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ANALYZING ELEVATOR USE FOR NORMAL EVACUATION OF HIGH-RISE BUILDINGS: İŞ TOWER AND MERSİN METROPOL BUILDING CASES

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Muhsin Selçuk SATIR

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YÜKSEK BİNALARIN NORMAL TAHLİYESİNDE ASANSÖR KULLANIMININ ANALİZİ: İŞ KULE VE MERSİN METROPOL BİNASI ÖRNEKLERİ

(Yüksek Lisans Tezi)

Muhsin Selçuk SATIR

GAZİ ÜNİVERSİTESİ

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ÖZET

Normal tahliye ve acil durum tahliyesi, binaların tahliye analizlerinde kullanılan iki yöntem olarak karşımıza çıkmaktadır. Normal tahliye, acil durum tahliyesinin aksine, acil durum koşullarını ve binada oluşan panik ortamını çalışma dışı bırakarak binanın tahliye verimliliğine odaklanır. Acil durum tahliyesinde ise belirli bir acil durumda bina tahliyesinin nasıl gerçekleşeceği üzerinde çalışılır. Bu çalışmada yüksek binaların normal tahliyesi üzerine çalışılmıştır. Yüksek binaların tahliyesinde karşılaşılan en büyük sorun olan uzun tahliye sürelerinin kısaltılmasında asansörün etkisi araştırılmıştır. En efektif tahliye süresine ulaşmak için asansör/merdiven kullanımının hangi oranda olması gerektiği ve bunu etkileyen tasarım parametreleri araştırılmıştır. Bu bağlamda Türkiye'nin yakın tarihinde en yüksek binalarından olan İş Kule ve Mersin Metropol binaları üzerinde simülasyon çalışmaları yapılmıştır. Her iki binanın internet üzerinde halka açık yayınlanmış olan taranmış planları, yazar tarafından CAD ortamında tekrar çizilmiş ve Pathfinder^{TM} programında binaların modellenmesinde kullanılmıştır. Pathfinder^{TM}, bir tahliye analizi programı olup akademik literatürde binaların tahliye analizinde sıklıkla kullanılan bir programdır. Çalışma kapsamında, program üzerinde her iki bina için farklı oranda merdiven ve asansör kullanımları üzerine beş farklı senaryo modellenmiştir. İş Kule’nin tahliye süresinin, asansör ve merdivenin ortak kullanımıyla (senaryo 2-%25 asansör, %75 merdiven (27 dk.)), sadece merdiven kullanımına (senaryo 1-%100 merdiven (33 dk.)) göre yaklaşık %18 kısaldığı görülmüştür. Mersin Metropol Binasının tahliye süresi ise asansör ve merdivenin ortak kullanımıyla (senaryo 3-%50 asansör, %50 merdiven (29 dk.)), sadece merdiven kullanımına (senaryo 1-%100 merdiven (49 dk.)) göre yaklaşık %40 kısaldığı görülmüştür. Ayrıca İş Kule için, sadece merdiven kullanımı (senaryo 1 (33 dk.)), sadece asansör kullanımına (senaryo 5 (52 dk.)) göre daha hızlı tahliye sağlamıştır. Mersin Metropol Binasında ise sadece asansör kullanımı (senaryo 5 (39 dk.)), sadece merdiven kullanımından (senaryo 1 (49 dk.)) daha hızlı tahliye sağlamıştır. Mersin Metropol Binasında, asansör lobisinin merdiven lobisinden ayrı tasarlanmasının, asansörlerin daha etkin kullanılmasına olanak sağladığı görülmüştür. Bina merdivenlerine ulaşım sağlayan koridorların, merdivenlerin tahliye anındaki kapasitesine doğrudan etkisi olduğu gözlenmiştir. Çoğu yüksek bina, dikey bölümlere ayrılarak bu bölümlere ayrı asansörler ile ulaşım sağlanmaktadır. Bu bölümler planlanırken, bölümlerin kullanıcı yükünün ve asansörün gidiş-dönüş süresinin hesaba katılması gerektiği, aksi takdirde asansörlerin maksimum verimde çalışamayacağı gözlenmiştir. Ayrıca binada yüksek kullanıcı yüküne sahip mekanların binada mümkün olduğunca alt katlara yerleştirilmesinin de tahliyeyi kolaylaştırıcı etmenler arasında olduğu gözlenmiştir.

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(M. Sc. Thesis)

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ABSTRACT

Normal evacuation and emergency evacuation are the two methods used in the evacuation analysis of buildings. Normal evacuation focuses on the evacuation efficiency of the building by eliminating the emergency conditions and the panic atmosphere that occurs in the building. Emergency evacuation, on the other hand, studies how the building evacuation will take place in a certain emergency situation. In this study, the normal evacuation of high-rise buildings was studied. The effect of the elevator in shortening the long evacuation times, which is the biggest problem encountered in the evacuation of high-rise buildings, has been investigated. The fraction of elevators/stairs use for the most efficient evacuation and the related design parameters were investigated. In this context, simulation studies were carried out on İş Tower and Mersin Metropol Building, which are among the tallest buildings in Turkey's recent history. The scanned plans of both buildings, which were published publicly on the internet, were redrawn by the author in the CAD environment and used in the modeling of the buildings in the Pathfinder^{TM} program. Pathfinder is an evacuation analysis program that is frequently used in the academic literature for the evacuation analysis of buildings. Within the scope of the study, five different scenarios for both buildings were modeled on the use of stairs and elevators at different fractions. It has been observed that the evacuation time of İş Tower is shortened by approximately 18% with the combined use of elevators and stairs (scenario 2- 25% elevator, 75% stairs (27 min)) compared to using only stairs (scenario 1-100% stairs (33 min)). It has been observed that the evacuation time of Mersin Metropol Building is shortened by approximately 40% with the combined use of elevator and stairs (scenario 3-50% elevator, 50% stairs (29 min)) compared to using only stairs (scenario 1-100% stairs (49)). Also, for İş Tower, using only stairs (scenario 1 (33 min)) provided faster evacuation than using only elevators (scenario 5 (52 min)). In Mersin Metropol Building, using only the elevator (scenario 5 (39 min)) provided faster evacuation than using only stairs (scenario 1 (49 min)). It has been observed that the design of the elevator lobby separately from the stair corridor in Mersin Metropol Building allows the elevators to be used more effectively. Also, the corridors providing access to the building stairs have a direct effect on the capacity of the stairs during evacuation. Most high-rise buildings are divided into vertical sections and these sections are accessed by separate elevators. It has been observed that while planning these sections, occupant load of these sections and the round-trip time of the elevator should be considered, otherwise the elevators will not be able to operate at maximum efficiency. In addition, it has been observed that placing the floors with high occupant loads in on the lower parts of the building is among the factors that facilitate evacuation.

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LIST OF SYMBOLS AND ABBREVIATIONS

In this study symbols and abbreviations used is presented below with descriptions.

Abbreviations	**Explanations**
ASET	Available Safe Egress Time
IBC	International Building Code
NFPA	National Fire Protection Association
RSET	Required Safe Egress Time
RTT	Round Trip Time
SFPE	The Society of Fire Protection Engineers
TRFP	Turkey’s Regulation on Fire Protection
WTC	World Trade Center

1. INTRODUCTION

Thesis topic

Buildings need to be evacuated urgently in cases such as fire, flood, tsunami, earthquake, and terrorist attacks. Safe evacuation of building is related to the design of the building. Ensuring safe evacuation is possible by evacuating the building without dangerous and unbearable situations arise for building occupants. Normal evacuation and emergency evacuation are two methods used in the evacuation analysis of buildings. Normal evacuation focuses on the evacuation efficiency of the building by eliminating the emergency conditions and the panic atmosphere that occurs in the building. In emergency evacuation, on the other hand, it is studied how the building evacuation will take place in a certain emergency situation. The desired situation in both emergency evacuation and normal evacuation is that the building to be emptied in the most effective way. Therefore, it is imperative that the building to be evacuated as soon as possible. While rapid evacuation of the building may be possible for small buildings, it is more difficult for higher buildings with bigger occupant loads. The reasons why high-rise buildings are difficult to evacuate quickly can be listed as follows, increased distance to the exit in parallel with the increase in the height of the building, big occupant loads, people getting tired when descending from higher floors, and increased merging effect.

