4.6.2 Effective Flow Capacity

![Diagram of flow capacity and density relation](image)

Figure 57: Relation between density and passing ability

The Fundamental Diagram shows the relation between flow capacity and occupant density. The density of people influenced the discharge capacity of the exits. The shortest egress route means neither it is the safest nor the egress time is the shortest. It depends on the occupants density and the contaminate level. The relation between the number of occupants and the density of occupants is illustrated in Figure 57 (26).

\[ N_{\text{eff}}(D) = 1.34 D \left[ 1 - e^{-1.93(1.54 - D)} \right] \]  

(1)

Where,

- \( N_{\text{eff}} \): Flow capacity of the exit (persons/s/m)
- \( D \): Occupant density
4.6.3 TRAVEL DISTANCE ON STAIRS

Pauls, Predtechenskii and Milinskii, Pauls, Proulx et al, and Peacock et al. All used the slope of the treads for determining the travel distance \( T \).

\[
T = \sqrt{n(d^2 + h^2)^{0.5}} \\
T = nd
\]

Where,

- \( T \): Tread horizontal length
- \( T \): Tread slope length
- \( n \): The number of treads
- \( d \): The tread depth
- \( h \): The riser height

4.6.4 FLOORS TO BE EVACUATED

Generally, evacuation will be from the floor on which the emergency has occurred and the two floors immediately below and above the 'emergency floor' to a safe point below or above the critical area. Evacuation should be accomplished by way of fire resistance stairwells. If smoke or fire has penetrated a stairwell, alternate stairwells should be used. Building management and maintenance personnel should proceed immediately to fire stairwells and assist in the evacuation of occupants of the involved floor or floors. Definite priority must be given to those floors directly involved and floor immediately adjacent to the emergency. On the emergency-involved floor, evacuation should be to the nearest available exit that can be reached safely.

4.6.5 DISCUSSION ON DEFEND-IN-PLACE STRATEGY

Some big cities use defend-in-place approach in the United States. Around 1990, James McDonald of Travelers Insurance Co. published a report entitled: 'Non-evacuation in compartment fire resistive buildings can save lives and it makes sense'. According to his research, with regard to 21 fires in high-rise residential buildings, hotels and hospitals between 1961 and 1988, all the 113 casualties, 85% or 75% occurred on the fire floor. James McDonald' conclusion is that in fire resistive compartment buildings, it is safer not to evacuate and evacuation from fire floor will increase the possibilities of death. Several fires have resulted in occupants who attempted to leave the protected area died while exiting, and those who stayed in place survived. In May 2000, at NFPA World Fire Safety Congress, Prof. John Bryan, Charles Jennings, Robert Schifiliti, and Mary Marchone reported that between 1987 and 1991, around 15000 high-rise fires in the United States, 60% of the fatalities were in the same room as the fire when ignition occurred \( T \).
4.6.6 Capacity Drop Phenomenon

In phased evacuation, we need to take into account the capacity drop phenomenon in designing egress routes (69). It is defined as the significant reduction in maximum cross-section capacity. A capacity drop occurs in an oversaturated situation, usually around the bottleneck. This phenomenon may be provoked by exceeding a critical density and reduced capacity persists during the entire congestion period (Figure 58).

Figure 58: Flow against time at a cross-section

The effect of capacity drop phenomenon is illustrated in Figure 59. N(t) refers to the cumulative number of pedestrian flow.

Figure 59: Effect of 'capacity drop'

Experiments were organized in July 2005 and took place in the Pamela laboratory at the University College London, for the SPIRAL project (Scientific Pedestrian Interaction Research in an Accessibility Laboratory, International Joint Project founded by the Royal Society, 2004/R3-EU). The layout of the experiment place and experimental data are showed in the following figures. A capacity drop occurs at the bottleneck entrance, thereby delaying the flow. Consideration of capacity drop could make a better egress plan. Reducing capacity drop phenomenon could improve the pedestrian environment.

Figure 60: First experimental layout: the arrows show the direction of movement
Figure 61: The cumulative number of pedestrian between the InFS and OutFS cross-section against time

4.6.7 DISCUSSION ON REFUGE AREAS

In general, refuge is an area where people whose abilities or impairments might cause their evacuation to be delayed can await assistance. Actually with respect to skyscrapers, it is served as a place of ultimate safety not only for disabled occupants, but everybody. Refuge floors are normally put into use for relocation strategy. The relocating movement can be vertical, horizontal or a combination. Especially in super high-rise buildings, elevators are usually programmed to bypass the refuge floors. While awaiting the assistance, occupants need to be protected so that they are reasonably safe from the effects of a fire (BS 9999:2008).

For instance, the World Financial Center in Shanghai incorporates refuge floors and two express elevators stop at refuge floors and observation deck on the top floor. Occupants not capable of using the stairs to reach a refuge floor would be picked up by a fire-fighter driving an interior elevator under fire-fighters emergency operation. In Chengdu, China, refuge floors are designed in most buildings higher than 100m. Sometimes underground garages are put into use as refuge floor. According to the Building Codes of Hong Kong (MOE 1996), for buildings above 25 stories, a refuge floor has to be provided. Additional refuge floors are required for every other 25 stories. They should have a minimum clear height of 2.3m and at least two open sides since only one side open results in the worst natural ventilation (81).

---

81 MOE 1996: Code of practice of the provision of means of escape in case of fire. Build. Auth. Hong Kong
Apart from refuge floors, area of refuge can be designed as integration with the egress routing. After arrive at the vertical transportation shaft, China and Korea have the requirements for vestibules at the entrances to egress stairs and elevators. People with disability can take a rest there. Some high-rise buildings in the Middle East are equipped with occupant evacuation elevators. During the egress, a protected lobby is usually provided. As show in Figure 62 (left), Korean regulations require a separate vestibule for stairs and elevators. In China the elevator vestibule could have a door into the stair and serve both. Egress elevators in the Middle East include a separate vestibule even where located on a staging floor (Figure 62, right) [33].

However, problems rise at the same time, some people prefer continuing escaping rather than waiting on the refuge floors. And the area of refuge should have a certain storage capacity for occupants' accumulation.

### 4.6.8 Researches on Elevator-Assisted Evacuation

As the height of building increases, it brought more concerns to include elevators in the egress design. Whether it is appropriate to enact elevators evacuation in the fire code is still controversial, while many researches have been done currently around the world. In general, most people would not use elevator in the event of fire unless they are designed as evacuation elevators for people who are otherwise relatively mobile simply do not have the physical capability to descend numerous flights. The following paragraphs will discuss several researches on elevator-assisted evacuation.

Sometimes egress can be safe and effective by emergency elevator with proper fireproof measures. Take the World Trade Center for example, 16% of the occupants of tower 2 of World Trade Center escaped through the elevators before the second airplane struck the building. It is not uncommon for full evacuation of tall high rise facilities to require 30 to 60 minutes or more [4]. Emergency elevators must be protected. For one thing, they can be
used for those who cannot exit down a great deal of flights. For another, occupants can travel to refuge floors or sky lobbies by stairs and transfer to the street level by elevators (10). In the Unites States, experts are researching on using all elevators to escape, and protected elevators for firemen (32).

**Research 1**

The choice of using elevators to escape depends on numerous factors, such as the initial location of the occupant, the fire condition, the elevator waiting time, congested situation, the walking distance to the elevator, function of the building (for instance the number of disabled people in the hospitals is higher, then it is recommended to utilize elevator to egress), and so forth. Researchers from Lund University, Sweden presented some critical factors on people’s choice of their evacuation routes in high-rise buildings (103).

**METHOD**

In order to gather material for the analysis on egress by elevator, researchers created a questionnaire survey based on previous investigations. It involved people from different age and sex etc. The survey included participants’ opinion on whether they would use the stair or elevator to escape, their view on different evacuation system, and the acceptable elevator waiting time etc.

**RESULTS**

With the help of questionnaire, a correlation between the percentage of occupants that are willing to use elevator evacuation and their building floor has been derived in Figure 63.

![Figure 63: Percentage of evacuees that are willing to use an elevator for evacuation](image)

![Figure 64: The correlation modified to account for people who are unable to make their escape down a stair case](image)
It is difficult to predict the proportion of people that would use elevators or stairs. The correlation can be described by the following equation.

\[ p = 1.05 + 0.84v \]  \hspace{1cm} (4)

Where,

\( p \): The percentage of evacuees that will choose the elevator to evacuate in an emergency;

\( v \): Building floor

In terms of the choice of using elevators, 58% of the participants answered that they would not wait for the elevator at all, while 39% indicated they can wait about 5 minutes.

![Accepted waiting time](image)

**Figure 65**: The proportion of participants who will keep on waiting for the elevator at different building floors as a function of waiting time

**CONCLUSION**

Their study showed that stairs are perceived as less safe to use for people who are located on higher floors. Figure 65 is a graphic representation of the acceptable waiting time for most users is between 0 to 5 minutes, which can be used in the future research.

**Research 2**

In 2002, Marja-Liisa Siikonen & Henri Hakonen from KONE demonstrated two egress simulation results with the help of KONE Building Traffic Simulator (70). Their research was based on two situations, total evacuation and partial evacuation. In terms of the first simulation, all occupants evacuated through either stairs or elevators only. The width of the stairs is 1.2m and four different floor areas with 50, 100, 150 and 200 persons per floor are investigated.
While in the partial evacuation simulation, the entire population was allocated as two groups. Half of them would use elevators and the other half went down by stairs. As well as the previous simulation in Figure 66, the buildings were kept the same. Congestion was taken into account, which occurred in all cases. N refers to the number of people per floor.

As we can conclude from the two figures, elevators do contribute to reducing the evacuation time in some cases. Especially for super tall buildings, it took two hours to vacate the 70-floor building by stairs in the densest case. Table 24 gives a suggestion of the preference for the way of egress, which is based on the different building heights, occupant density and the egress plans.
Table 24: Results of research 1

<table>
<thead>
<tr>
<th>Population</th>
<th>Full population egress</th>
<th>Half population egress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( N = 200 )</td>
<td>( N = 150 )</td>
</tr>
<tr>
<td>Residential</td>
<td>(&lt; 27 f : S )</td>
<td>(&lt; 35 f : S )</td>
</tr>
<tr>
<td></td>
<td>( &gt; 27 f : E )</td>
<td>( &gt; 35 f : E )</td>
</tr>
<tr>
<td>Office</td>
<td>(&lt; 15 f : S )</td>
<td>(&lt; 18 f : S )</td>
</tr>
<tr>
<td></td>
<td>( &gt; 15 f : E )</td>
<td>( &gt; 18 f : E )</td>
</tr>
</tbody>
</table>

Attention:
- ‘\( f \)’ refers to the number of floors;
- ‘S’ refers to evacuate by stairs;
- ‘E’ refers to elevators;

**CONCLUSION**

Egress by stairs for population of 50 persons per floor is much favorable concerning the total egress time. Evacuated by stair only is an option, and the combination of stairs and elevators could be considered as well. Clearly the utilization of elevators reduced the total egress time, especially for high-rise buildings.

**Research 3**

Since previous studies indicate that elevator-assisted evacuation is effective in some cases. The second research by University of Greenwich, United Kingdom, focuses on the way of integrating elevators and stairs, and modeling elevator-assisted evacuation (106). They simulated a building with four stairwell cores and four lift banks containing 8 elevators each. The information about the simulated building can be found in Table 25.

Table 25: Building information

<table>
<thead>
<tr>
<th>Floors</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor-to-floor height (m)</td>
<td>3</td>
</tr>
<tr>
<td>Total height (m)</td>
<td>150</td>
</tr>
<tr>
<td>Total population</td>
<td>7840</td>
</tr>
<tr>
<td>Population on each floor</td>
<td>160 (except the ground floor)</td>
</tr>
</tbody>
</table>

Some specific floors are designed as refuge floor or sky lobbies where occupants can transit to use an elevator or have a rest. Different combination of elevators and stairs were explored. Based on full building evacuation, II scenarios were designed with the help of buildingEXODUS. At the beginning of each scenario, all agents were assigned to either use a lift or stairs based on their original location. In each scenario, all of them were assumed to react immediately at the beginning of an event. Approximately the number of agents who are going to use the lift bank is equal.
SCENARIOS

Table 26: Overview of the evacuation scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Diagram</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1.png" alt="Diagram 1" /></td>
<td>Stairs only (4 stairs)</td>
</tr>
<tr>
<td>2</td>
<td><img src="image2.png" alt="Diagram 2" /></td>
<td>8 lifts (1 lift bank)</td>
</tr>
<tr>
<td>3</td>
<td><img src="image3.png" alt="Diagram 3" /></td>
<td>16 lifts (2 lift banks)</td>
</tr>
<tr>
<td>4</td>
<td><img src="image4.png" alt="Diagram 4" /></td>
<td>24 lifts (3 lift banks)</td>
</tr>
<tr>
<td>5</td>
<td><img src="image5.png" alt="Diagram 5" /></td>
<td>32 lifts (4 lift banks)</td>
</tr>
<tr>
<td>6</td>
<td><img src="image6.png" alt="Diagram 6" /></td>
<td>32 lifts, with the lower half of the building (floors 0-25) population using the stairs and the upper half (26-49) using lifts to shuttle to the ground floor.</td>
</tr>
<tr>
<td>7</td>
<td><img src="image7.png" alt="Diagram 7" /></td>
<td>32 lifts, with the lower-half of the building (floors 0-25) population using the stairs and the upper half (26-49) using the lifts to shuttle to the middle floor (floor 25) from the agents floor of origin, then continue their evacuation via the stairs.</td>
</tr>
<tr>
<td>8</td>
<td><img src="image8.png" alt="Diagram 8" /></td>
<td>32 lifts, with the lower-half of the building (floors 0-25) population using the stairs and the upper half (26-49) initially using the stairs to walk to a sky lobby on floor 26 where agents would be shuttled via lifts to the ground floor.</td>
</tr>
<tr>
<td>9</td>
<td><img src="image9.png" alt="Diagram 9" /></td>
<td>32 lifts, 4 shuttle zones - each lift bank servicing a series of 12 floors of agents, with each zone being evacuated from the top-down of the zone to the ground floor.</td>
</tr>
<tr>
<td>10</td>
<td><img src="image10.png" alt="Diagram 10" /></td>
<td>32 lifts, 4 shuttle zones + 1 Stair zone - each lift bank servicing a series of 10 floors of agents, with each zone being evacuated from the top-down of the zone to the ground floor. Agents below floor 10 only use the stairs to evacuate.</td>
</tr>
<tr>
<td>11</td>
<td><img src="image11.png" alt="Diagram 11" /></td>
<td>32 lifts, 4 Sky lobbies – there is a sky lobby every 10 floors in the building (4 sky lobbies in total) with each lift bank servicing one of the sky lobbies. Agents travel down the stairs to the next sky lobby below where the lifts shuttle them to the ground floor. Agents below floor 10 only use the stairs to evacuate.</td>
</tr>
</tbody>
</table>

LIFT ATTRIBUTION

- Maximum capacity for each lift: 13 agents
- Maximum speed: 6m/s; Accelerate rate: 1.2m/s²; Jerk rate: 1.8m/s³
- Door opening time: 0.8s; Door closing time: 3.0s
- A dwell delay time: 3.0s; A motor delay time: 0.5s
- Each lift starts at the ground floor.
- The priority for lifts is to service the upper floors first
Observations and Results

- No occupants on 10F and below used an elevator to evacuate;
- Sometimes the agents initially consider to take the lift but redirect to the stairs because of the waiting time, the average waiting time for those redirect to the stair is 3.4min in the lift waiting area;
- Only a small portion of agents in the lower part of the building considered using a lift;

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Time saved compare to stairs only (%)</th>
<th>Lift user (%)</th>
<th>Stair only (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>9.7</td>
<td>13.3</td>
<td>49</td>
</tr>
<tr>
<td>3</td>
<td>13.6</td>
<td>17.7</td>
<td>49</td>
</tr>
<tr>
<td>4</td>
<td>17.5</td>
<td>20.9</td>
<td>49.3</td>
</tr>
<tr>
<td>5</td>
<td>18.9</td>
<td>22.8</td>
<td>48.5</td>
</tr>
<tr>
<td>6</td>
<td>18.1</td>
<td>20.7</td>
<td>63.6</td>
</tr>
<tr>
<td>7</td>
<td>0.6</td>
<td>22.6</td>
<td>63.6</td>
</tr>
<tr>
<td>8</td>
<td>30.6</td>
<td>36.8</td>
<td>63.1</td>
</tr>
<tr>
<td>9</td>
<td>23.4</td>
<td>27.7</td>
<td>48.5</td>
</tr>
<tr>
<td>10</td>
<td>25.9</td>
<td>29.2</td>
<td>50.3</td>
</tr>
<tr>
<td>11</td>
<td>33.1</td>
<td>48.1</td>
<td>50.1</td>
</tr>
</tbody>
</table>

Attention:
- Lift user: the overall proportion of agent that use the lift due to congestion in the lift waiting area
- Stairs only: the overall proportion of agent that use the stairs due to time expiration and congestion in the lift waiting area

Conclusion

The model demonstrated the likelihood people will use a lift for evacuation. Based on the results from these simulations, scenario 11 (four sky lobbies) shows the largest lift usage produced the shortest overall evacuation time. At the same time, the most effective strategy involves multiple sky lobbies. Agents walk to their nearest sky lobby and transfer to a lift. In addition to that, the speed of the lift, as well as the lift capacity should be properly designed. It is found that the impact of the lifts status is also important.
4.7 SYNTHESIS AND CONCLUSION

This chapter has focused on literature review and fire legislations through a global perspective. We have explained the basic egress concept such as the design principles, egress strategies and different types of vertical egress methods. To substantiate all the legal requirements and design principles, several case studies have been carried out. Lastly, new developments in elevator-assisted evacuation have been investigated.

4.7.1 COMPARISON BETWEEN EGRESS STRATEGIES

Egress strategies refer to the evacuation process in case of an emergency, which can be generally classified into two categories on the time basis: simultaneous and phased evacuation. A comparison between the aforementioned four egress strategies is given below.

- Simultaneous egress strategy is implemented within the total building. But for tall buildings with large population, the key problem with this strategy is that insufficient capacity of vertical transportation would lead to unexpected congestion, which hinders the egress progress.
- Phased evacuation takes place in a time sequence. Since not all occupants are using the various egress components, people in immediate harm can be able to egress faster. Difficulties arise with respect to building management, however, when an attempt is made to implement this strategy. If occupant notification and fire compartmentation zones are not identical, when people who remain in the building are given inappropriate information, there is a risk of panic.
- People who cannot get all the way out of the building bring the need of relocation strategy, or the evacuation zone scheme. However, the most difficult obstacle to overcome in a relocation strategy is the complexity of coordinating the occupant notification system with building construction features.
- The only difference between defend-in-place and relocation strategy is the evacuating group. Only the fire floor is required to escape in defend-in-place strategy. Successfully control of the fire would be the premise of applying this strategy.

One major drawback of simultaneous evacuation is that stairs are likely to become highly congested in skyscrapers with large population. Meanwhile, phased evacuation, relocation or defend-in-place strategy reveals their benefits:

1) Occupants who remain in the building are protected from the developing fire so that they do not have to walk in corridors and stairwells which might be contaminated by smoke;
2) During fleeing, the evacuees do not impede the fire department who may be conducting firefighting operations from the stairwells;
3) Not the entire population uses the vertical transportation at the same time, which optimizes the egress system efficiency;
4) The evacuation process can be halted at any phase once the fire is extinguished;
5) Relocation, defend-in-place strategies also reduce the business interruption due to false alarm;

4.7.2 COMPARISON BETWEEN VERTICAL EGRESS APPROACHES

People regard stairs as the most traditional method of vertical circulation in buildings. It guarantees the egress safety when serves as an enclosure and proper fire-prevention measures have been taken. But in skyscrapers, perhaps the most serious disadvantage of using stairs is that traveling down thousands of steps is undesirable and exhausted. To lessen the time of simultaneous evacuation in buildings with large occupant density, fire and smoke proof elevators can be recommended. More importantly, these elevators should be equipped with fire extinguisher, emergency lighting and other fire-protection facilities which ensure them to withstand fire within a certain period.

Apart from common egress methods, integration of other innovative approaches could optimize the egress process. Just as the case of the MGM Grand Hotel, on condition that people were able to reach the roof, helicopter rescue may have advantages in saving life from tall buildings. However, this method has a number of limitations. Using only helipad cannot function very efficiently due to the limited capacity of one helicopter. The major drawback of rescue by helicopters, however, is the cost if the entire building is rescued by merely helicopters. But it works better when combined with other apparatus. The application of escape chutes has its pros and cons. Escape chute is easy to use since no extra power is needed. When all other means of emergency egress are blocked, it is an alternative method of evacuating from a high location. It might also be noted that before the application of escape chute, people must check whether there are obstacles by the exit at the bottom. In comparison with other measures, abseiling presents relatively high risks, especially for unsupervised people. Not everybody can succeed in rappelling down with his/her feet.

4.7.3 CONCLUSION REGARDING FIRE REGULATIONS

The purpose of fire regulation is to provide for the direction of construction work, ensure that occupants would use the building safely without endangering their health, and be able to escape from fire. The numerous requirements in regulations are in large part based on the building height, function and occupant load of each space within a building. Measures shall be taken to provide protection against the outbreak and spread of fire.

As heat and smoke are the main causes of casualties, much attention was paid to control fire spread and smoke propagation in all fire norms. Control of smoke can be achieved by pressurized staircase, smoke prevented lobby, fire curtain, self-closing doors and so on. Mechanical code regulates the power of smoke extraction, and hygienic code regulates the allowable amount of hazard. Egress design should be considered along with the hygienic codes as well. Furthermore, smoke propagation has something to do with the
compartmentation, fire-resistant time of the structure and escape routes. Architectural design according to building regulations laid the foundation for fire egress design.

In some countries like the United States, China and Australia, there will also be a need for refuge zones in skyscrapers. Sky lobby or several floors below the fire floor can be the refuge zone.

Egress routes shall be fire-protected. Planning of egress routes is considerable because it relates to human safety. Proper egress routes result in arriving at a secure area successfully before get injured. Most of the time, at least two egress routes should be provided. Walking distance to the stairs is usually between 30m and 45m. As required in most countries, communication system contributes to egress in guiding occupants, in particular, for large complex buildings. It is much efficient since communication system provides the appropriate route and saves time, and evacuees do not need to figure out the way on their own.

In conclusion, life safety is the most crucial subject in every code, while property protections are not included in almost all norms. In addition to technical aspects, effective and safe egress depends on good organization and training as well. A good egress design should be based on regulations and integrate all these factors stated in this chapter.
5

KONINGIN JULIANAPLEIN
EGRESS PLANS
5.1 **INTRODUCTION**

This chapter presents four egress plans for a certain tower Koningin Julianaplein. The scope of this chapter, with a focus on describing each plan in general, we derived the structural fire-resistant requirements for each plan based on the theoretical egress time calculation. Some variations such as using stairs, elevators or other combinations will be integrated with different egress strategies. To begin the chapter, we will first make a comparison of the three Dutch projects provided by DGMR, and clarified the reasons for redesign of Koningin Julianaplein.

5.1.1 **PROJECTS COMPARISON**

As has been stated, egress concept A in SBR (chapter 3.2.3.2) was adopted in all three towers. Calculations and capacity check from DGMR indicated that the structural fire resistance attributes were able to ensure the egress safety. However, there can be more diversifications when we looked into the egress strategies from an international perspective. Accordingly, Koningin Julianaplein has been chosen from the three projects for a further development. Evaluating criteria were described briefly in the next table.

<table>
<thead>
<tr>
<th>Building Selection criteria</th>
<th>Coolsingeltoren</th>
<th>Koningin Julianaplein</th>
<th>Hoog aan de Maas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architectural design</td>
<td><img src="image1.png" alt="Coolsingeltoren" /></td>
<td><img src="image2.png" alt="Koningin Julianaplein" /></td>
<td><img src="image3.png" alt="Hoog aan de Maas" /></td>
</tr>
<tr>
<td>Floor layout</td>
<td><img src="image4.png" alt="Coolsingeltoren" /></td>
<td><img src="image5.png" alt="Koningin Julianaplein" /></td>
<td><img src="image6.png" alt="Hoog aan de Maas" /></td>
</tr>
</tbody>
</table>
Egress as Part of Fire Safety in High-rise Buildings

<table>
<thead>
<tr>
<th>Building functions</th>
<th>Offices</th>
<th>Conference rooms</th>
<th>Retail</th>
<th>Theater</th>
<th>Restaurant</th>
<th>Parking garage</th>
<th>Bicycle storage</th>
<th>Offices</th>
<th>Conference rooms</th>
<th>Retail</th>
<th>Auditoria</th>
<th>Restaurant</th>
<th>Residential</th>
<th>Parking garage</th>
<th>Bicycle storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor area</td>
<td>Circa 1200 m²</td>
<td>Maximum 2300 m²</td>
<td></td>
<td>Circa 805 m²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Every floor is the same</td>
<td>Different along with the shape of the tower</td>
<td></td>
<td>Every floor is the same</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From the comparison above, we can see that in terms of evacuation, occupants in Coolingseltoren are able to enter the stairwell easily because of the limited floor area. Hoog aan de Maas is a structure built on an existing building. Because of that, the location of the structural elements is hard to adjust. Similarly, the variation of floor area and building function are placed under restriction. While the floor plans of Koningin Julianaplein diverse from the bottom to top due to the irregular architectural shape. All in all, Koningin Julianaplein is a challenging project, as well as the most applicable tower for a redevelopment. In the end, recommendations will be given on both Koningin Julianaplein and the future high-rise projects in the Netherlands.

Figure 68: Koningin Julianaplein, The Hague
5.1.2 Influences on Egress Design

As has already been stated, the design concept will not be defined as same as the Dutch code Bouwbesluit and SBR guideline. Four egress plans have been made for Koningin Julianaplein based on the knowledge gained from publications. It is a synthesis of reasonable egress strategies and diverse vertical egress methods. A number of factors would influence the egress design of high-rise buildings, and hence, it is essential to draw attention to these aspects beforehand. Not only from the fire safety point of view, but also:

- Architecture: Fire safety design plays an important role in the architectural design of tall buildings. The floor layout, the shape and height of the building, building function, the types of construction materials, the dimension of transportation spaces, even the urban surroundings can affect evacuation in fires. This can be treated briefly by an example. When a theater is designed on a certain level, as we all know that the occupant density is higher. To reduce the effect of crushing and congestion, this theater will possibly result in different egress strategy such as phased evacuation. In addition to the building function, the corridor layout and location of exits affect the egress routing. Furthermore, when sky lobbies act as refuge in a relocation plan, whether they are expected to be seen on the facade related to the exterior design in consultation and coordination with the architects. Moreover, architects should leave spaces for the extinguish facility during design. Consequently, to avoid contradiction, meetings and discussion with architects are of great importance.

Figure 69: Visible refuge floors on the facade

- Structure: Egress plan have impact on structural design and construction. Construction materials and types vary in different projects. As has been mentioned in the chapters before, all the building elements (bearing walls, facade, floors, interior walls, roof, and structural frames) should have a fire-resistant period. To ensure the egress safety of all occupants, the main load bearing structure should remain its integrity for a reasonable long period. In a phased or relocation evacuation, the egress starting time differentiates depending on the evacuees' initial location, requirements of structural fire-resistant time could be even longer. On the other side, we need to consider the feasibility of the construction techniques as well. Sometimes egress concepts presented go beyond traditional building code provisions supposing that the architectural design is irregular, which means that some extraordinary design may require 300 minutes fire resistance rating for instance. It would be impossible as the size of this component may be too large to fabricate.
Additionally, for relocation strategy, the orientation of the refuge floor could also have significant impact on structure on account of the opening and wind load\textsuperscript{20}.

- Economic: Building design is closely relate to the construction budget, as well as egress plan. One tower with several egress plans available, for instance, Plan A requires two larger staircases while plan B requires three smaller stairwells. Each stair shaft needs to be fire-protected. Since most of the building cores contain elevators and stairs, which play an important role in the structural system. On the one hand, when the designers increase the dimension or the number of stairwells, the flow capacity may become larger, but the cost of a concrete core growths at the same time. On the other hand, making the core as small as possible can give more usable areas to the occupants and maximizing the profits for the building owner. But the size of a core should have a certain storage capacity to serve the required quantity of evacuees during egress. Likewise, keeping a limited walking distance to the staircase improves the safety level, while usable floor area needs to be optimized. When we larger the transportation area, it will probably occupy the areas for renting offices and dwelling, and influence the developers’ revenue.

### 5.1.3 Calculation Methodology for Egress Time

To achieve a well-designed egress plan, egress time calculation is thus essential. Initially, we need to find a tool to carry out the computation with all the architectural and structural input of that building. Basically, egress time calculation results can be attained either by manual calculation, or complex computer simulating models. In this section, we begin with the determination of our desired output, so to speak, what kind of results we want to achieve after the calculation. Next, an appropriate calculation tool will be chosen to fulfill these output requirements. Finally, the section ends with a brief statement on the design principles, and an analysis of all the towers in Koningin Julianaplein.

To date various methods have been developed and introduced to calculate the theoretical egress time in emergencies. Calculation of egress time is a process from simple to complex, decided by how many factors we want to achieve in the end. We made a list of the most relevant design factors so as to find an applicable calculation tool for Koningin Julianaplein. Table 29 presents the information that can be considered in an egress time calculation, and followed by an evaluation.

\textsuperscript{20} Find further information from literature (79) if interested.
Table 29: Overall features of egress plan

<table>
<thead>
<tr>
<th>Relevant egress design factors</th>
<th>Do we want to know?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Fire load</td>
<td>No</td>
</tr>
<tr>
<td>2 Fire location</td>
<td>Yes (1)</td>
</tr>
<tr>
<td>3 Fire and smoke spread</td>
<td>No</td>
</tr>
<tr>
<td>4 Toxicity</td>
<td>No</td>
</tr>
<tr>
<td>5 Route choice</td>
<td>No</td>
</tr>
<tr>
<td>6 Counter flow</td>
<td>No</td>
</tr>
<tr>
<td>7 Groups</td>
<td>Yes (2)</td>
</tr>
<tr>
<td>8 Disabled agents</td>
<td>Yes</td>
</tr>
<tr>
<td>9 Movement</td>
<td>No</td>
</tr>
<tr>
<td>10 The location of every agent at every moment</td>
<td>No</td>
</tr>
<tr>
<td>11 Delay/ pre-movement</td>
<td>Yes</td>
</tr>
<tr>
<td>12 Interaction between agents</td>
<td>No</td>
</tr>
<tr>
<td>13 Impact on agents' familiarity</td>
<td>No</td>
</tr>
<tr>
<td>14 Speed on stairs</td>
<td>Yes</td>
</tr>
<tr>
<td>15 Storage capacity of the transportation facility</td>
<td>Yes</td>
</tr>
<tr>
<td>16 Flow rate of the transportation facility</td>
<td>Yes</td>
</tr>
<tr>
<td>17 Exit block/ Availability of the route</td>
<td>No</td>
</tr>
<tr>
<td>18 Congestion and queuing (globally)</td>
<td>Yes</td>
</tr>
<tr>
<td>19 Assigning exit usage according to occupant familiarity</td>
<td>No</td>
</tr>
<tr>
<td>20 The time spent in congestion for each occupant</td>
<td>No</td>
</tr>
<tr>
<td>21 Compartment dimension</td>
<td>Yes</td>
</tr>
<tr>
<td>22 Distinguishing emergency exits from normal exits</td>
<td>No</td>
</tr>
<tr>
<td>23 Total length of route</td>
<td>Yes</td>
</tr>
<tr>
<td>24 Vertical distance moved on stairwell</td>
<td>Yes</td>
</tr>
<tr>
<td>25 Individual floor clearance time</td>
<td>Yes</td>
</tr>
<tr>
<td>26 Use of lift/elevator</td>
<td>Yes</td>
</tr>
<tr>
<td>27 Demonstrating the results of a simulation graphically/ 2D</td>
<td>No</td>
</tr>
<tr>
<td>28 Egress simulation animation</td>
<td>No</td>
</tr>
</tbody>
</table>

Remarks:
1 Fire location will be assumed except simultaneous evacuation
2 The assumption in the egress time calculation is that the group distribute equally.

**Manual calculation**

A number of manual computation methods based on traveling by stairs only have been discussed in Appendix A, including Melinek and Booth, Pauls, Kikuji Togawa, Australian method and method based on assumptions given in the SFPE Handbook applied in America. These formulas help us to carry out the building egress time in general. The input of simple hand calculations are parameters like the number of floors, occupant density, and dimension of transportation facilities. However, all the previously mentioned methods suffer from some limitations. For instance, some of them require a same floor plan for every floor. Even the occupant density and floor-to-floor height are fixed value. Apparently, the

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²¹ SFPE: Society of Fire Protection Engineers of the United States.
application is confined to uncomplicated structures unlike Koningin Julianaplein. On the contrary, more elaborated approaches like the SFPE or the Australian method are regulation-based. They have more input information, like the stair dimension, different density per floor, different floor plan, the exit size can be varied et cetera, which possibly will lead to a better result.

**Computer models**

Certainly, egress time calculations can be done with the help of computer simulation. Most of the factors in Table 29 can be achieved by different models. There are three types of modeling in general: micro, meso, and macro model. Micro model gives the most detailed calculation, since all the input information is specific and relatively comprehensive. Macro model provides a global egress calculation with few parameters, while meso model is something in between. The underlying theory behind these models is based on a large sum of literature, experiments and fire drills. Computer simulations possess many benefits that hand calculation cannot attain. However, using computer models suffer from weaknesses at the same time. To achieve a better result, it usually takes a long time to build the model and run the simulation. Today, some prevalent software is available such as SimPed, buildingEXODUS, EGRESS et cetera. Moreover, most of them are not free of charge.

**Conclusion regarding methodology**

Considering the total research period and the aforementioned factors, ‘More Detailed Analysis’ of SFPE method contains all the results that we want to achieve, thus has been applied for egress time calculation in our research. The entire calculation can be found in Appendix D. Within SFPE method, the population will use all exit facilities in the optimum balance, meanwhile consideration also gives to queuing effect and merging effect of the flow from the level above. Some benefits of applying SFPE method are:

- Travel speed on corridors and stairs are calculated individually;
- It is appropriate for simultaneous evacuation, and variations can be based on it regarding other strategies;
- Stair dimension, occupant density, door and corridor width can be different in every floor in this method, which fit for Koningin Julianaplein;

While to be critical, there is no general agreement about the precision of hand calculation and computer simulation. Since fire evacuation is a special case that every fire acts differently and people react differently in every evacuation drill, it is influenced by numerous parameters. Between hand calculation and computer simulation, we can neither prove nor confirm which result is much reliable and closer to reality.

**Principles of egress time calculation**

Total egress time depends on the egress strategy, traveling time to a place of safety, time to queue and flow time through the exits. The principles of the egress time calculation in Appendix D are described as follows.

- Occupant density is the maximum probable number of occupants present per square meter at any time;
- Calculation of storage rooms for dwelling is based on the worst-case situation, which means one person presents in each room;
- The horizontal traveling time to the staircase door is determined by the walking speed, and the longest walking distance on that floor;
- Bicycle shop, bicycle store and the underground parking garage will not be considered in the redesign of Koningin Julianaplein. Normally the occupant loads for these places are quite low;
- To simplify the egress time calculation, in Appendix D, the division of the area and routing between the office towers is: half of the population uses the scissors stairs in tower 1; and the rest escape via the scissor stairs in tower 2;
- Assumption for both the egress time calculation and the building egress design is that the structure would not collapse during evacuation.

5.1.4 Towers Analysis

Koningin Julianaplein is basically composed of four towers, two for offices and two for residences. Dissimilar with traditional architecture, each tower has unique floor layouts. As a result, egress routing, travel distance and occupant loads vary from one tower to another. As several floors merge at the top, the necessity of redesign is demarcating a clear boundary for each tower. This section provides an analysis of each tower, and discusses the possible vertical egress methods for Koningin Julianaplein.

5.1.4.1 Floors and Tower Boundaries

Assumptions have been made for the egress time calculation that half of the area between tower 1 and 2 belongs to tower 1, while the other half belongs to tower 2. Hence axis 6
acted as the boundary between tower 1 and 2, which is nearly in the middle of the two towers. From the figure above we can see that tower 3 and 4 can be separated by the partition wall between the dwellings. The assumption also indicated that occupants would generally apply the vertical egress facilities within the tower boundary.

Table 30: The floor information of Koningin Julianaplein

<table>
<thead>
<tr>
<th>Functions</th>
<th>Tower 1 and 2</th>
<th>Tower 3 and 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floors</td>
<td>Retail, office, auditorium, meeting room, technical room</td>
<td>Retail, storage room, residence</td>
</tr>
<tr>
<td>Connection</td>
<td>22 floors in total</td>
<td>26 floors in total</td>
</tr>
<tr>
<td>Floor-to-floor height</td>
<td>Connected from the 15th floor</td>
<td>Connected from the 20th floor</td>
</tr>
<tr>
<td></td>
<td>5.4m (ground floor)</td>
<td>4.5m (ground floor)</td>
</tr>
<tr>
<td></td>
<td>3.6m (from 1F to 22F)</td>
<td>3.0m (from 1F to 26F)</td>
</tr>
</tbody>
</table>

5.1.4.2 Vertical Egress Methods

In terms of egress time calculation, the first step was to determine the vertical means of egress. Initial consideration has been given to the building function since it closely related to the occupant density. Occupants’ travel speed and travel time can be derived from the occupant density. Most vertical egress methods mentioned in chapter 4.3 were integrated in the redesign of Koningin Julianaplein. Among them, stairways serve as the main vertical means of egress in our research. Figure 71 describes the vertical egress methods we concerned for each egress strategy.

![Diagram showing vertical egress methods](image-url)
5.1.4.3 Office Towers

From the ground floor to the 14th floor, office tower 1 and 2 are separated from each other. The top parts meet and merge, and the largest floor area even reaches 2292 m² at the 17th floor (Figure 72).

Fire compartments and horizontal travel distance

Throughout this research the term horizontal travel distance is used to refer to the distance from the evacuee’s original location to the staircase entry door with respect to egress design. Larger floor area may result in longer horizontal travel distance, which could potentially endanger those evacuating in fires. From the 18th to the 21st floor in tower 2, the utmost point to the stairwell reaches 60 meters. It is imperative to take some actions to divide the compartments and shorten the walking distance to another compartment. Figure 72 illustrates the suggested smoke barriers such as self-closing fire resisting door and smoke proof partition walls. Table 31 exhibits the summarization of the largest floor area and the longest horizontal travel distance. We can see that the maximum horizontal travel time is 50.4 seconds, which was calculated according to the occupant load and the corridor capacity. Even if the travel distance is long, this floor layout is acceptable, provided that the last occupant is able to reach the staircase entry door within 60 seconds. It should also be noted that the horizontal distance we applied in the calculation of Appendix D did not take account of the smoke barriers, since the travel time would certainly be reduced when sub-compartment is introduced. All escaping corridors should be fire-protected as an enclosure to prevent people from hazard. Moreover, we can increase the limit of horizontal travel distance to some degree when the building is equipped with automatic sprinkler installation.