Focus and scope

The main focus of this thesis is the use of elevators in normal evacuation of high-rise buildings. In this context, an analysis has been made on the İş Tower and Mersin Metropol Building, which were the tallest buildings in Turkey in the recent past. The effects of the difficulties encountered in the evacuation of high-rise buildings and the use of elevators for evacuation, which has become widespread with both regulations and practices in recent years, have been investigated. The reason why İş Tower and Mersin Metropol Buildings were chosen within the scope of the thesis is that both buildings have similar number of elevators and have approximately the same number of floors and height. In addition, the fact that these buildings were the tallest buildings in Turkey in recent past is another factor.

Research problem and research questions

After the stairs, the first element that comes to mind to decrease the evacuation time of high-rise buildings is the elevator. However, the use of elevators for evacuation purposes was not recommended or even prohibited by the authorities because it is not considered safe. Nonetheless, this stereotypical thought gradually loses its effect with the developing technology. Nowadays, elevators can be equipped with measures such as air tightness and uninterrupted power supply. Also, building regulations all around the world have begun to recognize elevators for evacuation purposes. In this context, research has been started with the following research questions on the evacuation of high-rise buildings by elevators.

- RQ 1: In which fraction of pre assumed quartiles of the building occupants should use elevators, to achieve the most effective evacuation?
- RQ 2: What is the effect of using elevators in evacuation of high-rise buildings on evacuation time?
- RQ 3: Which design factors should be considered for the most effective use of elevators and stairs during evacuation of high-rise buildings?

Objectives

Within the scope of this thesis, it is aimed to measure the possible shortening of the evacuation time with the use of the elevator during evacuation of high-rise buildings. Simulation used as a research method and carried out with Pathfinder™ program. This program is widely used in evacuation studies in the academic literature. It has been investigated at what fraction the building occupants should use the elevators and stairs to reach the most effective evacuation.

Anticipated outcomes of the research

Within the scope of the thesis, the 2 selected high-rise buildings are modeled in the Pathfinder program. In order to observe the effect of the elevator in the evacuation of buildings, 5 different scenarios were modeled. In the 5 scenarios, the use of elevators and stairs in different fractions (with 25% increments) by building occupants was modeled. It is assumed that the evacuation time obtained by using only stairs in the building can be shortened by the combined use of elevator and stairs. The aim of the thesis is to find this ratio and determine the design factors that affect this ratio.

2. LITERATURE REVIEW

In the following five subsections, the literature within the scope of the thesis is given. Definition of high-rise buildings in section 2.1, building evacuation in section 2.2, approaches to evacuation calculations in section 2.3, evacuation problems of high-rise buildings in section 2.4, and research on evacuation by elevator in section 2.5 are presented.

2.1. Definition and Development of High-rise Buildings and Elevators

In the rise of buildings from past to present, social, cultural, technological, and economic factors can be mentioned. The need for space, which increased with the acceleration of urbanization in the 20th century, directed people to vertical architecture. The emergence of different building types and the need for housing after the World War I and II were also other factors that accelerated the vertical rise of the buildings. Advances in building materials and the efficient use of steel have made it possible to push the limits.[1]

2.1.1. Development of high-rise buildings

The history of high-rise buildings with masonry walls goes back to the ancient Roman period [1]. These buildings were up to 10 floors and the wall thickness decreased from the ground floor to the last floor. In this period, arches, domes, and vaults used for large spans. The floors have been made of reinforced concrete since the second half of the 19th century. Monadnock Building (1891-Chicago (Figure 2.1)), was one of the most iconic masonry multi-story building of 19th century with 1.8 m thick walls on the ground floor [1] and 46 cm at the top [2]. %15 of the building’s floor gross area was occupied by the load bearing walls [3]. This also made the building to be very heavy. The building sank more than 50 cm in time [4]. Some of other high-rise buildings erected in the 19th century was Reliance Building (Chicago-1894 (Figure 2.1)) [5], Guaranty Building (1904-Buffalo (Figure 2.1)) [6], Carson Pirie Scott Department Store (1904-Chicago) [3].

Figure 2.1. Monadnock Building [2], Reliance Building [5] and Guaranty Building [6]

In 19th century, evolution of steel took part in rise of buildings and other structures like bridges. This evolution took more than 100 years and the race to rise for buildings is still going on. Crystal Palace (1851-Londra) was the first unique steel framed building [1]. This building also considered as the first prefabricated steel building [1]. First implementations of steel frame were with the use of load bearing walls on the façade but in time, lighter steel buildings were built without load bearing walls. Another factor accelerated the rise of the buildings and remove limitations of the height was the invention of safe elevator. Elevators made available to easily use higher floors and this way, the rent of higher floors increased while the rent of lower floors decreasing [7].

The first skyscraper of the world according to Council on Tall Buildings & Urban Habitat is Home Insurance Building (1885-Chicago (Figure 2.2)) [8,9]. This building was constructed with masonry façade with steel beams inside of the building [1]. The first steel framed building with no load bearing wall was II. Leiter Building (1889-Chicago (Figure 2.2)) [1,10].

Concrete entered the building sector with the invention of Portland cement [1] by Joseph Aspdin in 1824 [11]. Joseph Monier, a French gardener used iron to reinforce concrete [12]. Rue Franklin Apartment (1903-Paris) is considered as the first reinforced concrete framed building [1]. Same year, Ingalls Building was built in America as the first reinforced concrete high-rise building with 16 story and 64 m height [1].

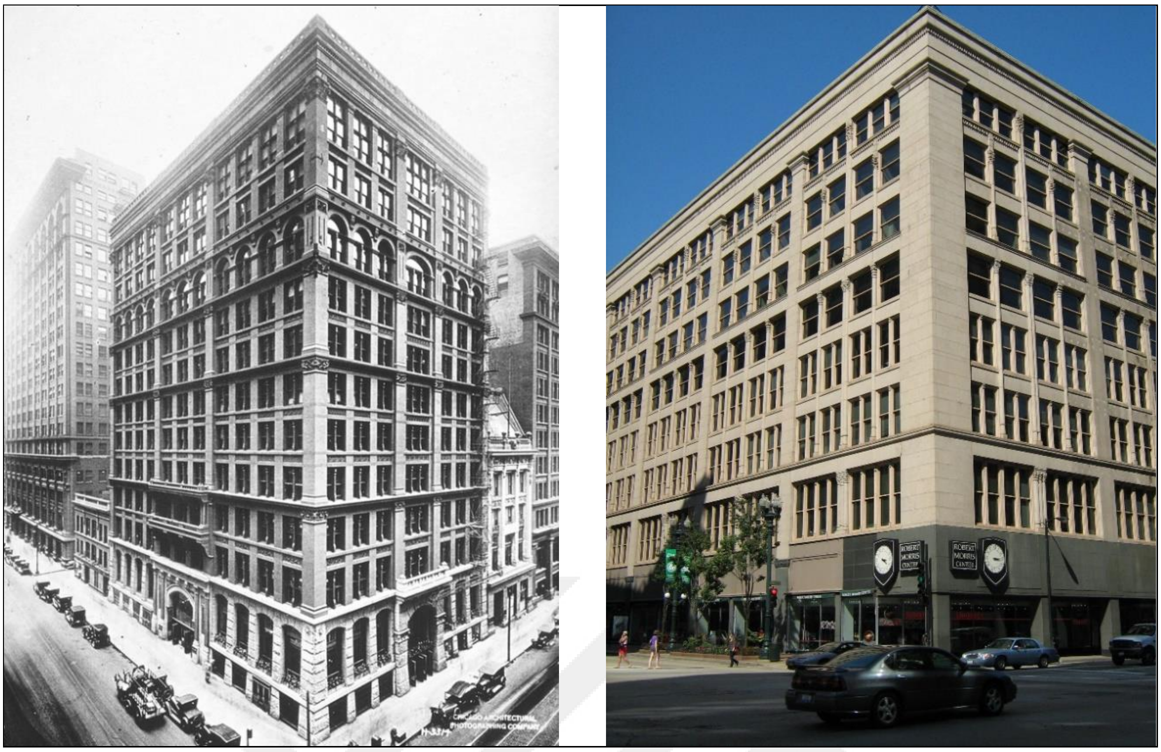

Figure 2.2. Home Insurance Building [9] and II. Leiter Building [10]

Consequently, 19th century was the first step to industrialization and technological improvements for high-rise buildings. At the end of the century, invention of safe elevator, air conditioning systems and fire protection systems made available to build higher and safer buildings [13].