![Figure 72: The largest connected floor in the office tower (17F)](image)
Table 31: Maximum horizontal travel distance in the office towers

<table>
<thead>
<tr>
<th>Office towers</th>
<th>Tower 1</th>
<th>Tower 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 to 14F</td>
<td>15F to 22F</td>
</tr>
<tr>
<td>Longest walking distance (m)</td>
<td>35.6 (14F)</td>
<td>46.9 (18F)</td>
</tr>
<tr>
<td>Horizontal travel time (s)</td>
<td>29.9 (14F)</td>
<td>39.4 (14F)</td>
</tr>
<tr>
<td>Largest floor area (m²)</td>
<td>383 (13F)</td>
<td>869.5 (20F)</td>
</tr>
</tbody>
</table>

Routing

By following the emergency exit sign, the office staffs evacuate through their nearest stairway in the scissors staircase. Because of this, the population can be halved in each stairway. With an assumed fire location, Figure 73 and 74 illustrate the layout of the largest floor in each tower and egress routes for the furthest room. Two separate routes are available to permit prompt evacuation. Stairway is the most common means of egress for these towers, since most people working in offices can move freely without elevator assistance. The evacuees are considered safe when they reach the protected enclosure (door).

OFFICE TOWER 1

Scissors stairs
- Stairway 1: the stairs lead eventually to the ground floor opens to the Rijnstraat, near the public transport terminal;
- Stairway 2: the stairs on the ground floor eventually joins the Rijnstraat on the side of the Hertenkamp Deer Park.

OFFICE TOWER 2

Scissors stairs
- Stairway 1: the stairs leading eventually to the ground floor opens out to the Koningin Julianaplein;
- Stairway 2: the stairs on the ground floor which eventually joins the Rijnstraat.

In addition, it is also assumed that a fire occurs between the two towers (Figure 75), the most affected offices near the fire source can be provided with at least two different exit routes. As a matter of fact, there are more available means of egress, Figure 75 only depicts two routings as examples.
Figure 73: The largest occupied floor in the office tower 1 (20F)

Figure 74: The largest occupied floor in tower 2 (17F)
Analysis of the auditorium

It is common for high-rise buildings to house more than one function. However, areas like restaurant, gymnasium or theater usually gather more people and lead to higher occupant load. Sometimes the crowd poses serious problems during fire egress. Koningin Julianaplein, in particular, the occupant density is not identical due to diverse function and floor layouts. The following paragraph carries out an analysis and the optimum solution for a critical space in the tower 1 and 2 - the auditorium.

The auditorium locates in the office tower across the 15th and 16th floor. There will be a maximum of 200 audiences concurrently. Since the occupant density is much higher than other floors, crushing and congestion may arise when audiences rushed toward the exits in an emergency. The cross section shows the surrounding stairwells that can be used (Figure 76). Considering the layout of the auditorium, the involvement of fire communication system can improve the egress efficiency. By following the spoken signal, audiences are distributed into four groups according to their seat numbers. Five rows were designed as one escaping group (Figure 77).
Figure 76: Cross section of the auditorium and the nearest stairs

As depicted in Figure 77, group 2 and group 4 use the two back exits and travel to the higher floor, and use the scissors stair in tower 1 from the 16th floor. Audiences sitting in the front such as group 1 and 3, take the scissors stairs of the 15th floor. As a consequence of the distribution of evacuees, overcrowding can be avoided to some extent.

Figure 77: Auditorium egress plan
Analysis of the atrium

Atrium is popular in large office buildings as it gathers people for social activities, admits sufficient natural light, and provides the visual impression of openness. Despite the advantages of atria, buildings with atria can be dangerous for occupants in a fire. It also brings challenges in fire-protection. A 28.8 meters high atrium locates in the office tower 2 from the 14th floor till the roof. The gathering area on the 15th floor is around 227m². The entire atrium forms a large fire compartment across eight levels. Therefore for egress design, special attention should be paid to the smoke control and extraction system.

Since column of smoke and gases diffuses and rise towards the ceiling, large exhaust fan should remove the smoke from the atrium. Otherwise, the smoke layer at the ceiling will spread downwards gradually and reduce the clear height. Because of the rising smoke, with respect to phased evacuation concept, those located on upper floors shall evacuate first.
5.1.4.4 Residential Towers

Residential towers 3 and 4 encompass mainly dwelling units. Storage rooms are located on the 2nd and 3rd floor beneath the dwellings. Each residential tower has totally 26 levels. In comparison with the office towers, the vertical travel distance via stairs is longer since each tower has four more stories.

Figure 80: The largest unconnected floor in the residential towers (16F)

Figure 81: The largest unconnected floor in the residential towers (25F)

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22 Each dwelling has its own storage room. In the Netherlands, it is common to have storage rooms under apartment units.
Fire as Part of Fire Safety in High-rise Buildings

Fire compartments and horizontal travel distance
Residential buildings are mostly highly compartmented, and the horizontal travel distance to the staircase entry door decreases considerably. The average usable area for each dwelling is approximately 150m². Every dwelling forms an individual fire compartment. Figure 80 and 81 illustrate the largest unconnected and connected residential floors, respectively. Apparently, there is almost no corridor in these towers. The distance between the staircase and the dwelling door is very short. We apply the worst-case situation for our research. In case of a fire, the maximum horizontal walking distance will be at a distance from the most remote position in a dwelling to the inner stair entry door.

Table 32: Maximum horizontal travel distance in the residential towers

<table>
<thead>
<tr>
<th>Residential towers</th>
<th>Tower 3</th>
<th></th>
<th>Tower 4</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 to 19F</td>
<td>20F to 26F</td>
<td>0 to 19F</td>
<td>20F to 26F</td>
</tr>
<tr>
<td>Longest walking distance (m)</td>
<td>36 (10F-16F)</td>
<td>30 (20F-26F)</td>
<td>28.8 (19F)</td>
<td>36 (20F-26F)</td>
</tr>
<tr>
<td>Horizontal travel time (s)</td>
<td>30.3 (10F-16F)</td>
<td>25.2 (20F-26F)</td>
<td>24.2 (19F)</td>
<td>30.3 (20F-26F)</td>
</tr>
<tr>
<td>Largest floor area (m²)</td>
<td>488.8 (10F-16F)</td>
<td>390 (25F)</td>
<td>356 (19F)</td>
<td>532 (25F)</td>
</tr>
</tbody>
</table>

Table 32 describes the maximum horizontal travel distance and travel time in the residential towers. We can figure out that generally people can reach a safe area within 30 seconds. However, the 30 seconds do not include the time of pre-movement. Since in residential buildings normally there are a host of factors that affect people's reaction. Ignition cues need to be perceived, and then people can react. On one hand, once the fire occurs at night when the occupants are sleeping, it is hard for them to escape and react as fast as in daytime. On the other hand, residents usually form a wide age range. People's physical condition plays an important role as well. For instance, a fire happens in the kitchen of an elderly family, they cannot notice the fire because they neither see the flame nor smell the burning stuff. Then the pre-movement time can be quite long and delays the entire egress process. In consequence, the utilization of elevators should be considered for the people who need assistance or with wheelchairs, and refuge areas can be used for temporary rest.

Routing
The basic scenario is that all evacuees evacuate by stairs alone, variations will be the integration of elevators, helicopter et cetera. Residential exits are close to the staircase doors. Unlike the office tower, the stairs in the residential towers is without intermediate landing. The figure below illustrated the drawing of vertical transportation for dwellers.

Figure 82: Stairs in the residential tower
Every stairwell has two doors at each side, which ensures the residents to reach their nearest one. Once one route is blocked, people can also use the stairs by the other door, and they are quite close. The available egress routing example of the 10th to 16th floor is illustrated in Figure 83 with an assumed fire location in the kitchen.

Figure 83: Available egress routes in the residential towers (10F to 16F)
5.2 PLAN 1 - SIMULTANEOUS EVACUATION

5.2.1 GENERAL EGRESS PLAN

The first plan has tended to focus on vacating each floor, and all occupants start to evacuate simultaneously upon the fire alarm signal. For that reason, it is not necessary to determine the fire location. Emergency signs and lighting system provide guidance for the occupants to find their way to escape. Everyone leaves the building through the exit(s) on the ground floor eventually.

Assumptions

The simultaneous evacuation plan and egress time calculation has been carried out according to the subsequent assumptions:

- Everyone starts to egress at the same time. The total evacuation starts 4.9 minutes (4:54) after the ignition
- In each tower, there is one emergency elevator available for the fire department;
- When elevator is integrated within the egress plan, all elevators start on the ground floor initially. The priority of service is to vacate the upper floors first (top-down mode). We assume that the elevators work at an average speed, and the accelerate speed and jerk rate are neglected;
- The square in front of the Hague Central Station is used as the external emergency assembly point for occupants after exiting the building.

Initial egress schemes

To start with, several egress possible situations have been considered for simultaneous evacuation. As has been noted, two office towers meet and merge from the 15th floor, and the residential towers are connected from the 20th floor to the top. Take the Petronas Tower as a reference, Koningin Julianaplein can be divided into top zone and low zone as well. Stairs, elevators, escape chute and other vertical egress methods mentioned in chapter 4.3 were integrated in this research. The four initial schemes are stated below:

1) Stairs only: The entire population use only stairways to evacuate.
2) Stairs in combination with elevators: Three situations were discussed within the second scheme. Elevators operate as a means of egress for the top zone, since normally occupants below the 10th floor would like to use stairs. When elevators and stairs are considered together, the transition floor is necessary.
   2.1) The top zone gets down to the transition floor. Some evacuees chose to wait for the elevator, while some of them continue their way on stairs. The low zone evacuate only by stairs;
   2.2) The towers are not divided into zones. Stairs and elevators can be used for all occupants on every floor, depending on their own choice;

23 4.9min including the detection time (48s), alarm time after detection (6s), occupant decision time (120s), and occupant investigation time (120s). (BS7974:2001 Application of fire safety engineering principles to the design of buildings)

24 The choice of using elevators or not, so to speak, the proportion of using elevators was derived from the literature (103). Detailed explanation of the egress time calculation is in Appendix D.
2.3) The towers (1 and 2) are divided into three zones, top, middle and low zone. Every zone contains about 7-8 floors. The low zone use only stairs to evacuate, while the higher zones egress by stairs to the transition floor and transfer to elevator and use the elevators to get to the ground floor.

3) Elevators only: The entire population evacuate the whole building by elevators only;

4) Combination: Combination of different means of egress components, such as stairs, elevators, helicopter, escape chute and abseiling.

![Simultaneous Evacuation Diagram](image)

Figure 84: Simultaneous evacuation diagram

5.2.2 EGRESS TIME CALCULATION

SFPE method (Appendix A) was applied to calculate the egress time of simultaneous evacuation. Both horizontal and vertical egress times were reckoned. The purpose of calculating the horizontal traveling time is to figure out whether the users can reach the vertical facility in time. It is determined by the walking speed and travel distance. Appendix D contains the egress time calculation of simultaneous evacuation in the four towers. Calculation results are demonstrated in Table 33, and Table 34 gives the theoretical egress time according to the Dutch SBR guideline and NEN 6089.

<table>
<thead>
<tr>
<th>Egress approach</th>
<th>Egress time (mm:ss)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tower 1</td>
</tr>
<tr>
<td>Stairs only</td>
<td>18:00</td>
</tr>
<tr>
<td>(1) 22:00</td>
<td>(1) 28:00</td>
</tr>
<tr>
<td>(2) 16:54</td>
<td>(2) 24:30</td>
</tr>
<tr>
<td>Stairs &amp;</td>
<td></td>
</tr>
<tr>
<td>elevator</td>
<td>Top zone: stairs and elevator; Low zone: stairs only; Entire building: stairs and elevators</td>
</tr>
<tr>
<td>Variations</td>
<td>Top zone: elevators only; Low zone: stairs only; Entire building: stairs and elevators</td>
</tr>
</tbody>
</table>

Table 33: Egress time of simultaneous evacuation (SFPE method)
Table 34: Egress time of simultaneous evacuation (Dutch method)

<table>
<thead>
<tr>
<th>Location</th>
<th>Tower 1</th>
<th>Tower 2</th>
<th>Tower 3</th>
<th>Tower 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stair 1</td>
<td>11:53</td>
<td>20:45</td>
<td>5:38</td>
<td>5:38</td>
</tr>
<tr>
<td>Average</td>
<td>11:56</td>
<td>20:42</td>
<td>5:42</td>
<td>5:44</td>
</tr>
</tbody>
</table>

SBR method (mm:ss)

<table>
<thead>
<tr>
<th>Location</th>
<th>Tower 1</th>
<th>Tower 2</th>
<th>Tower 3</th>
<th>Tower 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free walk</td>
<td></td>
<td></td>
<td>5:38</td>
<td>5:38</td>
</tr>
<tr>
<td>Hindered walk</td>
<td>13:22</td>
<td>13:22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theoretical egress time</td>
<td></td>
<td></td>
<td>5:42</td>
<td>5:44</td>
</tr>
</tbody>
</table>

NEN6089 / MR2012 method (mm:ss)

<table>
<thead>
<tr>
<th>Location</th>
<th>Tower 1</th>
<th>Tower 2</th>
<th>Tower 3</th>
<th>Tower 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Each scissor stair</td>
<td>15:30</td>
<td>2:3:30</td>
<td>13:30</td>
<td>13:30</td>
</tr>
</tbody>
</table>

Stairs only
The theoretical egress time calculation by means of Dutch method was based on SBR guideline and NEN6089. It was implicitly shown that both calculation approaches gave similar results according to Table 34. While table below summarized the comparison between these two approaches, we deducted the 294s pre-movement time in SFPE method. We took the top floor and several top floors in each tower as examples and simply compared the floor clearance time (Table 35). Appendices D and E present the relevant calculations in detail.

Table 35: Analysis of the two calculation methods

<table>
<thead>
<tr>
<th>Location</th>
<th>SFPE</th>
<th>Comparison 1</th>
<th>NEN6089</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top floor of office tower</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30s</td>
<td>32 people pass the staircase entry door; 33 people waiting at the staircase entry door;</td>
<td>24 people pass the 21F staircase entry door; 14 people on the upper platform in the staircase; 27 people on the 21F stairs; 27 people on the stairs and the middle platform; 0 people pass the 21F staircase entry door; 12 people on the upper platform in the staircase; 26 people on the 21F stairs; 37 people on the stairs and the middle platform;</td>
<td></td>
</tr>
<tr>
<td>90 to 120s</td>
<td>97s: all people evacuated 22F 108s: the end of the flow reaches 21F</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Comparison 2

<table>
<thead>
<tr>
<th>Location</th>
<th>Tower 1</th>
<th>Tower 2</th>
<th>Tower 3</th>
<th>Tower 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor clearance time (s)</td>
<td>60</td>
<td>180</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td>Tower 1</td>
<td>22F</td>
<td>97</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>21F</td>
<td>150</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20F</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tower 2</td>
<td>22F</td>
<td>238</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td></td>
<td>21F</td>
<td>304</td>
<td>390</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20F</td>
<td>382</td>
<td>480</td>
<td></td>
</tr>
<tr>
<td>Tower 3</td>
<td>22F</td>
<td>45</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>21F</td>
<td>60</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20F</td>
<td>75</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Tower 4</td>
<td>26F</td>
<td>51</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25F</td>
<td>67</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24F</td>
<td>84</td>
<td>120</td>
<td></td>
</tr>
</tbody>
</table>
With the identical structural configuration and the same occupant load, walking speed of SFPE method was slightly quicker so that after 30s, a slightly more occupants (8 more people) passed the stairwell entry door. After they enter the staircase, it took 1:30 to 2:00 to vacate the top floor (NEN6089), while at a time of 1:48, the end of the flow reaches one floor below (SFPE). Although SFPE method provides much exact results while NEN6089 focuses on a time period of 0.5-minute (Appendix E), no evidence showed which method works superior since we cannot prove the calculation results correspond with a real emergency egress. However apparently, when comparing the outcomes of both approaches, tracking the location of the flow is one of the major benefits of the Dutch method.

**Stairs in combination with elevators**

The premise for 'stairs in combination with elevator strategy' is that each tower provides one service elevator for the fire department. Hence, the number of available elevators equals to the total number of elevators minus one. For the egress time calculation, we assumed that all elevators work at a uniform speed of 3m/s. Since the occupants are divided into zones, it is much clear to show a timeline for each tower to clarify the entire evacuation process. The following tables state the shortest egress timeline for the four towers (Table 36 to 39).

Table 36: Tower 1 Simultaneous evacuation timeline (stairs and elevator)

<table>
<thead>
<tr>
<th>Time (mm:ss)</th>
<th>Tower 1 egress process (Top zone: 12F - 22F; Low zone: 0F - 11F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:24</td>
<td>All people travel by elevators reach the ground floor</td>
</tr>
<tr>
<td>12:54</td>
<td>The top zone (% of occupants) evacuated the 12F</td>
</tr>
<tr>
<td>16:54</td>
<td>The top zone reaches the ground floor</td>
</tr>
</tbody>
</table>

Table 37: Tower 2 Simultaneous evacuation timeline (stairs and elevator)

<table>
<thead>
<tr>
<th>Time (mm:ss)</th>
<th>Tower 2 egress process (Top zone: 12F - 22F; Low zone: 0F - 11F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13:42</td>
<td>All people travel by elevators reach the ground floor</td>
</tr>
<tr>
<td>17:54</td>
<td>The top zone (% of occupants) evacuated the 12F</td>
</tr>
<tr>
<td>24:30</td>
<td>The top zone reaches the ground floor</td>
</tr>
</tbody>
</table>

Table 38: Tower 3 Simultaneous evacuation timeline (stairs and elevator)

<table>
<thead>
<tr>
<th>Time (mm:ss)</th>
<th>Tower 3 egress process (Top zone: 17F - 26F; Low zone: 0F - 16F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:36</td>
<td>The top zone reaches the ground floor by elevators only</td>
</tr>
<tr>
<td>8:54</td>
<td>The low zone reaches the ground floor by stairs only</td>
</tr>
</tbody>
</table>
### Table 39: Tower 4 Simultaneous evacuation timeline (stairs and elevator)

<table>
<thead>
<tr>
<th>Time (mm:ss)</th>
<th>Tower 3 egress process (Top zone: 17F - 26F; Low zone: 0F - 16F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:36</td>
<td>The top zone reaches the ground floor by elevators only</td>
</tr>
<tr>
<td>8:48</td>
<td>The low zone reaches the ground floor by stairs only</td>
</tr>
</tbody>
</table>

**Combination**

**STAIRS & HELICOPTER**

The capacity of helicopter ranges from 1 to 18 passengers (42). If we take this method into account, occupants need to go up to the rooftop and wait for assistance, or some areas that the helicopter can approach. It should be in discussion with the architect in advance. Concerning Koningin Julianaplein, actually the counter flow will not produce serious problem in the residential towers because of the low density. But the average population in the office tower is around 100 per floor, some floors even with 150 to 200 occupants. People going up and down would certainly meet each other and influence the egress process. The total egress time slightly differs to the full evacuation, because most people will choose to use stairs in case of a fire, the number of people who need to be assisted is small. An example of the aspects in relation to the helicopter assistance has been given below (34).

- Name: AS332L1 Super Puma
- Capacity: 19, 2 crew
- Costs: 12.5 million euro (2006)
- Length: 16.29 m
- Height: 4.8 m
- Empty weight: 4,500 kg
- Maximum takeoff weight: 8,600 kg

**STAIRS & ABSEILING**

Abseiling can be taken into account because normally young people in the office tower can move freely. Some may be even good at rock climbing. It can be fast to descend through a rope but it is not recommended as it is dangerous. Anything can happen even if you think you have done everything to ensure your safety. Fortunately, abseiling techniques can be used by the rescue team to access injured or disabled people.

**STAIRS & ESCAPE CHUTE**

When the means of emergency egress is blocked for whatever reason, escape chute can help to rescue lives. Because of its property, it protects the occupants from fire, smoke and heat. Escape chute can be installed inside a protected vertical shaft enclosure connected to a specific exterior access point, or installed outside of the building through the balcony. Thus, it should be designed together with the HVAC engineers.
5.2.3 FIRE-PROTECTION REQUIREMENTS

Every occupant follows the same procedure and makes their way to escape. The sounding of an alarm system needs to be involved throughout the whole building. When simultaneous evacuation strategy is implemented, the following fire-protection measures are required:

- Fireproof compartmentalization
- Fire control panel
- Valves\(^{25}\) installed between fire compartments
- Pressurize each stairway of the scissors stairs
- One fire lift in each tower
- Automatic sprinkler system (partly-sprinklered)
- Fire hydrants
- Emergency lighting system
- Fire alarm system
- Smoke screen in the atrium (optional)

\(^{25}\) Valve, also called fire damper, shall be installed at the interface between two compartments. It closes automatically when the temperature increases to a certain threshold, and prevents the flames spread into another compartment. Sometimes it is connected to the installation ducts with extra protection.
5.3 PLAN 2 - PHASED EVACUATION

5.3.1 GENERAL EGRESS PLAN

As implied by the name, the total evacuation procedures are divided into several stages. Phased evacuation process only represents the vertical direction within Plan 2. People from the most critical floors (the first group) will be prioritized to evacuate. Those who are not in immediate danger (the second group) are notified of the event, and told to remain in place pending further instruction. In order to avoid congestion, the rest of the building exit 5 to 10 minutes after the first group. In this time period, the first group is able to descend about 10 floors. Skyscrapers are usually divided into more groups. Whereas the principle remains the same, which allows several following groups egress after a time lag.

Assumptions

The phased evacuation plan and egress time calculation has been carried out based on the subsequent assumptions:

- The total evacuation starts 4.9 minutes (4:54) after the ignition;
- In every tower, there is one emergency elevator available for the fire department;
- Fire will not affect the people outside the designated areas, before those occupants in the affected areas are able to evacuate safely;
- The square in front of the Hague Central Station is used as the external emergency assembly point for occupants after exiting the building.

Fire locations

In contrast to simultaneous evacuation, it is necessary to determine some specific fire locations in phased evacuation. Two fire locations were assumed in each tower, one above the merging floor while the other situated below. In light of the worst-case principle, we assumed the fire locates on higher floor which result in the longest egress time.

1) Office tower: above the 15\textsuperscript{th} floor (assume 21F)
2) Office tower: below the 15\textsuperscript{th} floor (assume 14F)
3) Residential tower: above the 20\textsuperscript{th} floor (assume 25F)
4) Residential tower: below the 20\textsuperscript{th} floor (assume 14F)

Corresponding egress plans

As we have decided the fire locations, there are many combinations to implement a phased evacuation. Assuming the \(n\textsuperscript{th}\) floor catches on fire, we have listed several variations in Table 40. We only consider egress by stairs in this plan. Egress process begins after the activation of the fire alarm. The egress time calculation of phased evacuation can be found in Appendix D.

\[^{26}\] This is an estimation, since each incident is different depending on the queuing situation and the severity of the fire.
Table 40: Phased evacuation – Plan 2A, 2B and 2C

<table>
<thead>
<tr>
<th>Phased evacuation plans</th>
<th>Egress processes</th>
<th>Plan 2A</th>
<th>Plan 2B</th>
<th>Plan 2C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Group 1</td>
<td>Floor (n-1)/n/(n+1); The rest of the building start to egress simultaneously after 5 to 10 minutes; &amp; 200x670; Floor (n-1)/n/(n+1); And the three top floors;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Group 2</td>
<td>Floor (n-1)/n/(n+1); The rest of the building start to egress simultaneously after 5 to 10 minutes; &amp; 200x670; Floor (n-2)/n/(n+2) start to egress simultaneously after 5 to 10 minutes;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Group 3</td>
<td>-</td>
<td>-</td>
<td>Floor (n-3)/n/(n+3)</td>
</tr>
<tr>
<td></td>
<td>Group 4</td>
<td>-</td>
<td>-</td>
<td>Floor (n-4)/n/(n+4)</td>
</tr>
<tr>
<td></td>
<td>Group 5</td>
<td>-</td>
<td>-</td>
<td>Floor (n-5)/n/(n+5)</td>
</tr>
<tr>
<td></td>
<td>...</td>
<td>-</td>
<td>-</td>
<td>Until every floor is cleared, or the fire is extinguished</td>
</tr>
<tr>
<td>Remarks</td>
<td>- If the fire is under control, it is not necessary to evacuate other floors (similar to relocation or defend-in-place); - Every group described above use only stairs to get to the ground floor;</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Most design aspects were remained the same as the simultaneous evacuation strategy, such as fire compartmentalization, horizontal travel distance, and the routing design. The only difference was the fire location, while in the simultaneous evacuation strategy there is no need to determine a certain fire location. Since the residential tower is highly compartmented, it may slow the fire spread and benefits for phased evacuation strategy. To avoid reaching the hazardous conditions, it is important to evacuate before the situation become untenable.
5.3.2 **Egress Time Calculation**

Table 41 to 48 demonstrates the egress time of phased evacuation in each tower. It should be noted that two separate fire locations were assumed in each tower, but the design did not include multiple events. The second group starts 5 minutes after the egress of the first group.

**Table 41: Egress time for tower 1 (Fire floor: 14F, Phased evacuation)**

<table>
<thead>
<tr>
<th>Time (mm:ss)</th>
<th>Tower 1 egress process (Fire floor 14F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6:48</td>
<td>The first group (0 to 15F) evacuated 13F</td>
</tr>
<tr>
<td>9:18</td>
<td>The first group (0 to 15F) reaches the ground floor</td>
</tr>
<tr>
<td>16:18</td>
<td>The second group (0 to 12F) reaches the ground floor</td>
</tr>
<tr>
<td>20:00</td>
<td>The second group (6F to 21F) reaches the ground floor (all)</td>
</tr>
</tbody>
</table>

**Table 42: Egress time for tower 1 (Fire floor: 21F, Phased evacuation)**

<table>
<thead>
<tr>
<th>Time (mm:ss)</th>
<th>Tower 1 egress process (Fire floor 21F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7:36</td>
<td>The first group (20 to 22F) evacuated 20F</td>
</tr>
<tr>
<td>11:06</td>
<td>The first group (20 to 22F) reaches the ground floor</td>
</tr>
<tr>
<td>20:00</td>
<td>The second group (0F to 19F) reaches the ground floor (all)</td>
</tr>
</tbody>
</table>

**Table 43: Egress time for tower 2 (Fire floor: 14F, Phased evacuation)**

<table>
<thead>
<tr>
<th>Time (mm:ss)</th>
<th>Tower 2 egress process (Fire floor 14F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:12</td>
<td>The first group (0 to 15F) evacuated 13F</td>
</tr>
<tr>
<td>11:00</td>
<td>The first group (0 to 15F) reaches the ground floor</td>
</tr>
<tr>
<td>17:30</td>
<td>The second group (0 to 12F) reaches the ground floor</td>
</tr>
<tr>
<td>24:24</td>
<td>The second group (6F to 21F) reaches the ground floor (all)</td>
</tr>
</tbody>
</table>

**Table 44: Egress time for tower 2 (Fire floor: 21F, Phased evacuation)**

<table>
<thead>
<tr>
<th>Time (mm:ss)</th>
<th>Tower 2 egress process (Fire floor 21F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:18</td>
<td>The first group (20 to 22F) evacuated 20F</td>
</tr>
<tr>
<td>18:48</td>
<td>The first group (20 to 22F) reaches the ground floor</td>
</tr>
<tr>
<td>25:48</td>
<td>The second group (0F to 19F) reaches the ground floor (all)</td>
</tr>
</tbody>
</table>

**Table 45: Egress time for tower 3 (Fire floor: 14F, Phased evacuation)**

<table>
<thead>
<tr>
<th>Time (mm:ss)</th>
<th>Tower 3 egress process (Fire floor 14F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6:24</td>
<td>The first group (0 to 15F) evacuated 13F</td>
</tr>
<tr>
<td>8:30</td>
<td>The first group (0 to 15F) reaches the ground floor</td>
</tr>
<tr>
<td>14:48</td>
<td>The second group (0 to 12F) reaches the ground floor</td>
</tr>
<tr>
<td>15:54</td>
<td>The second group (6F to 21F) reaches the ground floor (all)</td>
</tr>
</tbody>
</table>
### Table 46: Egress time for tower 3 (Fire floor: 25F, Phased evacuation)

<table>
<thead>
<tr>
<th>Time (mm:ss)</th>
<th>Tower 3 egress process (Fire floor 25F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6:12</td>
<td>The first group (24 to 26F) evacuated 24F</td>
</tr>
<tr>
<td>10:12</td>
<td>The first group (24 to 26F) reaches the ground floor</td>
</tr>
<tr>
<td>17:30</td>
<td>The second group (0F to 23F) reaches the ground floor (all)</td>
</tr>
</tbody>
</table>

### Table 47: Egress time for tower 4 (Fire floor: 14F, Phased evacuation)

<table>
<thead>
<tr>
<th>Time (mm:ss)</th>
<th>Tower 4 egress process (Fire floor 14F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6:00</td>
<td>The first group (13 to 15F) evacuated 13F</td>
</tr>
<tr>
<td>8:12</td>
<td>The first group (13 to 15F) reaches the ground floor</td>
</tr>
<tr>
<td>14:24</td>
<td>The second group (0 to 12F) reaches the ground floor</td>
</tr>
<tr>
<td>16:06</td>
<td>The second group (16F to 21F) reaches the ground floor (all)</td>
</tr>
</tbody>
</table>

### Table 48: Egress time for tower 4 (Fire floor: 25F, Phased evacuation)

<table>
<thead>
<tr>
<th>Time (mm:ss)</th>
<th>Tower 4 egress process (Fire floor 25F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6:18</td>
<td>The first group (24 to 26F) evacuated 24F</td>
</tr>
<tr>
<td>10:18</td>
<td>The first group (24 to 26F) reaches the ground floor</td>
</tr>
<tr>
<td>17:06</td>
<td>The second group (0F to 23F) reaches the ground floor (all)</td>
</tr>
</tbody>
</table>

### 5.3.3 Fire-protection Requirements

Phased evacuation can be adopted with the help of automatic fire detection and voice alarm. Especially for this strategy, the fire warning system should be capable of giving several distinct signals (warning and evacuation) along with different phases. People in the immediate danger zone are instructed to leave the building, following the signed escape routes and the emergency voice communication signal. The fire source was recognized by the fire detector and forwarded to the fire control panel, which in turn triggers the voice alarm system. The alarm sounding systems was activated one by one. The following fire-protection measures are required in this strategy:

- Fireproof compartmentalization
- Fire control panel
- Valves installed between fire compartments
- Pressurize each stairway of the scissors stairs
- One fire lift in each tower
- Automatic sprinkler system (full-sprinklered)
- Fire hydrants
- Emergency lighting system
- Fire alarm system
- Smoke screen in the atrium
- Voice communication system
5.4 Plan 3 - Relocation

5.4.1 General Egress Plan

When a fire happens on a lower level in a complex building, there is no need to evacuate people in the unaffected zone. Therefore in addition to full building evacuation, partial evacuation can be implemented as well. Since fire developed gradually as time went on, once it became uncontrollable, the action of passing through the fire floor may result in injuries. Supposing that a fire breaks out on the top floor of Koningin Julianaplein, occupants from the critical areas could escape by stairs and relocate to another temporary refuge. The critical zone in our research included the fire floor, two floors above and two floors below. Meanwhile, the rest of the building stays in place. Relocation plan aims at creating another safe area, and the critical zone do not need to leave the building, provided that the fire department is able to control the fire soon enough.

Assumptions

The relocation evacuation plan and egress time calculation has been made on the basis of the subsequent assumptions:

- The total evacuation starts 4.9 minutes (4:54) after the ignition;
- In every tower, there is one emergency elevator available for the fire department;
- Fire will not affect the people outside the designated areas, before those occupants in the affected areas are able to evacuate safely;
- The refuge floor is the final destination of the evacuees which can withstand the fire load for such a long period, and there is no demand for them to leave the building.

Refuge floors

Much attention should be paid to the office towers of Koningin Julianaplein due to the high occupant load. We have planned to make the 11th and 12th floors in the office towers as the refuge zone. However in reality, refuge area is a sky lobby or a protected enclosure composed of one level. Even though the sum area of the corridor and the atrium is sufficient to hold all people of the five upper floors (Table 49), relocate at the atrium can be dangerous due to smoke propagation. As we knew that corridors beneath the atrium is part of the egress route, and must be protected. We gave thought to relocate the evacuees at the fireproof corridors, but the corridor area of one floor in Koningin Julianaplein is not sufficient to hold all the relocated population. Finally, we came up with the plan of making two floors together serving as the refuge zone (Table 49). Calculation of the required area in the two tables was based on the maximum Dutch density requirement of 4 persons/m².
Table 49: The refuge zone in the office towers

<table>
<thead>
<tr>
<th>Five floors with the highest occupant density (persons)</th>
<th>Area (m²)</th>
<th>Required area</th>
<th>Atrium area on 15F</th>
<th>Corridor area of 11F</th>
<th>Corridor area of 12F</th>
</tr>
</thead>
<tbody>
<tr>
<td>22F</td>
<td>21F</td>
<td>20F</td>
<td>19F</td>
<td>18F</td>
<td>Total</td>
</tr>
<tr>
<td>523</td>
<td>231</td>
<td>244</td>
<td>244</td>
<td>244</td>
<td>1486</td>
</tr>
</tbody>
</table>

Figure 87: Refuge zone 11F and 12F (a)

Figure 88: Refuge floor 11F and 12F (b)
Fire locations

Similar with the phased evacuation, it is essential to determine some specific fire locations in the relocation plan. As has been stated, totally fire floors constituted the relocation group. In the light of the worst-case principle, on one hand, we assumed the fire happens on a higher level that results in the longest egress time. On the other hand, another principle of assuming the fire source was the five floors with the highest occupant density. Consequently, the egress time will be shorter than our calculation wherever the fire breaks out. According to these principles, two fire locations in each tower were selected correlated to the position of refuge floors.

1) Office tower: above the refuge (assume 20F)
2) Office tower: below the refuge (assume 8F)
3) Residential tower: above the refuge (assume 22F)
4) Residential tower: below the refuge (assume 8F)

5.4.2 EGRESS TIME CALCULATION

Egress time represents the total relocating time, which starts from the original position (critical floor) to the relocated area. Egress downward is the only direction of traffic in this plan. 11F and 12F were designed as the refuge zone. Wherever the fire source is, occupants on the critical zone would never ascend and relocate to higher levels. Hence, when a fire occurs beneath the refuge, the five critical floors escape and leave the building eventually.

Table 50: Egress time (Relocation)

<table>
<thead>
<tr>
<th>Fire location</th>
<th>Egress time (min:sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tower 1</td>
</tr>
<tr>
<td>Below the refuge</td>
<td>8:42</td>
</tr>
<tr>
<td>Above the refuge</td>
<td>11:24</td>
</tr>
</tbody>
</table>

5.4.3 FIRE-PROTECTION REQUIREMENTS

Occupants in the affected zone should be able to receive appropriate voice messages so that they can have the awareness of egress routing. Possible measures must be taken to slow the speed at which a fire can spread. When relocation strategy is applied, the following fire-protection measures are required:

- Fireproof compartmentalization
- Fire control panel
- Valves installed between fire compartments
- Pressurize each stairway of the scissors stairs
- One fire lift in each tower
- Automatic sprinkler system (full-sprinklered)
• Fire hydrants
• Emergency lighting system
• Fire alarm system
• Smoke screen in the atrium
• Voice communication system
5.5 PLAN 4 - PROTECTION-IN-PLACE

5.5.1 GENERAL EGRESS PLAN

At times immediate evacuation may not be necessary and evacuation may not be necessary at all. For a few specialized applications the best strategy may be to protection-in-place (8). Except the fire floor, everybody stays in their origin place during the fire. On floors above and below the fire floor, occupants are protected by the construction in between. They should not be intimate with the first materials burning (10). Unlike the relocation strategy, the critical zone involves only the fire floor. Occupants from this floor are requested to leave the building and reach the ground floor exit(s).

Assumptions

The protection-in-place evacuation plan and egress time calculation has been made based on the subsequent assumptions:

- The total evacuation starts 4.9 minutes (4:54) after the ignition;
- In every tower, there is one emergency elevator available for the fire department;
- Fire will not affect the people outside the designated areas, before those occupants in the affected areas are able to evacuate safely;
- Fire can be controlled under one compartment;
- The square in front of the Hague Central Station is used as the external emergency assembly point for occupants after exiting the building.

Fire locations

Only the fire floor is required to evacuate. Owing to the particularity of this plan, we assumed that fire can break out in each floor. In most cases, congestion seldom happens due to the small escaping group. For that reason we took both stairs and elevators into account. If the fire breaks out on floors above the 7th floor, occupants on the fire floor can also use elevator to permit prompt evacuation.

Figure 89: Protection-in-place diagram
5.5.2 EGRESS TIME CALCULATION

Since stay-in-place is almost a non-evacuation strategy, calculation will be the time for occupants reach the ground floor and leave the building. Evacuation only takes place at the one fire floor. Table 5.1 illustrates the egress time for each floor.