High-rise office buildings came to the fore in this period with invention of elevators and improvements on fire protection [1]. Woolworth Building (1913-New York) [14], Chrysler Building (1930-New York) [15] and Empire State Building (1931-New York) [16] are some high-rise buildings that was built in this period. High-rise buildings continued to rise at an increasing rate [1].

Office buildings and residential buildings dominated the building market especially after the World War II [1]. In this period, thanks to the developments in reinforced concrete, it became possible to construct 20-storey houses with the wall thickness used in a 2-storey masonry building [1]. Highpoint I, one of the most striking residential buildings of this period, is seen by many architects and critics as the most successful residential building of its period [17]. Also in this period, the need to build multi-story buildings fast, has accelerated the construction of prefabricated and cast-in-place buildings [1].

Figure 2.3. Woolworth Building [14], Chrysler Building [15] and Empire State Building [16]

The development of high-rise buildings continued with the demand for open office spaces, large space requirements and the advantages of reinforced concrete and steel. Lake Shore Drive Apartments (1952-Chicago), which are considered the first examples of modern framed buildings, are one of the office buildings in this period [18].

After the World War II, construction techniques were developed with the investigation of the characteristics of reinforced concrete [1]. The 65-storey Marina City Towers (1968-Chicago), which emerged as a result of the effort to create 24-hour living spaces, are mixed-use structures that reflect the monolithic structure of concrete [19]. Bertrand Goldberg had the opportunity to emphasize the concept of "city within the city" even more with River City (1986-Chicago).

World Trade Center (1973-New York (Figure 2.4)) has taken the throne of the Empire State Building, the tallest building in the world since 1931 [20]. However, it’s reign did not last long and within a year, Sears Tower (Figure 2.4) took the title [20].

Figure 2.4. World Trade Center [20] and Sears Tower [21]

Figure 2.5 shows the tallest 10 buildings in the world by “Height to Architectural Top” which is the most widely accepted ranking [22]. Some other rankings are “Height to Highest Occupied Floor” and “Height to Tip”. Currently Burj Khalifa is the tallest in all 3 lists. Today, although the race of high-rise buildings is interrupted by the economic effects of the COVID-19 pandemic, there are many tall buildings that are under construction [23] and are in the design phase [24].

The biggest difference of high-rise buildings from low-rise buildings is increasing lateral forces (wind and earthquake forces) as the structure rises. These forces require differentiation in structural system as the building rises. This requirement has led engineers to develop structural systems in order to build higher buildings.[1] Structural systems that ensure the stability of structures have evolved from the traditional masonry system to frame systems with the effective use of reinforced concrete [1]. Rigid frames system that consist of beams and columns is the simplest approach to design a tall building [25]. In order to increase the resistance of the building to lateral forces, braced frame system is created with the diagonals added to the building structure [1]. Shear walls have been used to reduce the shear forces that occur as the building rises [25]. Tubular systems have emerged with the placement of the columns outside the building as a result of the need for wide openings in the building and the delicate integration with the facade. Mentioned systems are illustrated below.

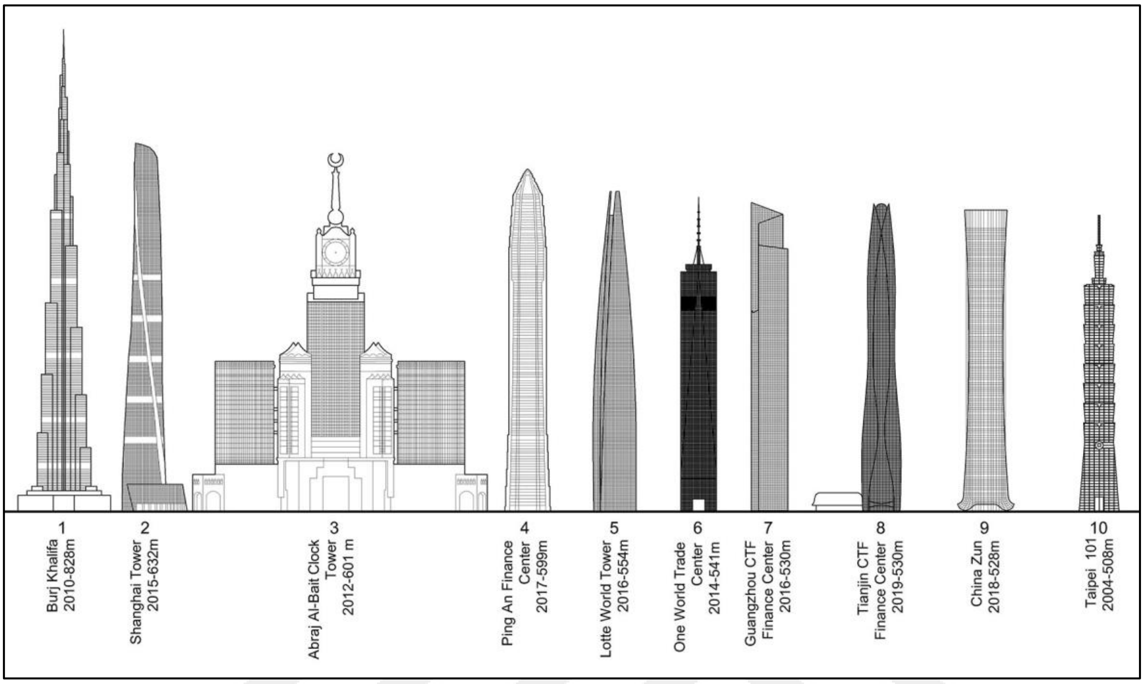

Figure 2.5. Highest 10 building in the world according to CTBUH [22] height to architectural top criteria (graphic is prepared by the author)

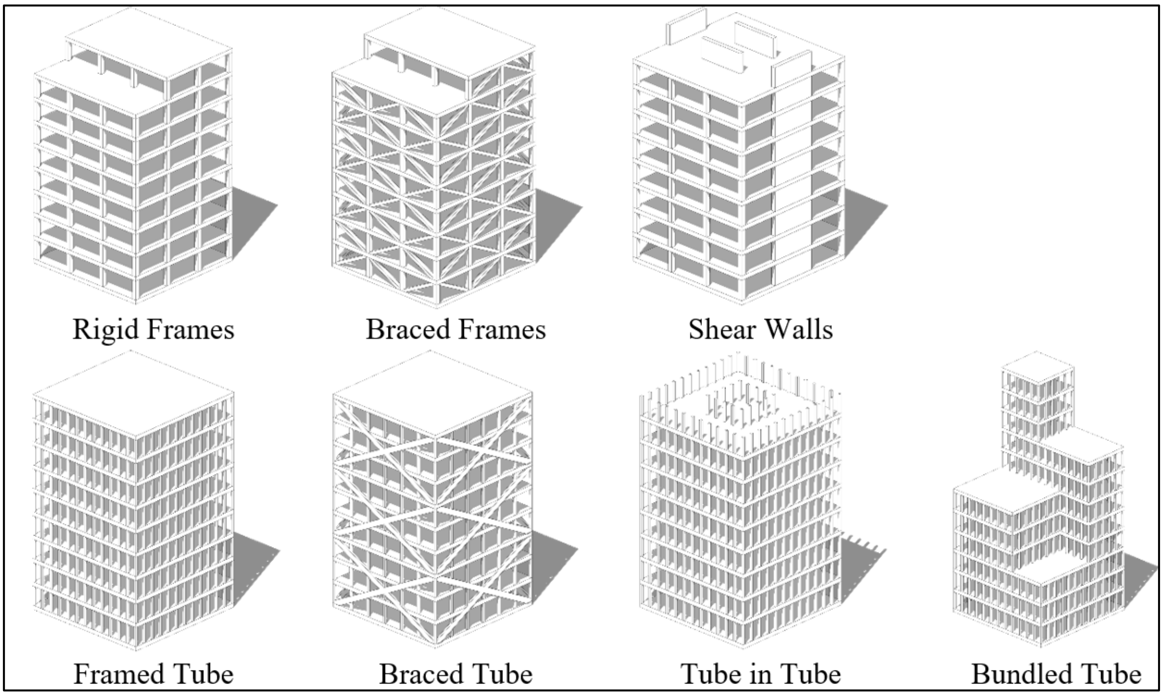

Figure 2.6. Structural systems of high-rise buildings (graphic is prepared by the author)

2.1.2. Definition of high-rise buildings in codes and regulations

Any building that is likely to be affected by lateral forces such as earthquake or wind can be defined as a high-rise building [26]. But the definition of high-rise building varies between codes in different countries. NFPA 101 – Life Safety Code is one of the most widely accepted one in terms of evacuation and fire. It defines high-rise as buildings with an occupiable floor higher than 23 m (75 ft) [27]. International Building Code describes high-rise as buildings with an occupied floor 23 m (75 ft) higher than the lowest fire vehicle access [28].