Table 5.1: Egress time (Protection-in-place)

<table>
<thead>
<tr>
<th>Floors</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tower 1</td>
<td>Tower 2</td>
<td>Tower 3</td>
<td>Tower 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stairs</td>
<td>Elevator</td>
<td>Stairs</td>
<td>Elevator</td>
<td>Stairs</td>
<td>Elevator</td>
</tr>
<tr>
<td>26</td>
<td>-</td>
<td>-</td>
<td>10:00</td>
<td>6:18</td>
<td>10:06</td>
<td>6:24</td>
</tr>
<tr>
<td>24</td>
<td>-</td>
<td>-</td>
<td>9:42</td>
<td>6:18</td>
<td>9:48</td>
<td>6:24</td>
</tr>
<tr>
<td>23</td>
<td>-</td>
<td>-</td>
<td>9:30</td>
<td>6:12</td>
<td>9:36</td>
<td>6:18</td>
</tr>
<tr>
<td>22</td>
<td>11:06</td>
<td>10:42</td>
<td>13:30</td>
<td>6:18</td>
<td>10:06</td>
<td>6:18</td>
</tr>
<tr>
<td>21</td>
<td>10:54</td>
<td>9:30</td>
<td>11:24</td>
<td>8:42</td>
<td>9:12</td>
<td>6:12</td>
</tr>
<tr>
<td>20</td>
<td>10:48</td>
<td>9:18</td>
<td>11:24</td>
<td>8:36</td>
<td>9:00</td>
<td>6:06</td>
</tr>
<tr>
<td>19</td>
<td>10:36</td>
<td>9:12</td>
<td>11:12</td>
<td>8:30</td>
<td>8:48</td>
<td>6:06</td>
</tr>
<tr>
<td>18</td>
<td>10:24</td>
<td>9:00</td>
<td>11:00</td>
<td>8:38</td>
<td>8:42</td>
<td>6:06</td>
</tr>
<tr>
<td>17</td>
<td>9:36</td>
<td>8:36</td>
<td>10:48</td>
<td>7:24</td>
<td>8:30</td>
<td>6:00</td>
</tr>
<tr>
<td>16</td>
<td>9:48</td>
<td>9:12</td>
<td>10:24</td>
<td>8:06</td>
<td>8:24</td>
<td>6:48</td>
</tr>
<tr>
<td>15</td>
<td>9:36</td>
<td>9:24</td>
<td>11:12</td>
<td>8:42</td>
<td>8:18</td>
<td>6:42</td>
</tr>
<tr>
<td>14</td>
<td>10:00</td>
<td>6:06</td>
<td>9:12</td>
<td>7:24</td>
<td>8:06</td>
<td>6:36</td>
</tr>
<tr>
<td>13</td>
<td>8:42</td>
<td>6:42</td>
<td>9:00</td>
<td>6:48</td>
<td>7:36</td>
<td>6:36</td>
</tr>
<tr>
<td>12</td>
<td>8:30</td>
<td>6:36</td>
<td>8:48</td>
<td>6:42</td>
<td>7:36</td>
<td>6:36</td>
</tr>
<tr>
<td>11</td>
<td>8:18</td>
<td>6:30</td>
<td>8:36</td>
<td>6:36</td>
<td>7:36</td>
<td>6:36</td>
</tr>
<tr>
<td>10</td>
<td>8:00</td>
<td>6:24</td>
<td>8:18</td>
<td>6:30</td>
<td>7:24</td>
<td>6:36</td>
</tr>
<tr>
<td>9</td>
<td>7:42</td>
<td>6:24</td>
<td>8:06</td>
<td>6:30</td>
<td>7:06</td>
<td>5:42</td>
</tr>
<tr>
<td>8</td>
<td>7:30</td>
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<td>7:56</td>
<td>6:24</td>
<td>6:54</td>
<td>5:42</td>
</tr>
<tr>
<td>7</td>
<td>7:18</td>
<td></td>
<td>7:42</td>
<td></td>
<td>6:48</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>7:06</td>
<td></td>
<td>7:24</td>
<td></td>
<td>6:36</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>6:48</td>
<td></td>
<td>7:12</td>
<td></td>
<td>6:24</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>6:36</td>
<td></td>
<td>7:00</td>
<td></td>
<td>6:12</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>6:24</td>
<td></td>
<td>6:48</td>
<td></td>
<td>7:00</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>6:12</td>
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<td></td>
<td>6:06</td>
<td></td>
<td>6:42</td>
<td></td>
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<tr>
<td>0</td>
<td>-</td>
<td></td>
<td>-</td>
<td></td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Koningin Julianaplein Egress Plans
5.5.3 Fire-Protection Requirements

Protection-in-place strategy correlated to human safety closely. Usually, these buildings are protected throughout with automatic sprinklers and fire compartmentalization is used to prevent smoke and fire spread between compartments. The fire resistant time of all building components must be long enough to provide the structural integrity, and compartmentalize the fire. Automatic sprinkler system is common in public buildings, while it is also recommended for each home. When protection-in-place strategy is implemented, the following fire-protection measures are required:

- Fireproof compartmentalization
- Fire control panel
- Valves installed between fire compartments
- Pressurize each stairway of the scissors stairs
- One fire lift in each tower
- Automatic sprinkler system (full-sprinklered)
- Fire hydrants
- Emergency lighting system
- Fire alarm system
- Smoke screen in the atrium
- Voice communication system
5.6 Structural Fire Resistance

Anything can contribute to fire safety creating more time for people to evacuate, and potentially reducing fire damage. Fire-resistant requirements are broadly defined as a time period, which normally relates to the total egress time, structural stability and integrity, the thermal insulating property of building elements and the classification of the construction. In the following sections, we mainly consider the egress time, since structural behavior and thermal properties are beyond the scope of this research.

![Diagram of fire development curve in office building](image)

**Figure 90: Normative fire development curve in office building**

We will come up with new requirements of structural fire resistance after proposing each egress plan. For one thing, during a full evacuation, all occupants exit or are assisted in exiting the building, ideally within less than half the duration of the fire-resistance rating of the exit enclosures (1). For another, extra time should be provided for the fire department to suppress the fire and rescue the victims. According to the Dutch egress concept in Figure 22, we assumed that the operating time for fire fighters is around 45 to 60 minutes. We added extra 50-minute to the calculated theoretical egress time in our design. While with regard to partial evacuation, unaffected occupants spend much longer time remain at their original location, thus the requirements of the main structure can be even higher. Figure 90 points out the fire operating time from the fire department point of view (27), which can be a reference to our design.

---

27 Figure 70: Brandbeveiligingsconcept Kantoorgebouwen en onderwijsgebouwen (April, 1996)
Figure 91 depicts the simple unquantifiable relation between structural fire resistance and the potential load from a fire. We regard the blue column as the structural fire-resistant rating, and the red column as the load from fire. In normal circumstances, the resistance of a building element should be much higher than the load from the fire so as to ensure the structural stability. Under the same fire condition, enhancing the level of structural fire resistance resulted in a greater difference between load and resistance (middle figure), which provided the structural safety guarantee for partial evacuation. On the contrary, with the same amount of fire load, poor fire-resistant component brought about danger to the occupants (right figure).

In general, the fire resistance period of a load-bearing structure is determined by carrying out standard fire tests in laboratories (5). The basis of those tests is standard fire, and the test ends when the structural element fails (10). So far, however, there has been little discussion between the additional constructional demand and the different egress strategies. Since most design aspects were based on fire codes, as far as we investigated, there is no such method to calculate the structural requirements. Combined with the statement in literature (1)28, it was hypothesized that the structural fire resistance demand was determined as displayed in Table 52, and additional 50 minutes was added up to partial evacuation for operating the fire. However, it might be conservative or underestimated since every fire act differently, when human behavior is taken into account, a number of factors will alter.

<table>
<thead>
<tr>
<th>Building component</th>
<th>Full evacuation $T_{f_{\text{full}}}$</th>
<th>Partial evacuation $T_{f_{\text{partial}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main load-bearing structure</td>
<td>$T_{\text{egress,max}} \times 2 + 50\text{min}$</td>
<td>$T_{f_{\text{full}}} + 50\text{min}$</td>
</tr>
<tr>
<td>Fire separation</td>
<td>$T_{\text{egress,max}} \times 2$</td>
<td>$T_{f_{\text{full}}} + 50\text{min}$</td>
</tr>
<tr>
<td>Smoke separation</td>
<td>30min</td>
<td>30min</td>
</tr>
</tbody>
</table>

Specifically, the main load-bearing structure involves the core, columns and beams, floors, vertical shaft, and the load-bearing structure on the roof. Fire separation is meant by the enclosure of the fire compartment, while smoke separation represents the smoke barriers inside the fire compartment. In short, both the egress time, thermal and mechanical

28 During a full evacuation, all occupants exit or are assisted in exiting the building, ideally within less than half the duration of the fire-resistance rating of the exit enclosures.
properties affect the fire resistance of a building component. It should be noted that there is no direct relation between the total egress time and the structural fire resistance, even if they are both expressed in 'time'.

We selected the longest egress time in each plan for each tower, Table 53 and 54 give the fire resistant time of the structure according to the aforementioned calculation approach in Table 52.

Table 53: Fire resistant time of the construction (Full evacuation)

<table>
<thead>
<tr>
<th>Building components</th>
<th>Fire resistant time: Plan 2 (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Office tower 28:00</td>
</tr>
<tr>
<td>Main load bearing structure</td>
<td>110</td>
</tr>
<tr>
<td>Fire separation</td>
<td>60</td>
</tr>
<tr>
<td>Smoke separation</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 54: Fire resistant time of the construction (Partial evacuation)

<table>
<thead>
<tr>
<th>Building components</th>
<th>Fire resistant time: Plan 3 (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Office tower</td>
</tr>
<tr>
<td>Main load bearing structure</td>
<td>160</td>
</tr>
<tr>
<td>Fire separation</td>
<td>110</td>
</tr>
<tr>
<td>Smoke separation</td>
<td>30</td>
</tr>
</tbody>
</table>
5.7 RECOMMENDATIONS

Various egress possibilities have been presented for Koningin Julianaplein in this chapter. As building design is a creative field, it would be interesting to assess the effects of some variations concerning evacuation. Several design aspects will be adjusted so as to find out a much appropriate way to evacuate Koningin Julianaplein. Due to the limited research time frame, we consider to vary the following factors within simultaneous plan:

- Stairways: stair widths, and that lead to different flow capacity and storage capacity
- Elevators: working speed, number of available elevators
- Occupant density: building functions
- Design of the refuge floor in the relocation strategy

5.7.1 FLOW AND STORAGE CAPACITY

Since vertical egress facilities have significant impact on evacuation, adjustment in the dimensions of the transportation systems bring about different storage and passing capacities. The original design of stair width was 1.2m in all towers of Koningin Julianaplein. For this research, due to the limitation set in scope and time, we only adjusted the stair width to find out the tendency of egress time. Meanwhile, the occupant load, door dimension and corridor dimension stayed the same.

![Figure 92: Variations in stair width (tower 1)](image1)

![Figure 93: Variations in stair width (tower 2)](image2)
Building codes of most countries regulated that a stair width of 0.8m to 0.9m is the minimum requirement, which was the starting point of this study. The figures above show that in most cases there has been a gradual decline in the egress time along with the increasing of stair width. While with a wider option, the occupant density and specific flow in the stairways was reduced, and result in a quicker egress time. As a result, additional population is permitted for wider stairs. Though there is one exception, namely: residential towers shown in Figure 94 and 95. The total egress time did not change together with the stair size. The main reason was that the staircase capacity was sufficient to serve the extremely low occupant load in these towers. No matter how large the staircase is, merging process seldom causes congestion, and at the same time the flow is able to travel one floor down within 15 seconds. Lastly, from analyzing the findings of this study several conclusions and recommendations can be drawn.

- Stair with 1.2m width was reasonable for Koningin Julianaplein office towers, while the dimension can be increased a little bit particularly in tower 2 when considering its large population.
- For the residential, it may be much economical to narrow the stairs, provided that the minimum width fulfills the legislations.
5.7.2 Elevators

Original proposal from OMA has designed two passenger elevators in tower 1 and 4 elevators in tower 2, respectively (Figure 96). The average working speed in our design was 3m/s. Actually in residential towers, the number of elevators will not influence the egress time since very few people present on each floor. There is no need to add more elevators. Thus we considered two types of variations: increase the speed to 10m/s, and enlarge the maximum capacity to 24 persons in scenario 2.

![Figure 96: Passenger elevators in each tower](image)

Obviously, the elevator working time was saved up to 58%. While the total egress time stands for the longest travel time, which normally indicates the last occupant using stairs. Even if the theoretical total egress time was identical with the original design, we recommended high-speed elevators for Koningin Julianaplein. Shorter egress time lowered the risk, when the fire spread at a fast speed, it was better to leave the critical area as fast as possible.

<table>
<thead>
<tr>
<th>Koningin Julianaplein</th>
<th>Elevator working time (min:s)</th>
<th>Enlarge the elevator capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3m/s</td>
<td>10m/s</td>
</tr>
<tr>
<td>Tower 1</td>
<td>12:24</td>
<td>5:18</td>
</tr>
<tr>
<td>Tower 2</td>
<td>13:42</td>
<td>5:54</td>
</tr>
<tr>
<td>Tower 3</td>
<td>14:42</td>
<td>6:24</td>
</tr>
<tr>
<td>Tower 4</td>
<td>13:06</td>
<td>5:36</td>
</tr>
</tbody>
</table>
5.7.3 Occupant Density

Occupant density is another alteration in egress design, which will lead to new building functions. New functions according to the adjusted occupant density are listed in Table 57, based on [11].

Table 56: Occupant density variation

<table>
<thead>
<tr>
<th>Koningin Julianaplein</th>
<th>Egress time (mm:ss)</th>
<th>Floors</th>
<th>Density (persons/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Original</td>
<td>Half population</td>
</tr>
<tr>
<td>Tower 1</td>
<td>18:00</td>
<td>15:24</td>
<td>27:24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>17F to 22F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15F to 16F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1F to 14F</td>
</tr>
<tr>
<td>Tower 2</td>
<td>26:54</td>
<td>20:12</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>22F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2F to 21F</td>
</tr>
<tr>
<td>Tower 3</td>
<td>13:24</td>
<td>12:54</td>
<td>16:36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20F to 26F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4F to 19F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2F to 3F</td>
</tr>
<tr>
<td>Tower 4</td>
<td>13:00</td>
<td>12:42</td>
<td>15:54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4F to 26F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2F to 3F</td>
</tr>
</tbody>
</table>

Attention:
- Double population of tower 2 did not take into account since the population was already dense.

Table 57: New functions

<table>
<thead>
<tr>
<th>Occupant density (persons/m²)</th>
<th>New functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01 to 0.08</td>
<td>• Storage</td>
</tr>
<tr>
<td></td>
<td>• Fitness center</td>
</tr>
<tr>
<td></td>
<td>• Swimming pools (water surface area)</td>
</tr>
<tr>
<td></td>
<td>• Gymnasia</td>
</tr>
<tr>
<td></td>
<td>• Showrooms</td>
</tr>
<tr>
<td></td>
<td>• Art galleries, museums</td>
</tr>
<tr>
<td></td>
<td>• Daycare centers</td>
</tr>
<tr>
<td></td>
<td>• Interview rooms</td>
</tr>
<tr>
<td></td>
<td>• Workshops</td>
</tr>
<tr>
<td></td>
<td>• Laundry and housekeeping facilities</td>
</tr>
<tr>
<td></td>
<td>• Shop spaces and shopping arcades</td>
</tr>
<tr>
<td>0.2 to 0.4</td>
<td>• Dining, beverage, and cafeteria spaces</td>
</tr>
<tr>
<td></td>
<td>• Exhibition areas, trade fairs</td>
</tr>
<tr>
<td></td>
<td>• Restaurant</td>
</tr>
<tr>
<td></td>
<td>• Spaces with loose seating and tables</td>
</tr>
<tr>
<td></td>
<td>• Lounges</td>
</tr>
<tr>
<td>0.7 to 0.9</td>
<td>• Dining, beverage, and cafeteria spaces</td>
</tr>
<tr>
<td></td>
<td>• Exhibition areas, trade fairs</td>
</tr>
<tr>
<td></td>
<td>• Restaurant</td>
</tr>
<tr>
<td></td>
<td>• Spaces with loose seating and tables</td>
</tr>
<tr>
<td></td>
<td>• Lounges</td>
</tr>
</tbody>
</table>
5.7.4 SKY LOBBY

In buildings where members of the public or persons unfamiliar with the layout of the buildings are present, there should be means available to identify the key escape routes, especially when relocation strategy was adopted. For the redesign of Koningin Julianaplein, initially we planned the corridors on 11th and 12th floor as refuge. However, the corridor has limited capacity with an average width of 1.5m (office towers) and 1.2m (residential towers), respectively. In the event of an emergency, two floors of refuge may confuse the panic crowd. Even though we can apply signs to inform the location of refuge, when the evacuees arrived at 12F, most of them peer and follow others and continue traveling down to 11F. As a result, it will get rather crowded in both 11F corridor and stairway.

One strategy is to introduce a specially designed sky lobby, where people can take refuge, or transfer to express elevators. Occupants in the high rise portions of Koningin Julianaplein could evacuate toward the sky lobby using stairs. Not only can this way of evacuation let occupants approaching safety areas with fire-protection in a short time, but decrease the exit jam and convergence in the stairwell. In conclusion, the appropriate refuge location in Koningin Julianaplein would be the 11th floor. Moreover, this intermediate interchange floor also provides the assembly place for fire fighters, which would be strongly recommended.
5.8 Results and Discussion

In high-rise buildings, egress strategies can range from evacuating all occupants, to evacuating some of the occupants, to defending occupants in place. This section will analyze the two types of strategies: full evacuation and partial evacuation, which have been expressed into four egress plans for each tower, namely: simultaneous, phased, relocation and defend-in-place. On account of the unique architectural design of Koningin Julianaplein, evacuation only takes place at the tower catches on fire. As multi-event was not included within this research, total evacuation of four towers at the same time will not happen.

5.8.1 Office Towers

If simultaneous evacuation strategy is employed, Plan 1,229 produced the shortest total egress time for tower 1 (16:54); the entire building use both elevator and stairs. A 'simultaneous stair only' evacuation took 18:00 to vacate tower 1, while it went up to 26:54 for tower 2 since the occupant density was relatively high, which led to a higher level of congestion. Once elevator was considered as part of the means of egress, the total escaping period of tower 2 decreased to 24:30. Apparently, the egress time difference was only 1 minute between these two scenarios. We can conclude that elevators cannot contribute much to reduce the egress time in offices of ciara 20 floors, therefore it is unnecessary to consider elevator as a means of egress in Koningin Julianaplein office towers. However, attention shall be given to tower 2 again due to the 348-cutomer restaurant on top. Capacity drop may occur at the merging sections where density can be exceeded. Also, the panic flow and crowd forces may result in dangerous situation in the restaurant and the adjacent corridors. Designers need to deliberate other egress strategies.

Table 58: Egress time comparison of the four plans (office towers)

<table>
<thead>
<tr>
<th>Koningin Julianaplein</th>
<th>Plan 1 (min)</th>
<th>Plan 2 (min)</th>
<th>Time comparison</th>
<th>Plan 3 (min)</th>
<th>Time comparison</th>
<th>Plan 4 (min)</th>
<th>Time comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office Tower</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>18.00</td>
<td>20.00</td>
<td>+ 11%</td>
<td>11.40</td>
<td>- 37%</td>
<td>11.10</td>
<td>- 38%</td>
</tr>
<tr>
<td>2</td>
<td>26.90</td>
<td>25.80</td>
<td>- 4%</td>
<td>15.30</td>
<td>- 43%</td>
<td>13.50</td>
<td>- 50%</td>
</tr>
</tbody>
</table>

Attention:
- Egress time comparison: '-' means the time is saved while '+' stands for the opposite.

From the calculation we can see that although phased evacuation was full evacuation, it provided a way to optimize egress system efficiency. The egress process took place floor by floor without considering the involvement of elevators. People from the same level were alerted and evacuated simultaneously. For instance, a fire occurred on 21F in tower 1, the first phase (20F, 21F and 22F) were able to arrive at the ground floor in 11:06 (Appendix D: P1,2,1), representing a 38.3% decrease compared to the simultaneous stairs only scenario (18:00). After a 5-minute period the second group at a time starting above the fire floor began to

29 Plan 1,2: Plan 1 (tower 1), 1 (plan 1: simultaneous evacuation), 2 (scenario 2) in Appendix D.
Egress as Part of Fire Safety in High-rise Buildings

evacuate, namely, the rest of the building excluding the first phase. This process is usually accomplished by voice communication over fire alarm speakers. Depending on the occupant load and building configuration, evacuees may merge at some lower levels. Fortunately, merging behavior has seldom occurred in Koningin Julianaplein with one exception of tower 2 when a fire outbreak on 21F (Appendix D: P 2.2.1). Because of the large population of the restaurant, people from the critical zone (20F, 21F and 22F) were able to leave this area totally in 11:18. In 5-minute period of time, they reached the 9th floor and then the second phase started. As a result, two flows merged at the 9th floor and below, which comprised of the evacuees from the critical zone (20F, 21F and 22F) and people under 9F who enter the stairwell in the meanwhile. Stairway of these floors became intersections when two links enter a node and one leaves. Eventually, people from the critical zone left the building in 18:48. Despite this, a marginal decrease in total egress time by 4% (1:06 30) was observed compared to simultaneous escaping scenario. Take office tower 2 as another example, when the fire locates on 14F, the top zone needs 24:24 to get down to the ground level. In comparison to Plan 2,1,1 (26:54), phased evacuation causes a time increase of 4:06 in this case. To sum up, egress time calculation indicated that a phased evacuation reduces crowding of escape routes and stairways, especially in buildings with relatively high occupant density such as Koningin Julianaplein tower 2. This strategy may also allow a reduction in the required width of the escaping stairs, which brings about lower construction budget.