Except these two widely accepted codes, some countries have their own standards like China which contains %87 of skyscrapers globally [29]. According to fire code in China, residential buildings higher than 27 m and other buildings higher than 24 m considered high-rise [30]. In Australia, buildings exceeding an effective height of 25 m and in India all buildings higher than 15 m are considered as high-rise buildings [31,32]. Hong Kong uses a similar standard. Buildings exceed 30 m are stated as high-rise and others under 30 m as low-rise buildings [33]. Zoning Regulation in Turkey describes 2 types of buildings; buildings higher than 21.5 m are high-rise and ones higher than 51.5 m are ultra-high-rise buildings [34].

Netherland differs from other countries in terms of its high-rise definition. Building code in Netherland (Bouwbesluit) define high-rise as buildings higher than 70 m [35]. Japan has a more specified classification of buildings. As can be seen in Table 2.1, all buildings divided into 4 groups based on their heights: small buildings, medium sized buildings, large sized buildings, and high-rise buildings (above 60 m). While first three of them are subject of a similar approach (statically), high-rise buildings require special study according to the code [36]. Singapore prefers a definition for super high-rise buildings and buildings above 40 story is considered super-high-rise [37].

As indicated above, there is not a consensus on the definition of high-rise buildings. Emporis aimed to create global standards with the goal to ease exchange of information. They defined low-rise, as buildings under 35 m. According to Emporis, 35-100 m buildings are high-rise and buildings above 100 m are skyscrapers [38]. Information given above summarized in Table 2.1. As can be seen, the general approach to define high-rise is by number of floors or building height according to the maximum height capacity of a standard fire fighting vehicle [26].

Table 2.1. Definition of high-rise buildings in codes, regulations, and standards

Code, Regulation, Standard	Low-rise	High-rise	Ultra-High-rise	Description
NFPA 101 (2018) [27]		23 m (75 ft)		Section 3.3.37.7
IBC (2018) [28]		23 m (75 ft)		Section 403
China National Standard of the People's Republic of China-Code for Fire Protection Design of Buildings (2014) [29]		27 m (residential) 24 m (other)		Section 2.1.1
Hong Kong Codes of Practice for Minimum Fire Service Installations and Equipment and Inspection, Testing and Maintenance of Installations and Equipment (2012) [33]	<30 m	>30 m		Part 3
Holland Bouwbesluit (2003) [35]		70 m		Part 3
Singapore Fire Code (2013) [37]			40 story (Super High-rise)	
Australia Automatic fire sprinkler systems (2018) [31]		25 m		AS 2118.1
Emporis Standards [38]	<35 m	35-100 m	>100 m (Skyscraper)	
India National Building Code of India (2016) [32]		15 m		Volume 1 Section 2.38
Turkey Zoning Regulation (2017) [34]		21.5 < 51.5 m	>51.5 m	First Section: aaaaa
Japan The Building Standard Law Enforcement Order [36]	1-2 floors small buildings <3 floors (wooden) 13 m (masonry) <2 floors (other buildings) medium sized buildings 13 m (wooden) ≥4 floors (steel) 20 m (reinforced concrete or steel reinforced concrete) large sized buildings	60 m		
Council on Tall Buildings and Urban Habitat [22]		<14 story 50-300 m (Tall Building)	300-600 m (Supertall) <600 m (Mega tall)	

Table 2.2. High-rise definition criteria in Earthquake Regulation of Turkey[40]

Bina Yükseklik Sınıfı	Bina Yükseklik Sınıfları ve Deprem Tasarım Sınıflarına Göre Tanımlanan Bina Yükseklik Aralıkları [m]		
	DTS = 1, 1a, 2, 2a	DTS = 3, 3a	DTS = 4, 4a
BYS = 1	$H_N > 70$	$H_N > 91$	$H_N > 105$
BYS = 2	$56 < H_N \leq 70$	$70 < H_N \leq 91$	$91 < H_N \leq 105$
BYS = 3	$42 < H_N \leq 56$	$56 < H_N \leq 70$	$56 < H_N \leq 91$
BYS = 4	$28 < H_N \leq 42$	$42 < H_N \leq 56$	
BYS = 5	$17.5 < H_N \leq 28$	$28 < H_N \leq 42$	
BYS = 6	$10.5 < H_N \leq 17.5$	$17.5 < H_N \leq 28$	
BYS = 7	$7 < H_N \leq 10.5$	$10.5 < H_N \leq 17.5$	
BYS = 8	$H_N \leq 7$	$H_N \leq 10.5$	

According to the regulations and standards of different countries, the high-rise building definitions are given above. It is expected that these definitions differ between countries. However, in some cases, more than one high-rise building definition can be seen within the country. An example of this is seen in Turkey. The definition of high-rise building is seen in the zoning regulation [34], fire regulation [39] and earthquake regulation [40]. While there are definitions of high-rise and ultra-high-rise buildings in the zoning regulation, only high-rise buildings are defined in the fire regulation. In addition, the definition of high-rise buildings in the earthquake regulation (given in Table 2.2) is different from zoning and fire regulations (21.5 m is the limit). Having more than one definition of high-rise buildings cause confusion.

2.1.3. Development of elevators

Elevators (“Lifts” in British English [41]) have become an inevitable part of buildings, especially for high-rise buildings. Although various simple types of elevators have been used since ancient times, safe elevators widely used today developed in 1854. Elisha Graves Otis promoted his invention of safe elevators at the Exhibition of the Industry of All Nations in New York City [42]. In 1857, the first passenger elevator was installed in a building by Otis. Steam powered passenger or freight elevators were already in use, but the innovation Otis brought was the safety. The invention of him made available the lift car to stop in the event if the rope broke [42]. In 1860’s elevators with different speeds were started to be established in Europe and in 1870 Equitable Life Building was the first multistory office building with an elevator [42].

In 1880, the first electric elevator was built by a German electrical engineer Werner von Siemens and Schuyler Wheeler's electric elevator design was patented in 1883 [43]. In 1867 Paris World Fair, hydraulic elevator was presented, and this system has widely accepted in Europe rather than Otis's model [42]. But until 1890's the use of elevators in Europe was very limited but US on the other hand, it was prevalent to make elevator shafts in the core of the buildings [42]. In the 20th century, most of the elevators were controlled by a staff called "elevator operators". A few weeks after World War 2, over 15.000 operators went on strike in New York for better working conditions. The effect of the strike on the economy was untenable and government settled the strike [44].

Elevators made high-rise buildings viable and usable [45]. In time, elevator traffic engineering has emerged. They design and calculate occupant load and passenger flow traffic of high-rise buildings that require complex calculations [45]. They are responsible for designing a traffic system that is capable of transporting passengers in minimum time with minimum cost. In addition, the building core should be used in a minimum way in order not to reduce the net area that can be used in the building. User requirements and designed system has its own parameters and there should be a balance between them. The design tool mentioned here could be calculation or simulation [45].

Some of the components of an elevator system can be listed as; elevator shaft, the counterweights, the landing doors, ancillary equipment and lobby space [45]. Elevator shaft is the vertical space that elevator cars move in through the core of the building. Counterweights balance the lift car's weight and ease the movement. Lobby space is needed in every floor that the elevator goes to for occupants to wait elevator cars [45]. This area is a loss for tenant because it decreases net usable area.

2.1.4. Classification of elevators

Elevators are divided into different classes according to their operating principles. This distinction in classification is also seen in the design of elevators and the equipment used. Elevators are divided into 3 classes according to the general classification used by designers and manufacturers [46]. These are electric lifts, hydraulic lifts, and pneumatic lifts.

Hydraulic elevators

The type of elevator to be used in the building should be selected according to the purpose of use. Oils are generally used in hydraulic systems. Elevators with hydraulic systems are generally suitable for heavy work. Because they can generate a significant amount of force. Also, they can work silently, and this may be an appropriate solution for some buildings where silence is desired [47]. However, the initial investment costs of hydraulic systems can be high. Contamination may occur as there may be oil leakage from pistons, therefore, they need regular maintenance.

Pneumatic elevators

Pneumatic elevators operate on the principle of compressing air at atmospheric pressure with the help of mechanical systems. However, this system cannot produce as much force as in the hydraulic system. They cannot compete with hydraulic systems in terms of providing long service life. These systems allow elevators that can move quickly. This system can be used where speed is more important than power. In addition, pneumatic systems are more economical than the other two elevator systems. There may be problems in working in very hot and very cold weather. Therefore, the temperature of the area to be used becomes important. [48]

Electric elevators

Although it cannot compete with pneumatic elevators, it can be said that electric elevators can move fast. One of the best special features about these elevators is their precision. Also, they work with only electricity, so they are clean and there is no leakage risk. These elevators cannot generate high forces and may not be suitable for places where heavy work is required. Cost/power ratio is higher than other elevators. [48]

2.1.5. Parameters of elevators

Elevators should be designed in such a way that the projected occupant load of the building can be brought to the desired floor of the building in a reasonable time. In order to achieve this, there are some parameters that should be considered during the design phase.

Distribution floor (or terminal) is the main gathering floor of the elevator. For most buildings, the ground floor is the distribution floor. In most simulations and calculations, it is assumed that the elevator is initially at the distribution floor (ground floor). The pickup floor is the floor where the elevator receives people in the building. Every elevator has at least one pickup floor. People on the pickup floors are transported to the distribution floor and leave the building. The person capacity of the lift is determined according to the nominal load carrying capacity of the lift. In addition, the elevator cabin should be designed wide enough to meet this load.

Maximum speed is the highest value the speed of the elevator gets. It is expressed in meters/second (m/s). Acceleration is defined as the change in elevator speed per second. It is expressed in meters per square second (m/s^2). Another parameter used in elevator design is jerk. It is defined as the change of elevator acceleration per second. It is expressed in meters/cubic second (m/s^3). Elevators generally work with top/down priority. This means that when the elevator is on the ground floor, it lists the calls it receives from top to bottom and stops in this order. It serves by gathering people from the top call to the bottom call. Open/close times are the time to open the door of the elevator when it reaches a floor and the time to close the door before leaving that floor. Elevators with an advanced opening system enable the elevator door to be opened before reaching the floor in order to prevent loss of time. [43]

Round trip time (RTT) is the time that take an elevator that is on the ground floor moving upper floors and returning to the same floor after leaving the person at the desired floor [45]. RTT is desired to be as short as possible in order to ensure optimum traffic control in the building. To achieve this, the speed or acceleration of the elevator can be increased. In addition, increasing the number of elevators and dividing the building floors into certain zones are among the options.

People generally do not want to wait for the elevator more than 30 seconds in office buildings and 90 seconds in residential buildings [45]. Therefore, different traffic planning algorithms can be used according to up peak and down peak times. RTT is expected to be less than 2-3 minutes. Elements of Round Trip Time is shown in Figure 2.7.

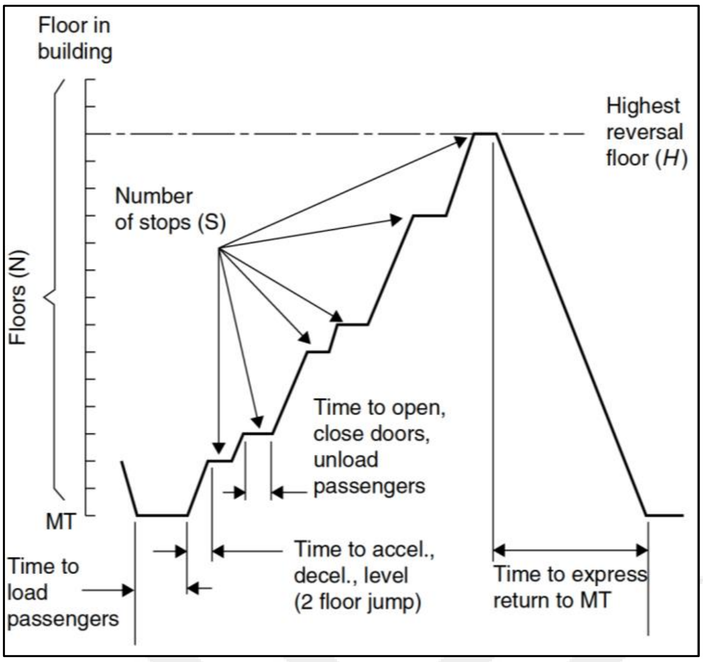

Figure 2.7. The elements of round trip time [45]

The human body feels discomfort in movements above a certain acceleration due to the movement of internal organs. Although this acceleration is not a definite value, the elevators used in daily life remain within this value. People cannot understand the speed of the elevator while in the car, but the acceleration is decisive in terms of comfort. Elevators that can move faster than 15 m/s were built [43]. However, more than 1.5 m/s² acceleration is generally not allowed [45].

The movement speed of the elevator will undoubtedly reduce the round trip time [49]. But by increasing the speed from 10 m/s to 20 m/s, only a few seconds will be gained. In this case, the speed of movement, which significantly increases the cost of the elevator, must find an optimum balance. Figure 2.8 shows a recommendation of optimum elevator speeds.

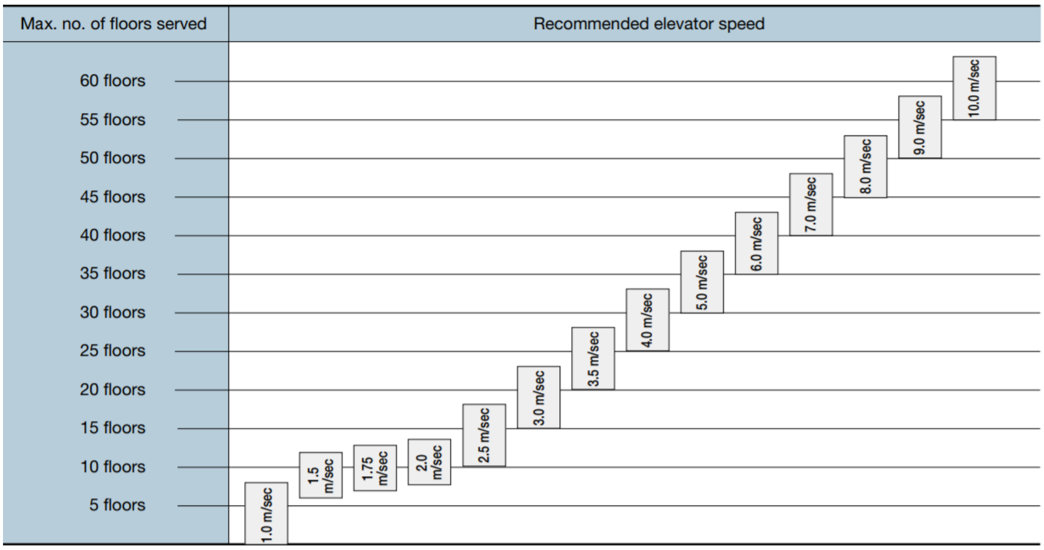

Figure 2.8. Recommended elevator speeds [50]

2.1.6. Capacity calculations of elevators

The buffer zone of a person should be considered in the cabin capacity calculation. The size of the buffer zone is smaller in Asia / Pacific countries than European people [45]. While 0.4 person/m² is a desirable density, 1 person/m² is comfortable, 2 person/m² is dense, 3 person/m² is crowding and 4 person/m² is considered crowded for waiting areas [45,51].

Stairs permit higher densities than flat surfaces but walking speed is lower on stairs [51]. For example, while an average person needs 2.3 m² when walking on a flat surface, on a stair 0.7 m² is enough [51]. On a stair, it can be said that the speed is halved compared to that on a flat surface, however, the speed on the stairs varies depending on the density of the stair, the walking speed of the slowest walking person, and the inclination of the stairs [51]. Stairway handling capacity is about 83% of corridor capacity [51].

Elevator design calculations differ between countries, codes, and standards. The designers need to consider the specification of that country while designing the building. Building type is another factor in the way of designing elevator traffic. Office buildings has maximum traffic load in the morning before working hours [46]. As the number of tenants in the office building increases, it is expected that this heavy traffic in the morning hours will spread over a longer period of time [46]. Traffic density can also be seen between meals and after work. A rule of thumb that can be used for office buildings is given below.

- 1 elevator for 3 floors is good,
- 1 elevator for 4 floors is fair and
- 1 elevator for 5 floors considered poor design [46].