In addition to complete egress, with the involvement of fire department and automatic suppression system, it can be much effective to implement a partial evacuation. Plan 3 aims at relocating a portion of the occupants to areas of ultimate safety. As the travel distance decreased, elevator evacuation did not take into account. In tower 1, when fire locates above the refuge floors, it took 11:24 to travel down to refuge representing a 37% decrease by contrast with total simultaneous egress (18:00). With a reduction in egress time of 43% compare to the simultaneous case, the longest relocation period of tower 2 lasted 15:18. Egress efficiency improved considerably towards full evacuation, with the consequence that relocation can be recommended for Koningin Julianaplein office towers.

The last egress plan, protection-in-place, produced the greatest reduction in the overall egress time. As can be seen from Table 58, the egress time of relocation and defend-in-place varies only 18 seconds (0.3 min) regarding tower 1. When we balance the egress time merely, relocation and defend-in-place make almost no difference in tower 1. Whether plan 3 or plan 4 is applicable relates to the actual fire circumstance. It is manifest that comparing to plan 1, the egress time of tower 2 even reduces by as much as 50% (13:30 is understood to mean the time it took for the occupants on the top floor to leave the building). However, when egress time is the only evaluating criterion, protection-in-place is the most recommended plan for tower 2.

In summary, high-rise buildings contains a large number of occupants. Just like office tower 2 of Koningin Julianaplein, people need a clear path away from the building and the potential danger. The larger the building, the more organization is required to ensure

\[ 4\% \text{ decrease: } 26.9 - 25.8 = 1\text{min} = 1:06 \ (\text{Table 58}) \]
everyone is evacuated effectively and safely as possible. Therefore life safety system such as lighting system has a significant effect on emergency egress. Unambiguous communication system and well-designed automatic suppression system shall work well especially in the partial evacuation plans.

5.8.2 RESIDENTIAL TOWERS

Residential towers are highly compartmented, which can be a major benefit of controlling fire and smoke. The table below shows that there were some similarities between tower 3 and 4. In terms of a full evacuation, tower 4 produced a small reduction of 24 seconds (0.4min) in maximum egress time. As can be seen from the drawings, the total floor area of tower 3 was 41m² smaller than tower 4, while the entire population was larger than that of tower 4, which caused a slightly longer total egress time.

Table 59: Egress time comparison of the four plans (residential towers)

<table>
<thead>
<tr>
<th>Residential Tower</th>
<th>Plan 1 (min)</th>
<th>Plan 2 (min)</th>
<th>Time comparison</th>
<th>Plan 3 (min)</th>
<th>Time comparison</th>
<th>Plan 4 (min)</th>
<th>Time comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower 3</td>
<td>13.40</td>
<td>17.50</td>
<td>+31%</td>
<td>8.50</td>
<td>-37%</td>
<td>10.00</td>
<td>-25%</td>
</tr>
<tr>
<td>Tower 4</td>
<td>13.00</td>
<td>17.10</td>
<td>+32%</td>
<td>8.70</td>
<td>-33%</td>
<td>10.10</td>
<td>-22%</td>
</tr>
</tbody>
</table>

Attention: 
- Egress time comparison: '−' means the time is saved while '+' stands for the opposite.

If a strategy for implementing simultaneous full building evacuation is required for residential towers, Plan 3,1,1 produced the shortest egress time: the top zone (17F to 26F) used elevators alone and the low zone (0F to 16F) applied only stairs to evacuate, which took 8.54 to clear tower 3. The involvement of elevator saved 4:30 as compared with stairs only scenario (13:24). Since the population of the top zone in tower 3 is small, we assumed 13 persons as the capacity of one elevator. It is efficient to bring 8 people down every time. However, for floors below 17F, 14 people were present per floor. When the assumption of the elevator capacity remains the same, it means the elevator should operate twice to transfer all 14 persons down, as well as tower 4. However, we can make variations on the elevator type, as Table 55 shows, larger capacity resulting in the decrease in the evacuation time. Furthermore, elevators during normal operations are neither waterproof, nor smoke proof, let alone fireproof, when they are designed to serve for emergency situations, extra fire-protection measures must be taken. Considering the low occupant load that congestion would hardly occur in stairwells, simultaneous evacuation with the help of elevator is economically unfeasible, thus not recommended.

Phased evacuation was adopted with a time delay of 5 minutes. Even if the total egress duration was longer in terms of phased evacuation, egress efficiency cannot be measured merely by egress time. The longest evacuation was the scenario P 3,2,1; when a fire
occurred on 25F, it took 17:30 for the second phase to leave the building. Fortunately, when we applied the 5-minute time delay, there was no merging due to the low population density. In comparison to simultaneous strategy, egress time increased by 31%. But then supposing that the 5-minute was eliminated, we figured out that the egress time of plan 1 and plan 2 almost equal:

- Tower 3: Simultaneous evacuation (13:24); phased evacuation (12:30)
- Tower 4: Simultaneous evacuation (13:00); phased evacuation (12:06)

The total egress time can be reduced by 1 minute since such strategy has a potential to increase the egress effectiveness of the first phase, and lower the flow density in stairwells of the second phase. The results of this research indicated that phased evacuation is not needed for Koningin Julianaplein residential towers.

Different from office towers, relocation strategy saved most time, some 33% to 37% faster than the simultaneous stairs only scenario. Relocation can be implemented efficiently when the fire is localized with structural integrity guaranty. Corridors of 11F and 12F act as the refuge area. Again, since the occupant load was very low, the storage capacity of these corridors is sufficient for dwellers to shelter. If the corridors are adequately protected and sized, relocation plan resulted in a safer egress due to the short travel distance to a safe area. This strategy is appropriate for highly compartmented residential buildings of around twenty floors.

Additionally, attention should be paid to the sleeping function of residential towers because it is hard to implement the abovementioned strategies once a fire incident occurs at night. Despite the fact that residential buildings contain more combustible materials, fire spread can be controlled to some extent because of the small compartment size. When protection-in-place was adopted in Koningin Julianaplein, the top residential floor caused the longest egress time (10:06 by stairs; 6:48 by elevators). Well-designed elevators were applicable in this strategy for disabled/elderly dwellers. Considering the compartment size, protection-in-place, whereupon occupants on the fire floor descend to the ground level is also advised for residential towers.
5.9 **Assessment and Conclusions**

The assessment set out to determine one or more efficient egress plans for Koningin Julianaplein. This section begins by describing the methodology for assessing all egress possibilities that have been proposed in this chapter. It will then bring the discussion into the comparison of all plans from some relevant evaluating criteria. Finally, this section is ended with a conclusion of the assessing result.

5.9.1 **Assessment Methodology**

The underlying framework for the assessment instruments was determined by four evaluating indicators. Each indicator has an associated concern to analyze and assess each egress plan.

1) Theoretical egress time should be the first evaluating factor for all the plans. As the time in which untenable conditions develop can vary greatly, the estimated time required for people to reach a place of safety influence the life safety of both occupants and firefighters.

2) Structural fire safety attributes were used as the second assessing indicator since the level of structural fireproof demands reflected building economics. Reduction in the overall building fire resistance rating resulted in cost savings to the project (10). Evaluation should therefore address the concerns over the structural requirements.

3) Further, high occupant density at top of the office tower increased the extent of congestion. Pedestrians congested both in the stairway and the staircase entry doors, which brought about the capacity drop phenomenon. While the extent of overcrowding was highly dependent on the egress strategy that has been applied.

4) More importantly, the involvement of occupants plays a major role in implementing an egress plan. With this purpose, a questionnaire was developed to gather information about people's attitude towards the four plans.

Assessment was based on the scoring methodology that establishes an equal weight for each criterion. Scores from 1 to 4 reflected the range of excellence in the evaluating criteria in response to each plan. We gave 4 points to the optimum plan, while 1 point to the relatively undesirable plan. Figure 97 illustrates the principle of assessing.

![Figure 97: Assessment criteria](image)
5.9.1.1 Comparison of Egress Time

In this chapter, at least ten egress possibilities have been presented for each tower according to different fire circumstances.

1) Plan 1 - Simultaneous evacuation by stairs \( P_{n,1,0} \)
2) Plan 1 - Simultaneous evacuation by stairs and elevators (Two-zone egress) \( P_{n,1,1} \)
3) Plan 1 - Simultaneous evacuation by stairs and elevators (The entire building as one-zone) \( P_{n,1,2} \)
4) Plan 1 - Simultaneous evacuation by the integration of several egress methods \( P_{n,1,3} \)
5) Plan 2 - Phased evacuation when fire happens above the merging floor \( P_{n,2,1} \)
6) Plan 2 - Phased evacuation when fire happens below the merging floor \( P_{n,2,2} \)
7) Plan 3 - Relocate to the refuge floors when fire happens above the refuge \( P_{n,3,1} \)
8) Plan 3 - Relocate and leave the building when fire happens below the refuge \( P_{n,3,2} \)
9) Plan 4 - Egress the fire floor by stairs, while others stay in place \( P_{n,4,1} \)
10) Plan 4 - Egress the fire floor by elevators, while others stay in place \( P_{n,4,2} \)

Summarized from the ten scenarios, Table 60 compares the longest egress time of each tower. This time is counted from the occupant’s original location to another safe area, which can be the ground level, the refuge zone or other spaces of ultimate safety.

<table>
<thead>
<tr>
<th>Tower</th>
<th>Egress time (mm:ss)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plan 1</td>
</tr>
<tr>
<td></td>
<td>Simultaneous evacuation</td>
</tr>
<tr>
<td>S</td>
<td>S and E</td>
</tr>
<tr>
<td>Tower 1</td>
<td>18:00</td>
</tr>
<tr>
<td>Tower 2</td>
<td>26:54</td>
</tr>
<tr>
<td>Tower 3</td>
<td>13:24</td>
</tr>
<tr>
<td>Tower 4</td>
<td>13:00</td>
</tr>
</tbody>
</table>

Attention:

- \( S \): Egress by stairs only; \( S \) and \( E \): Egress by both stairs and elevators;

Since simultaneous full evacuation is the most widely used strategy around the world, Table 61 gives another comparison between plan 2, 3, 4 and plan 1 (simultaneous strategy). It summarized the egress time between different plans when stairways are the only vertical means of egress. As shown in the table below, when we merely compare the egress time, defend-in-place is recommended for office towers, while relocation strategy works well in residential towers of Koningin Julianaplein. These two concepts can certainly be adopted, provided that fire and smoke is under control and is not likely to spread that fast. Occupants from the unaffected floors in plan 2 were required to leave their floor after the evacuation of the critical zone. There is a time delay of 5 minutes, which explains why a phased evacuation needs the longest escaping time (except office tower 2). In comparison with simultaneous full evacuation, except plan 2, both relocation and protection-in-place save much time due to the shorter travel distance and low occupant load.
Table 6: Egress time comparison of the four plans

<table>
<thead>
<tr>
<th>Koningin Julianaplein</th>
<th>Plan 1 (min)</th>
<th>Plan 2 (min)</th>
<th>Time comparison</th>
<th>Plan 3 (min)</th>
<th>Time comparison</th>
<th>Plan 4 (min)</th>
<th>Time comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office Tower</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>18.00</td>
<td>20.00</td>
<td>+ 11%</td>
<td>11.40</td>
<td>- 37%</td>
<td>11.10</td>
<td>- 38%</td>
</tr>
<tr>
<td>2</td>
<td>26.90</td>
<td>25.80</td>
<td>- 4%</td>
<td>15.30</td>
<td>- 43%</td>
<td>13.50</td>
<td>- 50%</td>
</tr>
<tr>
<td>Residential Tower</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>13.40</td>
<td>17.50</td>
<td>+ 31%</td>
<td>8.50</td>
<td>- 37%</td>
<td>10.00</td>
<td>- 25%</td>
</tr>
<tr>
<td>4</td>
<td>13.00</td>
<td>17.10</td>
<td>+ 32%</td>
<td>8.70</td>
<td>- 33%</td>
<td>10.10</td>
<td>- 22%</td>
</tr>
</tbody>
</table>

Attention:
- Egress time comparison: ‘-’ means the time is saved while ‘+’ stands for the opposite.

Figure 98: Egress time chart

As Figure 98 illustrates, the large population of the top floor (restaurant) in tower 2 has greater impact upon full building evacuation. Thus according to this scoring method, we can get the following outcomes:

- 1 point: plan 2 of all towers
- 2 points: plan 1 of all towers
- 3 points: plan 3 in office towers, and plan 4 of residential towers
- 4 points: plan 4 in office towers, and plan 3 of residential towers

5.9.1.2 Requirements of Structural Fire-protection

Egress time cannot be the only considered criterion for assessment. In reality, fire more or less act differently due to the fuels present, configuration of the area and so on. Partial evacuation required a higher level of structural fire resistance than full evacuation as occupants remain inside the building for a longer time, the structure must remain its integrity. It actually takes different amounts of time to bring the fire under control which is dependent on the environment and extinguishing devices. The calculation results based on chapter 5.6 are summarized in Table 62.
According to the scoring method, we can thereby achieving the following results:

- 1 point: plan 3 and plan 4 of office towers
- 2 points: plan 3 and plan 4 of residential towers
- 3 points: plan 1 and plan 2 of office towers
- 4 points: plan 1 and plan 2 of residential towers

### 5.9.1.3 Congestion Possibility

Despite that Appendix D has calculated the number of people queuing at the stair entry door, it only indicated the relation between occupant density and the flow capacity of stair entry door of a certain floor. In this assessment, congestion possibility was considered based on unquantifiable analysis. Congestion will likely occur on each floor due to several merging pedestrian flows, in particular when simultaneous egress was employed. As discussed before, phased evacuation improved the egress efficiency by introducing 5-minute time delay, and thereupon reduced congestion. By contrast, overcrowding hardly occurs when applying the partial evacuation strategy because few occupants enter the stairwell at the same time. Owing to the lowest flow density in the stairways, partial evacuation strategy provided relatively quicker egress time, in other words, congestion hardly occurs. Especially for protection-in-place, egress only took place at one level, thereby expecting no pedestrians merging from above the below, and the evacuation process would have speeded up. To conclude, we obtained the results below:

- 1 point: plan 1 of all towers
- 2 points: plan 2 of all towers
- 3 points: plan 3 of all towers
- 4 points: plan 4 of all towers

### 5.9.1.4 Questionnaire

Lastly, 148 people have participated in a questionnaire concerning egress from an office fire. Based on the survey findings and taking into account the reliability of answers, their opinions were taken into account as well. More details on this questionnaire can be found in Appendix C. It should be noted that this study aimed at office towers only. The statistics has been compiled into the following scores according to the choices of the participants:

- 1 point: plan 4 of office tower (19 people)
- 2 points: plan 1 of office tower (34 people)
3 points: plan 2 of office tower (35 people)
4 points: plan 3 of office tower (60 people)

5.9.2 ASSESSMENT

Assessment will be composed of four equally weighted parts. To assess the appropriateness of the egress plans, we summarized the overall scoring results in Table 63.

Table 63: Assessment of all egress plans

<table>
<thead>
<tr>
<th>Egress plans</th>
<th>Office towers</th>
<th>Residential towers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design aspects</td>
<td>Plan 1</td>
<td>Plan 2</td>
</tr>
<tr>
<td>Egress time</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Structural fire resistance/Project cost</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Congestion possibility</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Questionnaire</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Total score</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

5.9.3 CONCLUSIONS

Fire safety design shall be based on eliminating or minimizing the harm for people. Certainly, actual fire behavior is different in every condition, whether a simultaneous full evacuation is needed totally depends on the fire situation. Returning to the research question posed at the beginning of this study, it is now possible to state that the most effective egress plan(s) for Koningin Julianaplein:

Table 64: Recommended egress plan for each tower

<table>
<thead>
<tr>
<th>Koningin Julianaplein</th>
<th>Recommended plan(s)</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office towers</td>
<td>Plan 3: Relocation</td>
<td>• When the fire locates above the refuge floors: the fire floor, two floors above and two floors below evacuate to the refuge by stairs; • When the fire locates below the refuge floors: the fire floor, two floors above and two floors below evacuate to the ground floor by stairs.</td>
</tr>
<tr>
<td>Residential towers</td>
<td>Plan 3: Relocation</td>
<td>• When the fire locates above the refuge floors: the fire floor, two floors above and two floors below evacuate to the refuge by stairs; • When the fire locates below the refuge floors: the fire floor, two floors above and two floors below evacuate to the ground floor by stairs;</td>
</tr>
<tr>
<td></td>
<td>Plan 4: Protection-in-place</td>
<td>Only the fire floor evacuate to the ground floor by stairs or elevators.</td>
</tr>
</tbody>
</table>
Based on the assessment, relocation strategy is recommended for all towers of Koningin Julianaplein, while a notable exception is office tower 2. We also advise phased evacuation in this tower as this strategy can decrease total egress time, optimize the usage of stairway and balance the occupant load. This strategy allows the fire floor, one level above and one level below evacuate first, the rest of the building start their egress after 5 minutes.

Further, it is essential to understand the condition of applying these recommended egress plans, the fire-protection system in particular. In contrast to the offices, it is relatively hard for dwellers to notice a fire from the very beginning, in other words, the ignition. Offices are much transparent since they are usually designed with open spaces and large glass interior decoration. Employees can figure out whether there is a fire in the next office easily. While in terms of dwellings, occupants usually cannot see their neighbors directly because of the privacy protection. In consequence, at the early stage of an emergency, the delay in the action of egress for the apartment will be longer than office. A reasonable approach to tackle this issue could be to install smoke detectors properly and connect them to a central control center. At the fire outbreak stage in an apartment, neighbors can be informed about the event and prepare to escape. However, false alarm will create problems, while it falls outside of this research scope.

Besides, this study produced results which corroborate the findings of the previous work in this field. In terms of vertical egress methods, the results of our research also conformed to Table 24 from chapter 4.6.8 'Research on elevator-assisted egress'. For office buildings around 20 floors, the appropriate means of egress was using stairs during full evacuation, while elevators egress can be considered in partial egress. Successful and efficient evacuation depends on complete preplanning, organization, and supervision. No matter which plan is employed, the most efficient and economical method for residential buildings is egress via stairs.
5.9.4 **Inapplicable Plans**

It should be mentioned that with regard to simultaneous strategy by stairs and elevators, we also attempted to divide the tower into three zones based on the Greenwich research scenario II (chapter 4.6.8). For instance for tower 1 (page 126: Plan 2.3):

- **Top zone** (15F to 22F): occupants travel down the stairs to the next transition floor (15F) where the elevators shuttle them to the ground floor;
- **Middle zone** (7F to 14F): occupants travel down the stairs to the next transition floor (7F) where the elevators shuttle them to the ground floor;
- **Low zone** (0F to 6F): occupants below 6F only use the stairs to leave the building.

Nevertheless, calculation showed that this plan failed and was not applicable in Koningin Julianaplein. The main reason for that is the elevator working time lasted too long, which even reached 40 minutes for tower 2. Because of the large number of people and limited number of elevators in that tower, it must work more than 20 times to transfer all occupants. From literature (103) we know that in reality most occupants would redirect when the waiting time exceeded 5 minutes. Clearly this is a very inefficient strategy for emptying the building. However, research by (104) indicated that this plan was the most efficient way of evacuation in buildings with 50 floors, provided that there were enough elevators.