Hotel buildings need separate elevators for staff and customers. Elevator design considerations for residential buildings are highly similar with hotels [46].

There are 3 main traffic types in the building: incoming traffic, outgoing traffic and inter floor traffic. General rule of thumb is to split them into %45-%45-%10 or %40-%40-%20 respectively [45]. After that assumption, up peak and down peak traffic should be calculated. Up peak traffic is when incoming passengers is the dominant traffic and down peak traffic occurs when outgoing passengers is the dominant traffic [45]. Traffic survey may be conducted when necessary and results may be a good simulation input [45]. Figure 2.9 shows a representative office building traffic.

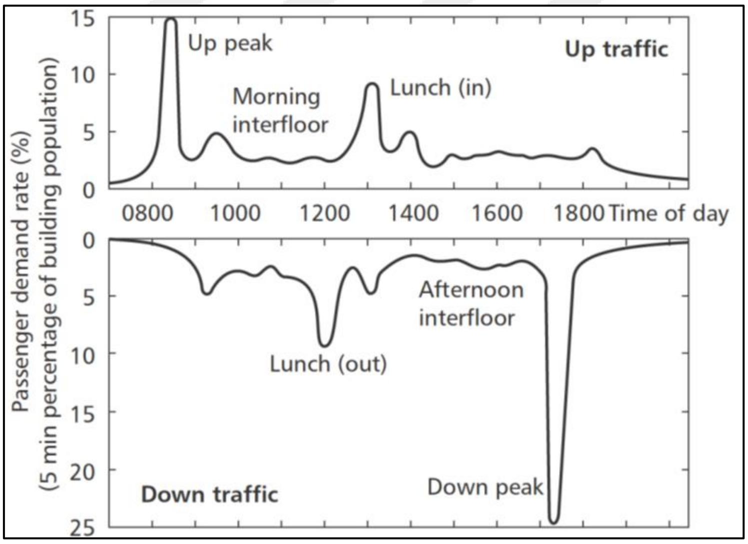

Figure 2.9. Traffic load of an office building [51]

As the number of floors to ascend or descend increases, the rate of using elevators increases. This situation is shown in Table 2.3. In addition, the number of floors on which people will ascend or descend and the ratio of elevators/escalators used also vary. As the number of floors up/down increases, the use of escalators decreases. This situation is shown in Table 2.4.

Table 2.3. Stair usage rates [45]

Floors travelled	*Usage up*	*Usage down*
1	80%	90%
2	50%	80%
3	20%	50%
4	10%	20%
5	5%	5%
6	0%	0%

Table 2.4. Lift and escalator usage rates [45]

Floors travelled	*Escalator*	*Lift*
1	90%	10%
2	75%	25%
3	50%	50%
4	25%	75%
5	10%	90%

2.2. Building Evacuation

Some emergencies in the built environment require buildings to be evacuated. Effective evacuation of buildings can be achieved by closely monitoring the academic literature in this regard and applying the design principles to the buildings. Human behavior in building evacuation, design factors to be considered for effective evacuation, approaches to evacuation calculations, evacuation problems of high rise buildings, and elevator use in evacuation of high buildings are given in detail in the following subsections.

2.2.1. Human behavior in evacuation

Understanding the human behavior has a crucial role in providing an effective evacuation [52]. Although there are a lot of researches on human behavior during emergencies, there are still blind spots and misinformation (e.g., contrary to popular belief, the researches showed that the human behavior during an emergency is not dominantly consist of panic [53].)

Human behavior comes after the decision making. The decision-making during an accident happens by two ways; automatic system and reflective system. While automatic system provide fast decisions like taking the daily commute, reflective system provide slow but

controlled decisions [53]. Some factors affecting human decision-making during emergency situations are given below.
During emergency situations, occupants' decisions affected by risk perception. Risk perception is directly proportional to willingness to act [54]. The more threatened one feels, the more willing he/she is to act. On the contrary, "normalcy bias" lead occupants to underestimate the threat and generally makes it longer to start the evacuation [53].

Data extracted from evacuations indicate that occupants firstly tend to investigate the alarm if it is false or not. After understanding there is something unusual, people generally contact with family or close friends and before beginning to evacuate, they take personal belongings. These behaviors generally make it longer to evacuate and have an important effect on evacuation time. [55]

While evacuating the building, human factor affects evacuation time. Researches showed that the leading person determines or limits the walking speed of occupants behind that person. This situation is called platoon effect. Platoon effect is the slowing effect composed by a person with slower velocity than occupants behind that person [56].

When drills and evacuations are analyzed, it is observed that occupants generally tend to evacuate the building via stair that they last used or most used [26]. This situation occurs especially on occupants who are not familiar to the building. 51% of the evacuees of WTC attack indicated they never used stairs of the building before [57]. This means that these people did not know where the stairs are. Researches show that the past experiences important to motivate occupants to move [58], the importance of drills and education can be seen.

Lastly the panic behavior has a negative effect on evacuation. An experiment conducted to investigate the phenomena called "faster is slower" [59]. This experiment conducted with mice shows the effect of panic during evacuation. It is observed that when occupants are panicked and frazzled, evacuation time extends.

2.2.2. Design considerations of building evacuation

Planning safe buildings in terms of evacuation, require some considerations. Defining occupant load and exit capacity at the design stage of the buildings, make it easier to plan emergency evacuation strategy for the building. Mentioned design considerations avert difficulties after the building is constructed.

Occupant load calculation for building evacuation

Occupant load is defined by NFPA as the total number of occupants that may be in the building at any given time [27]. Defining occupant load makes it easier to lead occupants to safe areas with correct strategy. Occupant load factor is given in NFPA 101 (Table 7.3.1.2) [27] and in International Building Code (IBC) (Table 1004.5) to indicate the occupant load for different occupancies [28]. Turkey’s Regulation on Fire Protection defines occupant load factors in Appendix 5/A [39].

Exit capacity calculation for building evacuation

Number of people that can pass through a given opening in 1 minute is defined as exit capacity. Turkey’s Regulation on Fire Protection defines exit capacity as number of people that can pass in 50 cm. in 1 minute and indicate exit capacities for different occupancies in Appendix 5/B [39]. In NFPA 101, capacity factors are given in Table 7.3.3.1 [27]. International Building Code shows exit capacities in section 1005 [28]. Exit capacity can be seen as an indicator that the time required for occupants to evacuate the building and it may be helpful to design exit widths of the building.

Stair use for building evacuation and merging effect

In accordance with the approach “In case of fire, use only stairs”, some integrated strategies have been proposed and the general approach to this topic is evolving to the idea of integrated strategies are more effective [60].

Stairs are generally considered most common egress component during emergencies. But evacuation by stairs is different than flat areas [61]. Although buildings with low number of floors are easier to descent to reach exits, it may be tiring to evacuate high-rise buildings via stairs. This is called fatigue effect and it can be said that fatigue effect needs to be researched deeper [62].

Designers must consider occupant load during design stage of the building to avoid congestion. Number of stairs, stair widths, location of stairs must be decided in accordance with occupant load. Locating floor exits on the opposite side of the incoming stair reduces the merging effect which will improve the evacuation efficiency [63].

Merging effect is observed on stairs where floor exits are connected as can be seen in Figure 2.10. Occupants of current floor who enter stairwell and occupants in stairwell who come from upper floors merge at stair door. According to researches, occupants coming from upstairs generally do not want to let occupants from current floor to get in the stair [57]. Generally, 3 different merging behavior are indicated on high-rise buildings. These are occupants coming from upper floors may override occupants entering the stair, occupants entering the stair may override occupants coming from upper floors and finally neither of them may override and they split evenly [64]. Merging effect is observed more on floors that have more occupants and local speed is higher after these floors [56]. Because of the stagnancy at floor exit, there is more room to move which lead occupants to move faster for a while. Researches show that floors should be linked to stairs on the opposite side of the incoming stairs to lighten the merging effect [63]. According to experimental studies, merge ratio should be 50: 50 for the most effective evacuation [65].

Figure 2.10. Merging effect on stairs (graphic is prepared by the author)

Elevator use for building evacuation

The idea of making elevators available to use during evacuation comes from early 1980's [57]. Advantages of the use of elevators during evacuation process can be listed as; moving faster than smoke, ease of evacuation for old, sick, disabled and the habit of using elevator during normal life [29]. Researches on effective use of elevator for evacuation purpose show that it is more effective to evacuate higher floors than lower floors [66,67]. According to Proulx, the use of elevators during evacuation must be allowed [55]. There are a lot of successful evacuations by elevators [68]. In World Trade Center 2 (South Tower), the use of elevators during evacuation after WTC 1 was hit, made it available to survive thousands of people [69]. One of the emergencies that successfully evacuated with the use of elevators is the Hiroshima Motomachi High Apartment Fire in Japan [70]. Another example given is that in a fire in an apartment in Ontario, Canada, 74% of people were able to reach the ground floor using elevator [71].