In addition, as for Koningin Julianaplein, the ‘elevators only strategy’ is not suitable. If elevators are the only way to get downstairs, which means all occupants must wait for the elevators and nobody takes the stairs. It is not realistic in practice. But ‘elevators only’ may be apt for simple buildings with very low occupant load.
CONCLUSIONS AND RECOMMENDATIONS
6.1 Scientific Contributions

As an end of this Master thesis, this chapter presents scientific contributions, the answers to the main research question, thereby the conclusions and recommendations. Prior studies that have noted the importance of egress design on the subject of high-rise fires. In the previous chapters, different egress plans have been made, clearly analyzed and assessed. Broadly, this study contributes to the development of fire safety engineering. From a scientific point of view, the research also contributes to the application of such egress strategies to solve the problem of high-rise evacuation. Based on the profound study of Koningin Julianaplein, the main findings are presented from three aspects: egress strategy, use of elevator and calculation approach regarding egress time.

1) Partial evacuation has a positive impact on the overall evacuation efficiency towards full evacuation in high-rise buildings. It works well for residential towers where approximately 3 to 4 dwellings located on each floor, and office towers with around 100 agents per floor, provided that fire compartments were adequately protected, well-sized and fully equipped with automatic sprinklers. The current study found that for towers with Low Occupant Load:
   - In terms of the full evacuation process, phased evacuation was unnecessary.
   - Relocation and protection-in-place make almost no difference regarding egress time.

For those with relatively High Population Density, e.g. 100 agents located on each floor, circa 25 floors, this study has shown that:
   - Full building evacuation causes congestion and a large number of occupants queuing at the staircase entry door. Phased evacuation has the potential to enhance the egress effectiveness of the first phase, particularly those floors housing gathering functions, in other words, the population remarkably increased at certain levels.
   - Egress efficiency of relocation strategy was improved considerably towards full evacuation. Defend-in-place is the most recommended approach when we merely balance the total egress time.

2) Another important finding was that whether Elevators could improve the efficiency of evacuation is highly dependent on the building geometry, population and lift strategy employed. Regarding buildings of circa 20 floors with 10 to 100 persons per floor, we found that elevators cannot contribute much to reduce the total egress time. Contrary to expectations, they even prolong the total egress time in some cases. The findings of the current study do not completely support the previous research from University of Greenwich on elevator-assisted evacuation (104). The most efficient overall strategy according to (104) involved using 32 elevators arranged into multiple sky lobbies where agents traveled down the stairs to their nearest sky lobby and uses elevators from the lobby to the ground. However, this scenario was not practicable in Koningin Julianaplein. The main reasons behind were the differences in hypothetical nature between the investigated building in (104) and Koningin Julianaplein:
Greenwich: Koningin Julianaplein:

- The number of floors 50 22 and 26
- Population per floor 160 8 to 100
- The number of elevators 8 to 32 1 to 4
- The number of sky lobbies 4 1
- Elevator working mode Top-down-shuttle Top-down

3) We employed both the American SFPE and Dutch Calculation Methods to compute the theoretical egress time for simultaneous evacuation. Results using SFPE method show that it took approximately 13 seconds to descend one floor with a height of 3.6m, and 10 seconds to descend a floor height of 3m (special stairs without middle landing). By comparison, both approaches gave similar results. With the identical structural configuration and the same occupant load, walking speed of the SFPE method was slightly quicker.

6.2 General Conclusions

This research was undertaken to develop efficient egress plans in case of fire for a Dutch high-rise building Koningin Julianaplein from a global perspective. From the knowledge obtained from case studies and literature review, a number of different egress possibilities have been carried out and compared via the assessment. In addition to chapter 6.1, during the execution of this research project there are many findings, both from the theoretical and implementation aspects that may lead to the further development of high-rise egress design.

We first come back to the main research question that motivates the objective of this study:

In the event of a fire, how to evacuate efficiently inside a high-rise building?

Not only a successful egress plan contributes to the efficient evacuation, but also occupants' behavior plays an important role. To answer this question, we present our conclusions from two different sides: the designer and the building user.

6.2.1 High-rise Building Designers

Along with the design process of a high-rise project, egress design fundamentals have been summarized for fire safety engineers. Prior to the fire safety design, engineers should be familiar with the architectural concept, such as function distribution of the building, floor layout and some critical dimensions of the structure. Different function leads to different occupant load according to fire regulations, while sometimes the expected population was provided by the client. Besides, normally buildings with sleeping function, such as apartment, hospital or day care center have higher structural fire resistance than offices in

33106 was the maximum population, but it was halved in the calculation because of the application of scissors staircases.
Conclusions and Recommendations

regard to egress from fire. In the course of overall egress design, attention should be paid to the key aspects stated below:

- Arrange the staircases reasonably to ensure the horizontal travel distance within local regulation, divide the area into sub-compartment if necessary.
- Provide at least two escape routes in case one way is blocked.
- Calculate the theoretical egress time, and check whether the descending time fulfills the demands within building codes.
- Check the storage and flow capacity of the stairwells, doors, corridors and other means of transportation along the egress route\(^{34}\). The width of the egress route is governed by the function of the building, and number of occupants who are likely to use the egress routes.
- On condition that congestion or other capacity drop phenomenon occurs in pedestrian flow, measures like delaying evacuation, adjust the capacity of means of egress should be taken.
- Apart from using stairs only, provide other vertical means of egress for hospitals, nursing home et cetera.

Reduction in RSET\(^{35}\)

One way to reduce the RSET is shorten the travel distance. Introducing protected routes, smoke prevention lobby in front of a staircase, fire safety curtain, smoke/fireproof corridors, sub-compartment, and avoiding dead ends ensure the occupants to reach the relevant safety nearby. Egress routes taken must remain tenable throughout the evacuation process. Furthermore, refuge floors also delays the need to use stairs and reduces the occupant load in stairwells. In terms of the circulation routes, wider routes bring about reduction in the flow density. But once the route is too wide, it lowers the flow speed at the same time.

In addition to building geometry, the second way to reduce RSET related to the architectural design and fire protection system affects occupants’ reaction and travel speed.

- Make open floor plan rather than cellular has beneficial effects on building users, which enhances the visibility of source of fire, and thus contributive to minimizing the pre-movement time. In practice, it is also a possible advantage of atria over separated floors.
- Psychological research\(^{36}\) indicated that people turn to follow daylight in emergency situation, thus egress routing should draw people to lighter and safer spaces.
- Simplifying the way finding for occupants also lessens the egress time. For instance, improving the orientation cues, making clear signage and interior design, avoid impediments, uneven surfaces or irregular steps et cetera.
- Early warning by automatic detection provides much time for people to react.
- Provide clear evacuation information to occupants using spoken message/alarm instead of plain sounder. In reality people normally take action after they see, feel,

\(^{34}\) Capacity check is needed in the Netherlands, not all other countries.

\(^{35}\) RSET: Required safe egress time, defined in chapter 1.1.

hear or smell the fire. They do not respond to the alarm since nobody knows what is it, and false alarm happens frequently.

**Conclusions in egress strategies selection**

The evidence from this study suggests that simultaneous full evacuation is the most common strategy for uncomplicated, low-rise or multi-story buildings. For a phased evacuation those in most immediate risk are evacuated first can improve the efficiency of use vertical egress facilities. In practice, this strategy can be carried out more often in skyscrapers or buildings with large footprint.

Nevertheless, full evacuation of a building may not always be a viable and necessary option. On one hand, if the physical characteristics of the occupants make a full evacuation difficult, and the structure of the building allows, you may consider partial or horizontal evacuation. On the other hand, buildings built with distinct fire barriers, smoke separations, horizontal exits which have a high degree of floor to floor fire resistance are suitable for partial evacuation. Fire and/or smoke compartmentation features provide protection for those occupants outside the affected fire area or floor. In reality, relocation, stay-in-place and phased evacuation are relevant to some extent, while relocation and defend-in-place are not appropriate for extreme event. In addition to that, horizontal phased evacuation can be applicable for hospitals or nursing homes with large footprint. Depending onto the fire situation it may be necessary to consider vertical evacuation eventually. Debates need to take place on the pros and cons about protection-in-place. It is often used in facilities that occupants have a limited ability to move or may not have fast first response, such as hospitals and nursing home. It may also be considered in blocks of apartments where each dwelling is a high level fire-resisting compartment, or public buildings when the vertical distance to the street level is extremely remote.

In conclusion, the selection of an appropriate egress strategy requires a good understanding of the building, involving the estimated population, the fire protection system and the expected emergency response.

**Involvement of various disciplines**

Last but not least, fire safety is a highly integrated field covers a large amount of subjects, and therefore another key issue is the involvement of various disciplines. Architects and civil engineers normally design the structure and determine the construction material. The high-rise fire example in Istanbul (chapter 12.4, page 22) indicated that fire spread upward much more rapidly, therefore facade finishing material must be fire-protected. From an exterior design standpoint, fire resistant glass and other protected measures must be taken. Meanwhile, building physics specialists make calculations on HVAC, water and electricity power distribution system. The design of the smoke extraction system, arrangement of sprinklers and fire hydrants should be done together with the fire safety engineers. Furthermore, suggestions and requirements from fire department and the government are of concern to the fire safety design. All the above mentioned domains are highly correlated and shall be integrated into the egress design process. Communicate frequently with all
relevant parties would balance fire safety design against all the other competing factors to get the better possible results.

6.2.2 BUILDING USERS

With the aim of evacuating successfully and efficiently, the other important influencing factor is the reaction of building users. Based on the research from Nancy Oberijé, fire response performance of people is dependent on three aspects:

![Recognition → Judgment → Action](image)

Figure 99: Human behavior - reaction to a fire

In the first stage, people normally need time to recognize and validate of fire cue. There have been a host of investigations into human behavior in fires. Most researches indicated that people would rather continue working than take any action. Whether people are able to respond in time in a confounding circumstance is dependent on various situations:

- Activities they are involved;
- Familiarity of the surroundings;
- Whether they keep their routine;
- Panic or not\(^{37}\);
- Individual conditions: age, gender, physical ability, clothing et cetera.

After an alarm, most people peer at each other, watch and follow the reaction of the group, which will result in a longer pre-movement time and evacuation delay. Besides, study by Nancy Oberijé reports that people in unfamiliar surroundings tend to use the way they entered as their sole exit route. As such, training some of the occupants or staff in the building as leaders makes the evacuation process much organized. Meanwhile everybody shall give assistance to physically disabled persons, which decreases the total egress time. The next paragraph gives some recommendations to the building users that contribute to implement an efficient egress:

- Participate in the fire drill, or other trainings relates to life safety, do not ignore the training or underestimate the danger of a fire;
- Better configuration knowledge guide the occupants to a safer space, improve the travel speed and lower the risk of getting hurt, therefore try to have a glimpse over the emergency plan before emergency happens.

\(^{37}\) Panic: Despite the numerous evidences that panic rarely occurs in case of fire, the idea of panic and the term continue to be used by the public as well as fire experts (30).
In short, an effective egress plan includes not only what should be done during the evacuation, but also preplanning, training, assigning responsibility to various individuals. Implementing a successful evacuation needs the contribution of both building designers and building users.

6.3 PRACTICAL RECOMMENDATIONS

All findings mentioned in chapter 6.1 were based on traditional fire incidents. It is deemed that the tower will need additional or more reliable fire safety measures for events other than 'traditional' events. Based on these findings, we suggest several courses of action:

1) When employing phased evacuation in High Occupant Density Buildings, it allows a reduction in the required width of the escaping stairs, which brings about lower construction budget. For apartments, since the study indicated the little difference between relocation and defend-in-place, considering the small compartment size and Low Occupant Load, protection-in-place is therefore advised. More importantly, proposing an appropriate egress strategy is not an absolute selection, which is greatly dependent on the fire situation and human behavior. In fact, egress strategy can be converted to one another. For instance, if the occupants are advised to stay in place, but the fire becomes untenable rapidly, a full evacuation is certainly required. Conversely, phased evacuation can be stopped at any step when the fire is extinguished. In theory, it then converted into a relocation strategy.

2) The application of Elevators in egress is economically unfeasible in towers with low occupant load (10 to 100 persons per floor) as congestion would hardly occur in stairwells. For buildings with high occupant load, when applying the top-down mode, the amount of time wasted in waiting for the elevators is quite long. People may redirect and result in counterflow that impedes the escaping occupants. Introducing high speed elevators (such as 10m/s) or enlarge the weight capacity can help to some extent, meanwhile it increases the construction cost. Consequently, elevator-assisted evacuation is not suggested for buildings below 25 floors.

3) The Approach on Egress Time Calculation used in the Netherlands is a combination of NEN norm and SBR guideline. The current study showed that this method is sound and feasible. Tracking the location of the flow is one of the major benefits of the Dutch method. It is evident to find out the location of the evacuees (e.g. just enter the stairs; on the steps; on the landing). Therefore we do not recommend applying other methods at the moment.

However, a few limitations to this pilot study need to be acknowledged. First, conclusions and recommendations apply only to buildings described in chapter 6.1. The geometry and building population should be comparable to Koningin Julianaplein to some extent. Second, calculation on egress time was based on SFPE approach with a little variation on the pre-movement time. In Appendix D, 4.9 minutes was added up to the total egress time according to British standard BS7974:2001. This study did not investigate the pre-movement time in detail since issues on human behavior was emerged from this topic. In reality, it might take a dozen of seconds or even an hour to response before action.
6.4 Recommendations for Further Study

This research can be a reference to future projects, and recommendations in this chapter aim at high-rise and low-rise buildings. More broadly, the findings from our study provide the following insights for future research:

- **Additional fire resistance on partial evacuation**: From the egress concepts we know that partial evacuation requires higher level of structural fire resistance. However, most researches in structural fire-resistant rating have only been based on the building regulations. There have been no controlled studies which compare the differences in structural requirements between full evacuation and partial evacuation. In other words, the relation between the egress strategy and structural fireproof attributes need to be further investigated.

- **Egress group**: Throughout this study, we found that there were considerable quantities of combinations in terms of phased evacuation. Depending on the number of floors and occupant load, after the first phase, priority can be given either to the top floor, floors adjacent to the fire incident, or the entire building as a whole group. The egress process can be divided into two phases, three phases or even more. With the help of computer simulation, there could be an optimum plan that benefits all the occupants.

- **Human behavior**: Since human behavior has great influence on the total egress time, which should always be considered as part of the design. Available data on human behavior indicated that even architectural design affects people’s reaction in evacuation. Egress can be much organized either by dividing the door using a railing in the middle which separates the pedestrian group, or moving the door to another location and thus reduces pushing and crowding. More specifically, even turning your body has impact on lengthening the egress time. Future studies on this issue will, to some extent, make egress plan much closer to reality.

- **Elevator egress**: Successful egress planning recognizes the importance of unaided and aided occupant movement from a fire to a protected exit. High-rise building occupants who cannot traverse stairs without special equipment and/or assistance must be presumed. Protected mechanical aids and evacuation elevator can help, though whether people are allowed to use elevators in a burning building is still controversial. A future study investigating the interaction between the employed elevator strategies, human behavior and various egress plans would be very interesting.
APPENDIX A: EGRESS TIME CALCULATION METHODS
A.1 AUSTRALIAN/ZELANIAN METHOD

**Travel speed**

For able-bodied adults, when the occupant density is less than $0.5 \text{ people/m}^2$, the travel speed is shown in Table 65. For occupant density exceeds $3.5 \text{ people/m}^2$, it is not possible to egress freely (11).

<table>
<thead>
<tr>
<th>Situation</th>
<th>Speed (m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncongested situation</td>
<td>70</td>
</tr>
<tr>
<td>On stairs</td>
<td>51 to 63</td>
</tr>
</tbody>
</table>

For occupant density $D_o$ greater than $0.5 \text{ people/m}^2$, the relationship between travel speed and density of occupants is:

$$ S = k_t (1 - 0.266 D_o) $$

(5)

Where,

- $k_t = 84.0$ for level corridors or doorways;
- $k_t = 51.8 (G/R)^{0.5}$ for stairs,

$G$: Length of the stair tread going and $R$ is the riser height of each step.

**Specific flow**

For any value of occupant density and corresponding value of speed from the abovementioned equation, there is a unique value of specific flow $F_s$ given by:

$$ F_s = S \times D_o $$

(6)

Where,

- $D_o$: Density of occupants,
- $S$: Travel speed.

A simple example is given to describe how to calculate. The function is restaurant, from (11) we can know that the occupant density is $0.9 \text{ people/m}^2$, $k_t = 84.0$ when traveling on corridors or doorways.
**Horizontal - corridor and floors**

Length of the room: \( L_r = 10\, \text{m} \)

Width of the room: \( W_r = 5\, \text{m} \)

Length of the protected stair: \( L_s = 5\, \text{m} \)

Floor area of the room: \( A_r = L_r \times W_r = 50\, \text{m}^2 \)

Occupant density: \( D_o = 0.9\, \text{people/ m}^2 \)

Number of occupants: \( N_o = A_r \times D_o = 50 \times 0.9 = 45\, \text{people} \)

\( k_t \) factor: \( k_t = 84.0 \)

Travel speed: \( S = k_t (1 - 0.266D_o) = 63.89\, \text{m/min} \)

Length of the escape route from the furthest to exit x: \( L_e = 15\, \text{m} \)

Traversal time: \( t_r = \frac{L_e}{S} = \frac{15}{63.89} = 0.23\, \text{min} \)

Detection time: \( t_d = 0.8\, \text{min} \)

Alarm time after detection: \( t_a = 0.1\, \text{min} \)

Occupant decision time: \( t_o = 2\, \text{min} \)

Occupant investigation time: \( t_i = 2\, \text{min} \)

Evacuation starts at \( t_d + t_a + t_o + t_i = 0.8 + 0.1 + 2 + 2 = 4.9\, \text{min} \) and the first person is assumed to enter exit B at this time.

Time for the last person to reach exit x: \( t_{ev} = t_d + t_a + t_o + t_i + t_r = 4.9 + 0.23 = 5.13\, \text{min} \)

Queuing effects at the doorway Exit B must first be considered as shown below:

Width of the door: \( W = 1.20\, \text{m} \)

Width of boundary layer: \( B = 0.15\, \text{m} \)

Effective width: \( W_e = W - 2B = 0.9\, \text{m} \)

Specific flow through door: \( F_s = S D_o = 63.89 \times 0.9 = 57.51\, \text{people/min/m} \)

Actual flow through door: \( F_a = F_s W_e = 57.51 \times 0.9 = 51.75\, \text{people/min} \)

Queuing time to travel through exit x: \( t_q = \frac{N}{F_a} = \frac{45}{51.75} = 0.87\, \text{min} \)

The last person enters Exit B 0.87 min after the first person enters Exit B, \( t_i = 5.13\, \text{min} \)

The evacuation time to Exit B is \( t_{ev} = t_d + t_a + t_o + t_i + t_q = 4.9 + 0.87 = 5.77\, \text{min} \)
Vertical - stairs

Width of the staircase \( W = 1.20 \text{ m} \)

Width of boundary layer \( B = 0.15 \text{ m} \)

Effective width \( W_e = W - 2B = 0.9 \text{ m} \)

Using the actual flow of people as they pass through exit \( x \), and the width of the space they enter, the specific flow in the stairway can be determined.

Specific flow \( F_x = \frac{F_s}{W_e} = \frac{51.75}{0.9} = 57.50 \text{ people} / \text{ min} / \text{ m} \)

Length of stair tread going \( G = 280 \text{ mm} \)

Height of the stair riser \( R = 180 \text{ mm} \)

\( k_r \) factor: \( k_r = 51.8 \left( \frac{G}{R} \right)^{0.5} = 51.8 \left( \frac{280}{180} \right)^{0.5} = 64.6 \)

The specific flow and people density can be related as follows to determine the density of people in the stair.

Density of occupants

\[ S = k_r (1 - 0.266 D_s) \text{ and } F_x = SD_s \]

\[ F_x = k_r D_s (1 - 0.266 D_s) \]

\[ 57.5 = 64.6 D_s (1 - 0.266 D_s) \]

\[ 17.18 D_s^2 - 64.4 D_s + 57.5 = 0 \]

\[ D_s = 2.31 \text{ people} / \text{ m}^2 \text{ or } 1.45 \text{ people} / \text{ m}^2 \]

Sensibly choose \( D_s = 1.45 \text{ people} / \text{ m}^2 \)

Travel speed in stair \( S = k_r (1 - 0.266 D_s) = 64.4 \times (1 - 0.266 \times 1.45) = 39.68 \text{ m} / \text{ min} \)

Length of stair \( L_x = 5.0 \text{ m} \)

Time to traverse the stairs \( t_s = L_x / S = 5 / 39.68 = 0.13 \text{ min} \)

The first person reaches and enters exit \( C \) at \( 4.9 + 0.13 = 5.03 \text{ min} \)

The last person reaches exit \( C \) at \( 577 + 0.13 = 5.90 \text{ min} \)

Specific flow at exit \( x \) \( F_x = SD_o = 39.68 \times 1.45 = 57.54 \text{ people} / \text{ min} / \text{ m} \)

Actual flow though exit \( x \) \( F_a = F_x W_e = 57.54 \times 0.7 = 40.28 \text{ people} / \text{ min} \)

Time to travel though exit \( x \) \( t_e = N / F_a = 45 / 40.28 = 1.12 \text{ min} \)

Thus the last person enters exit \( C \) 1.12 minutes after the first person has entered exit \( x \), therefore the stairway is clear and the evacuation time for the building is \( 5.03 + 1.12 = 6.15 \text{ min} \).

The design time for escape for the protected stairway is \( t_{\text{design}} = 2 \times t_e = 2 \times 6.15 = 12.30 \text{ min} \)
A.2 KIKUJI TOGAWA

The Japanese scholar Kikuji Togawa’s formula aims at calculating the minimum egress time with shortest distance for buildings using staircases (10).

\[ \text{Evacuation time} = \text{Flow time} + \text{Travel time} \]

\[ T_e = \frac{1}{N'B} \left[ N_e - \sum_{i=1}^{n} N_i(t) B_i \phi_i(t) dt \right] + T_0 \]  \hspace{1cm} (7)

Where,
\[ T_e : \text{Time required to escape (s)} \]
\[ N_e : \text{The total number of people escaping the building} \]
\[ N_i(t) : \text{The flow capacity of exit } i \]
\[ N' : \text{The flow capacity of the final exit (persons/m/s)} \]
\[ n : \text{The total number of exits} \]
\[ B_i : \text{Width of exit } i \text{ (m)} \]
\[ B' : \text{Width of the most limiting passageway (m)} \]
\[ \phi_i(t) : \text{The coefficient of people’s retention of exit } i, \text{ which is the percentage of people passing through the exit and the total number of people} \]
\[ T_0 : \text{Travel time for normal evacuation (s)} \]

Several parameters are needed for this method, such as coefficient of people’s retention, another limitation of applying this method is that travel time for normal evacuation should be available beforehand.
Appendix A: Egress Time Calculation Methods

A.3 Melinek and Booth

The Melinek and Booth flow model (Melinek and Booth 1975) can be applied to calculate the egress time by means of stairs for multi-floor buildings. It is similar to Togawa's method. They roughly divided the evacuation situations into two categories. The egress time is the maximum of the following two situations (70, 101).

- Congestion on the stairs, maximum flow
- Walk freely

\[
t_1 = \frac{nN}{F_S W} + t_s
\]

(8)

\[
t_n = \frac{N}{F_S W} + nt_s
\]

(9)

Where,

- \(t_1\): Egress time (congestion)
- \(t_n\): Egress time (free walk)
- \(n\): Number of floors
- \(N\): Number of people per floor and exit
- \(F_S\): Nominal occupant flow on stairs (persons / m / s)
- \(W\): Width of the staircase
- \(t_s\): walking time between adjacent floors (free walk) 16s usually used

Take the previous example to calculate the vertical egress time:

\[
t_1 = \frac{nN}{F_S W} + t_s = \frac{2 \times 45}{57.5 \times 60 \times 12} + 16 = 94.3 s = 1.57 \text{ min}
\]

\[
t_n = \frac{N}{F_S W} + nt_s = \frac{45}{57.5 \times 60 \times 12} + 16 \times 2 = 71.1s = 1.19 \text{ min}
\]

Melinek and Booth method shows that the egress time is 1.57 minutes in congested situation, while free walk is about 1.19min. The calculation results using Australian method is 1.12 minutes. It can be concluded that the calculation results are similar. This method focuses on multi-floor building, but the floor plan should be similar.
A.4 Pauls

Pauls' formula was summarized from many evacuation drills of multi-floor buildings. His study focused on high-rise buildings and was the most popular method. Pauls also investigated the effective width, which is the usable width that evacuees can walk through. Thus the boundary wall area and handrail width should be deducted. (99, 101)

\[ F = 0.206 \left( b - 0.3 \right) \left( \frac{P}{b - 0.3} \right)^{0.27} \]  

(10)

Where,

- \( F \): Flow capacity (persons / s)
- \( b \): Width of the stairs (m)
- \( P \): Number of occupants (persons)

When \( p \leq 800 \), \( T = 2.00 + 0.0117 \times p \)  

(11)

When \( p > 800 \), \( T = 0.70 + 0.0133 \times p \)  

(12)

Where,

- \( T \): The minimum time to complete an uncontrolled total evacuation by stairs (min)
- \( p \): The actual evacuation population per meter of effective stair width, measured just above the discharge level of the exit (persons / m)

Take the previous example to calculate the total egress time:

\[ F = 0.206 \left( b - 0.3 \right) \left( \frac{P}{b - 0.3} \right)^{0.27} = 0.206 \times \left( \frac{45}{12 - 0.3} \right)^{0.27} = 0.53 \text{ persons} / \text{s} \]

\[ p = \frac{P}{D_{\text{eff}}} = \frac{45}{12 - 0.3} = 50 < 800 \text{ persons} / \text{m} \]

\[ \therefore T = 2.00 + 0.0117 \times 50 = 2.00 + 0.585 = 2.59 \text{ min} \]

Thus, the total evacuation time of the two floors will be 2.59 minutes.

A number of limitations need to be considered. First, this method is not suitable for buildings with different occupant densities. Second, the actual evacuation population per meter of effective stair width is not a constant value for complex high-rise buildings like Koningin Julianaplein.
A.5 SFPE METHOD

This section is summarized from SFPE Handbook of Fire Protection Engineering (the 3rd edition). SFPE stands for Society of Fire Protection Engineers Bethesda, Maryland.

A.5.1 EGRESS TIME

The SFPE method is similar with Australian/Zealanian method. The principle of evacuation design is (25)

\[ \text{ASET} > \text{RSET} \]

\[ \text{RSET} = t_d + t_a + t_o + t_i + t_e \]

Where,

\( \text{RSET} \): Required safe egress time
\( \text{ASET} \): Available safe egress time
\( t_d \): Time from fire ignition and detection
\( t_a \): Time from detection to notification the occupants of a fire emergency
\( t_o \): Time from notification until occupants decide to take actions
\( t_i \): Time from decision to take action until evacuation commence
\( t_e \): Time from the start of evacuation until complete

![Diagram of ASET and RSET](image)

**Figure 10**: RSET and ASET

A.5.2 SPEED

- If the population density < 0.05 persons / ft^2 (0.54 persons / m^2) of exit route (20 ft^2 / person; 1.85 m^2 / person), individuals will move at their own pace, independent of the speed of others.
• If the population density > 0.35 persons / ft² (3.8 persons / m²), no movement will take place until enough of the crowd has passed from the crowded area to reduce the density.

• 0.05 persons / ft² < density limits < 0.35 persons / ft² (0.54 persons / m² and 3.8 persons / m²) the relationship between speed and density can be considered as a linear function. The equation of this function is:

\[ S = k - akD \]  

Where,

- \( S \): Speed along the line of travel
- \( D \): Density in persons per unit area
- \( k \): Constant, as shown in Table 68
  - \( k_1 \) and \( a = 2.86 \) for speed in ft / min and density in persons / ft²
  - \( k_2 \) and \( a = 0.266 \) for speed in m / s and density in persons / m²

<table>
<thead>
<tr>
<th>Exit Route Element</th>
<th>( k_1 )</th>
<th>( k_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corridor, Aisle, Ramp, Doorway</td>
<td>275</td>
<td>1.40</td>
</tr>
<tr>
<td>Stairs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Risor (in.)</td>
<td>7.5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>7.0</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>6.5</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>6.5</td>
<td>13</td>
</tr>
<tr>
<td>Tread (in.)</td>
<td>196</td>
<td>212</td>
</tr>
<tr>
<td></td>
<td>229</td>
<td>242</td>
</tr>
</tbody>
</table>

The next figure illustrates the determination of evacuation speed as a function of density, for stairs the speeds are along the line of the treads, which can be applied in the further calculation.

Figure 102: Evacuation speed as a function of density
Table 67 provides convenient multipliers for converting vertical rise of a stairway to a distance along the line of movement. The travel on landings must be added to the values derived from Table 67.

Table 67: Conversion factors for relating line of travel distance to vertical travel for various stair configurations

<table>
<thead>
<tr>
<th>Exit route element</th>
<th>Maximum specific flow</th>
<th>Conversion factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corridor, aisle, ramp, doorway</td>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>Stairs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Riser</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tread</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(in.)</td>
<td>(m)</td>
<td>(in.)</td>
</tr>
<tr>
<td>7.5</td>
<td>0.191</td>
<td>10</td>
</tr>
<tr>
<td>7.0</td>
<td>0.178</td>
<td>11</td>
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<tr>
<td>6.5</td>
<td>0.165</td>
<td>12</td>
</tr>
<tr>
<td>6.5</td>
<td>0.165</td>
<td>13</td>
</tr>
</tbody>
</table>

A.5.3 Specific Flow

Specific flow is the flow of evacuating persons past a point in the exit route per unit of effective width,

\[ F_S = S \times D \]  

Where,

\( F_S \): Specific flow (persons/min/f\(\text{feet} \)),  
\( S \): Speed (m/s),  
\( D \): Density (persons/m\(^2\)).

A.5.4 Calculated Flow

It is the predicted flow rate of the persons passing a particular point in an exit route.

\[ F_C = F_S \times W_e \]  

Where,

\( F_C \): Calculated flow (persons/s),  
\( W_e \): Effective width (m).
A.5.5 Time for Passage

This is the time for a group of persons to pass a point in an exit route, can be expressed as:

$$t_p = \frac{P}{F_C}$$  \hspace{1cm} (18)

Where,

$p$: Population in persons

A.5.6 SFPE Solutions

SFPE gives two kinds of solutions with respect to total egress time calculation, involving 'First order approximation' and 'More detailed analysis'. Each of them is briefly described in this section.

**First Order Approximation**

1. Assumption:
   - Queuing will occur;
   - Specific flow is the maximum flow;
   - All occupants start egress at the same time;
   - The population will use all facilities in the optimum balance

2. Estimate flow capacity of a stairway
3. Estimate flow capacity through a door
4. Estimate the speed of movement for estimated stair flow
5. Estimate building evacuation time

**More Detailed Analysis**

1. Assumptions:
   - Occupants use all exit facilities in the optimum balance;
   - All occupants start egress at the same time.
2. Estimate flow density, speed, specific flow, effective width and initial calculated flow of each floor
3. Estimate impact of stairway entry doors on exit flow
4. Estimate impact on stairway on exit flow
5. Estimate impact of merger of stairway flow and stairway entry flow on exit flow
6. Track egress flow

Since the second method achieves more results by tracking egress flow, merging effect of the floor above is also considered, for our calculation in Appendix D, we applied the method of SFPE 'More detailed analysis'.
APPENDIX B: ORIGINAL CLAUSES IN THE DUTCH NORMS
**B.1 Bouwbesluit 2012**

Bouwbesluit 2012 original clauses: 'Een te bouwen bouwwerk waarin een vloer van een verblijfgebied hoger dan 70 m boven of lager dan 8 m onder het meetniveau ligt, is zodanig ingericht dat het bouwwerk brandveilig is (Bouwbesluit artikel 2.208 lid 1).' Om aan deze eis te kunnen voldoen, zijn onderstaande functionele eisen van toepassing binnen de 'scope' van dit Masterplan:

1) Een te bouwen bouwwerk heeft een bouwconstructie die zodanig is ingericht dat het bouwwerk bij brand gedurende redelijke tijd kan worden verlaten en doorzocht, zonder dat er gevaar voor instorting is;

2) Een te bouwen bouwwerk heeft voorzieningen voor het veilig overbruggen van hoogteverschillen;

3) Een te bouwen bouwwerk is zodanig ingericht dat het ontstaan van een brandgevaarlijke situatie voldoende wordt beperkt;

4) Een te bouwen bouwwerk is zodanig ingericht, dat brand zich niet snel kan ontwikkelen;

5) Een te bouwen bouwwerk is zodanig ingericht dat de uitbreiding van brand voldoende wordt beperkt;

6) Een te bouwen bouwwerk is zodanig ingericht dat het zich snel ontwikkelen van rook voldoende wordt beperkt;

7) Een te bouwen bouwwerk is zodanig ingericht dat rook zich bij brand niet binnen korte tijd kan verspreiden naar een ander deel van het bouwwerk zodat op veilige wijze het aansluitende terrein kan worden bereikt;

8) Een te bouwen bouwwerk is zodanig ingericht dat een rookcompartiment en een subbrandcompartiment voldoende snel en veilig kunnen worden verlaten;

9) Een te bouwen bouwwerk heeft voldoende vluchtroutes waarlangs bij brand een veilige plaats kan worden bereikt;

10) Een te bouwen bouwwerk heeft zodanig ingerichte rookvrije vluchtroutes, dat in geval van brand snel en veilig kan worden gevlucht;

11) Een te bouwen bouwwerk is zodanig ingericht dat personen kunnen worden gered en brand kan worden bestreden;

12) Een te bouwen bouwwerk heeft zodanige voorzieningen voor de bestrijding van brand, dat brand binnen redelijke tijd kan worden bestreden.
B.2 NEN 6702

NEN6702 original clauses: "De hoofddraagconstructie onder brandomstandigheden is dat deel van de bouwconstructie dat leidt tot het bezwijken van een bouwconstructie die:
   a) niet in hetzelfde brandcompartiment is gelegen als de beschouwde brandruimte; dit geldt niet voor een woonfunctie;
   b) in het geval dat de brandruimte een subbrandcompartiment is of een deel van een subbrandcompartiment, zorgdraagt voor het instandhouden van niet-direct aangrenzende subbrandcompartimenten en niet-direct aangrenzende andere ruimten;
   c) in het geval dat de brandruimte deel uitmaakt van een (sub)brandcompartiment dat meer dan drie bouwlagen bevat, zorgdraagt voor het instandhouden van ruimten die niet direct aan de brandruimte grenzen, maar wel in het (sub)brandcompartiment zijn gelegen; daarbij mag worden uitgegaan van de voor het bezwijken meest ongunstige ligging van de brandruimte in een combinatie van drie bouwlagen."
APPENDIX C: QUESTIONNAIRE
C.1 QUESTIONNAIRE

As has been stated in the assessment, in order to evaluate the acceptability of the egress plans, a questionnaire was developed to examine people's attitudes towards fire egress in a hypothetical evacuation scenario. 148 of the questionnaires were filled in and returned, which gave a valuable insight into the population profiling and their preferences. The majority of respondents were from Europe, Asia and North America, of different ages and genders. More importantly, most of them are not fire specialists. We explained the four egress plans and provided the following scenario, which was based on the office tower 2 of Koningin Julianaplein:

Assuming that you are on the 22nd floor of a 22-story building, a fire occurs at 20F:
Four evacuation plans, which one would you like to use? ______
1) Simultaneous evacuate with others after the alarm by walking down stairs to the ground floor, it takes 26:54 (but congestion in stairways may occur)
2) You will be informed about the fire event, and escape 5 minutes after the alarm, and walk down to the ground floor, it takes 20:48 (congestion can be avoided to some extent, because you start to escape after the most affected zone)
3) Relocate to a safe refuge floor, which takes 15:18, and you do not need to leave the building at all
4) Stay in place, the evacuation only takes place at the 20th floor

Finally, Your age___, male/female

C.2 RESULTS

The results consisted of 51% (74) males and 49% (70) females with 64% (95) in the 18-30 year age bracket, and 36% (53) in the over 50 age bracket. The table below showed the information collected form the questionnaire.

Table 68: Questionnaire results

<table>
<thead>
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<th>Name</th>
<th>Age</th>
<th>Gender</th>
<th>Choice</th>
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<td>V</td>
<td>24</td>
<td>M</td>
<td>1</td>
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<td>2</td>
<td>J</td>
<td>25</td>
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<td>3</td>
<td>R</td>
<td>29</td>
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<td>3</td>
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It can be expected that there will be individual differences between the preferences of people to use one evacuation plan over another, and here we present an overview of the results. Of the entire sample population, 41% (60) tried to apply the relocation strategy, while 24% (35) chose a phased evacuation. 23% (34) considered to adopt simultaneous evacuation after the fire alarm. Only 13% (19) expected to stay in place in this specific scenario. In addition to that, one of them mentioned that she prefers to go upward to the roof since the building is quite high.
BIBLIOGRAPHY


(21) Siddens, S. (January, 2008). Rethinking high-rise egress, top to bottom


(31) Bukowski, R. W., Protected Elevators for Egress And Access During Fires In Tall Buildings. *NIST Building and Fire Research Laboratory*.


(36) Nystedt, F. & Rantatalo, T., Redefining fire safety in Swedish high-rise buildings,


(40) Dwyer, J. (May 26, 2002). Fighting to Live as the Towers Died. *New York Times*


(43) Isner, M. S. & Klem, T. J. (February 26, 1993). World Trade Center Explosion and Fire. *NFPA*


100] Lecture Note, R., CT5131 Fire Safety Design. Faculty of Civil Engineering and Geosciences, Delft University of Technology.
Regulations and Norms

- Approved Document for New Zealand Building Code Personal Hygiene Clause G1 (Second edition)
- Virginia Statewide Fire Prevention Code 2006
- Bouwbelsuit 2012
- Bouwbelsuit 2003
- NEN2580
- SBR brand veiligheid in hoge gebouwen praktijkrichtlijn 2005
- GB50045-95 Code for fire protection design of tall buildings 2005
- GB50016-06 Code of design on building fire protection and prevention 2006
- GB50352-05 Code for design of civil buildings 2005
- Singapore civil defence force fire emergency plan guidelines for commercial high rise building (above 30 storey) Annex D
- Singapore fire code 2007
- Swedish BFS 2011-26 2011
- Swedish Regelsamling för byggnande, BBR, 2012
- NFPA10I Life safety code 2012
- NFPA22O Standard on types of building construction 2012
- NFPA5000 Building construction and safety code 2012

Websites

- http://in2eastafrica.net/fire-ravages-42-storey-istanbul-skyscraper/
- http://macdyphotos.com/2011/05/04/taipei-101-%E8%87%BA%E5%8C%97101-at-night/
- http://www.escape-chute-systems.com/
- http://www.wisegeek.com/what-is-a-fire-compartment.htm
- http://www.escapechute.info/
- http://en.wikipedia.org/wiki/LVH_%26_Las_Vegas_Hotel_%26_Casino#Fire
- http://www.lrc.fema.gov/disasters_firesum_mgmgrand.html
- http://www.wisegeek.com/what-is-abseiling.htm
- http://www.realsafe.co.in/emergency-equipments.html
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