Refuge floors for building evacuation

Refuge floors defined as floors that are isolated from the effects of smoke and fire with at least 2 rooms separated by smokeproof components [27]. The occupants (especially sick, old, and disabled) are expected to go to refuge floors and wait to be rescued. After 9/11 incident, the idea of waiting to be rescued in refuge floors has changed [72] because the building (WTC2) was collapsed less than one hour which was not enough to rescue occupants may be in the refuge floors. But there is a wide consensus for disabled, sick ,pregnant and old occupants should use refuge floors to be safely rescued [73]. Some countries obligated the refuge floor for high-rise buildings. For example, according to Chinese Building Regulation, buildings higher than 100 m. must have refuge floor [66] and every refuge floor should service 15 floors max. [73]. According to Persian Gulf Cooperation Council, at least a refuge floor is required in every 20 floors [73]. India has required a refuge floor every 4-5 floors or every 15 meters. Korea required one refuge floor for every 30 floors, and stated that these floors could be shared with mechanical floors [73]. There is no legal obligation on refuge floors in Turkey.

2.3. Approaches to Evacuation Calculations

Although there are some back-of-the-envelope (hand) calculations to assess evacuation, performance-based approach is becoming more widespread [74]. For example, SBR Regulation in Netherland requires occupants to reach safe areas 1 minute after alarm and for clearance time, it adds 90 seconds for every segment higher than 50 meters [60]. These calculations used to clarify the egress time for buildings generally. However, calculation of egress times with performance-based calculations, allow safer solutions for different buildings.

2.3.1. Evacuation timeline

Certain emergency situations that people experience lead researchers to study on effective evacuation of the buildings. Experiences on this field show that evacuation timeline is related to egress strategies and human behavior. Evacuation timeline is an important part of the subject of evacuation of buildings. Numerous drills and accidents lead researchers to classify different components of evacuation process. Although different researchers [65,75–82] investigated the timeline of evacuation process with different levels of detail, general approach to this subject is to divide evacuation process into pre-evacuation time and evacuation time [83].

Pre-evacuation time defines the time interval between the alarm and the first movement to evacuate the building [76,79]. Pre-evacuation time can be very effective on evacuation timeline. Because especially for low density buildings pre-evacuation time may take longer than evacuation (movement) time, [76,79]. This is because for this type of buildings, it may be harder for occupants to communicate with other occupants who do not aware of the emergency. Two components of pre-evacuation time are recognition time and response time [80]. The time from the sounding of the alarm until the emergency is diagnosed is called recognition time. The time from the decision to evacuate until the movement is started as response time [80]. Pre-movement time is related to human behavior, therefore it is the most unpredictable phase of the evacuation process [79]. Since pre-evacuation time is hard to calculate, some researchers [79] built a database consist of fire incidents and drills so that the database can be used on evacuation simulations as an input.

Movement phase stands for the time interval between the first movement to evacuate and the last person to reach the exit [84]. This phase has a more physical characteristic since it involves occupants' movement. Engineers mainly researched the fundamental factors associated with movement time since they are calculable elements. Factors affecting movement time can be listed as; characteristics of stairs (bottlenecks), physical characteristics of occupants, fatigue, grouping effect, merging effect, counterflow and congestion [56].

Movement time and pre-evacuation time constitute total evacuation time (TET) [76]. RSET (Required Safe Egress Time) and ASET (Available Safe Egress Time) is two main definition to evaluate the safe egress for buildings. ASET stands for the time interval between the ignition and the establishment of conditions that human body cannot tolerate [85]. RSET is the time required for all occupants to reach safe area [86]. RSET constitute of detection phase, notification phase, pre-evacuation phase and evacuation phase [86]. Being RSET is shorter than ASET is an important check point. Otherwise, occupants may hurt during evacuation process. Mentioned terminology can be seen in Figure 2.11.

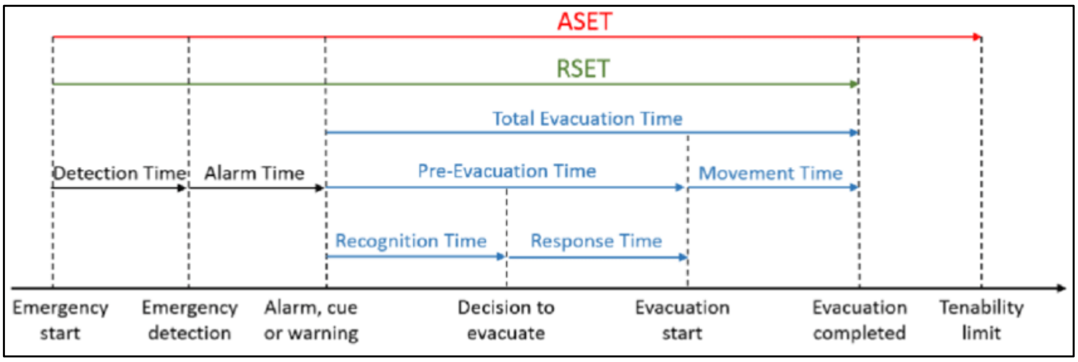

Figure 2.11. Evacuation timeline [87]

2.3.2. Manual calculations of evacuation

SFPE is a flow model defined by Society of Fire Protection Engineers [88]. In this model, the walking speed of the occupants are determined by occupant density of the room. Occupants use the shortest path to the exit and individuals can pass through each other. It can be said that this model is basically admit occupants as a fluid and make the calculations in this way.

NIST has developed Egress Estimator which is a simple tool to calculate evacuation time of a building using both elevators and stairs. As can be seen in the Figure 2.12, a certain fraction of occupants that use elevators can be defined. After putting in the required parameters, the program gives an estimated evacuation time that can be used as a preliminary data.

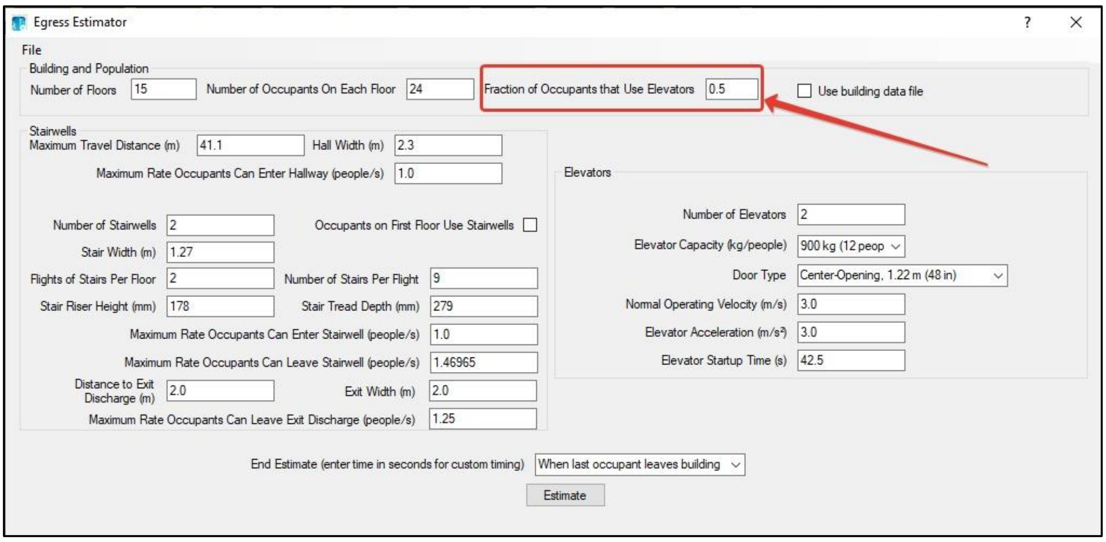

Figure 2.12. Egress Estimator [89]

2.3.3. Software calculations of evacuation

With the advancement in technology and wide spreading the use of performance-based calculations, computational models are beginning to take a wider place in our lives. Evacuation models generally designed for optimization, simulation and risk assessment [90]. This section mainly evaluated the simulation use of computational models. Simulation models, beside other advantages, make it easier for users to evaluate the effective evacuation of buildings. Since evacuation drills may not be available or safe for some buildings, modelling and simulating the evacuation is easier, cheaper, and safer.

Simulation models according to structure

Evacuation simulation models according to their modeling structure is given in the following three subsections.

Coarse Network Models

Egress models use 3 different strategies to evaluate the evacuation of buildings. One of these models is Coarse Network Model which is the most basic and oldest one. This model divides the building into rooms, corridors, and stairs to model the evacuation process. This evacuation model aims to calculate the evacuation time by moving the occupants from each division to the next. The biggest advantage of this model is that it can get fast results. For this reason, it is still used in studies requiring many trials. It is used to draw general conclusions about a building or to provide input for more detailed studies. [74]

Fine Network Models

Fine Network Models divide floor plan into grids. These grids are selected with a width representing the human body (usually 40-45 cm squares). Each building occupant is placed in a grid and their movements are modeled on these grids. Two occupants cannot be on the same grid at the same time. This model is more developed than the coarse network model and will give more accurate results. However, fine network model will demand more processor power and give slower results than the coarse network model. [74]

Continuous Network Models

Continuous Network Models allows occupants to move between starting point to exit point with the flexibility of more complex routes [74]. It finds the optimum way for building occupants to reach the closest and fastest exit and makes the necessary calculations. Although this model is a newer and more advanced model than the other two models, it requires high processing power and gives slower results. It gives more realistic results because it can better reflect human behaviors and movements to the simulation. With technological developments and increase of computer performances, the use of continuous network models and number of continuous network models increased [58].

Simulation models according to occupant perception

Macroscopic Models

Two simulation models classified in terms of occupant perception are macroscopic and microscopic models. Macroscopic models consider occupants as a group of people with same characteristics [91]. Control volume model and Takahashi models are some examples of macroscopic models that calculate the evacuation process with fluid dynamics.

Microscopic Models

Microscopic models are able to assign individual behaviors to occupants. Thus, the evacuation of people with different characters in a crowded group can be simulated. They are used to see the impact of the disabled, female / male distribution, child, or elderly population on the evacuation process.

Evacuation simulation programs are divided into 3 groups in terms of modeling method. These are behavioral models, movement models and partial behavioral models. By contrast with movement models, behavioral models are capable of assigning behaviors to occupants. [74]. Since there are large number of models may lead users to have difficulties to select the right model, Ronchi and Nilsson assessed the verification and validation of evacuation models for an easy use and selection of evacuation models [92].

2.4. High-rise buildings' evacuation problems

Evacuation of high-rise buildings is more important than low-rise buildings since they generally consist more people. And the fact that Istanbul is the 4th city with the most skyscrapers in the world shows the importance that should be given to this issue in Turkey [83]. Evacuation of high-rise buildings is different from low-rise buildings. Some of the differences and specific requirements for evacuation of high-rise buildings can be listed as; increasing the merge effect with increased number of floors, increasing required evacuation time, the use of refuge floors, occupants being tend to use elevators because of habits [72]. The chimney effect and stack effect are some factors make it harder to fight high-rise building fires [29,93]. There are numerous researches conducted to find an optimal solution of evacuation of high-rise buildings. One of the solutions offer that although evacuation from top to bottom floors extend the evacuation time, it makes evacuation more safely since congestion does not occur [94].

2.4.1. Egress strategies for high-rise building evacuation

The main purpose of egress strategies is to provide the safest evacuation for occupants to reach the exit. This purpose requires different approaches for different occupant types and building types. 4 egress strategy widely accepted are; simultaneous full building evacuation, protect-in-place, relocation and phased (or partial) evacuation [75].

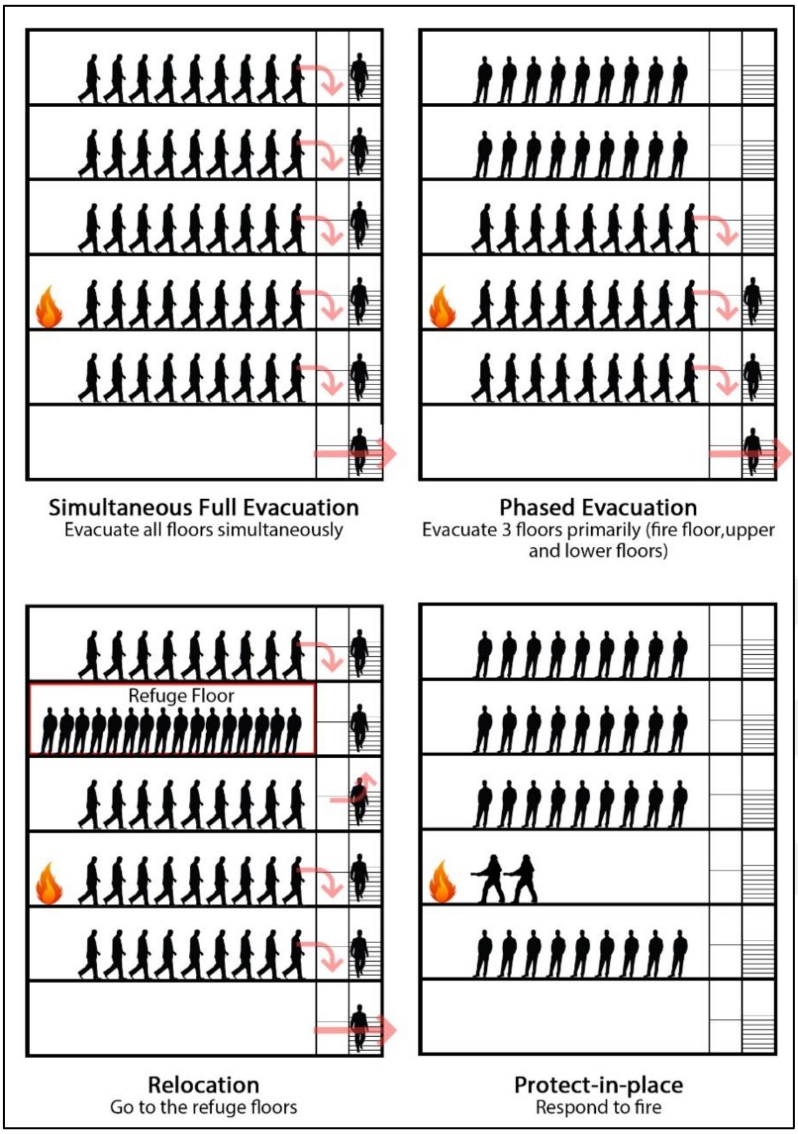

Figure 2.13. Egress strategies (graphics are prepared by the author)

Simultaneous full evacuation which is considered the most common one is a strategy that purpose to evacuate whole building with same alarm [13]. Protect-in-place strategy can be used for incidents that full evacuation may take too much time. In this strategy, fire fighters may be able to focus on extinguishing instead of evacuating the building [82]. Relocation strategy is used to move occupants from hazardous areas to safe areas like refuge room or other safe areas [75]. Lastly, phased evacuation may occur in 2 ways; compartmenting in same floor and compartmenting in different floors [82]. Mentioned egress strategies are illustrated in Figure 2.13.

2.4.2. Codes and regulations on elevator use for evacuation purpose

IBC recently allowed evacuation via preserved elevators [71]. This situation reflected to some countries' regulations. For example, evacuation elevators are compulsory for buildings higher than 24 m. in Singapore [14] and, fire elevator is compulsory for residential buildings higher than 32 m. in China [72]. Despite this, some countries do not allow elevator use for evacuation purpose. For example, Hong Kong Code of Practice on Building Works for Elevators and Escalators does not allow use of elevators for evacuation [73]. In Japan, emergency elevator is regulated in accordance with the height of the building [69]. Building Decree of Netherland permits fire department elevators to evacuate occupants and to carry fire fighters on condition that the elevator is designed against fire conditions [12]. Also, according to a report [95], published by NIST (The Use of Elevators for Evacuation in Fire Emergencies in International Buildings), following codes have specified that elevators may be used for evacuation from high-rise buildings:

- American Society of Mechanical Engineering Safety Code for Elevators and Escalators (ASME A17.1-2010),
- ICC International Building Code (IBC) -2012,
- NFPA 101-2012, Life Safety Code,
- NFPA 5000-2012,
- Building Construction and Safety Code,
- European Standards EN 81-73 2006 (Safety rules for the construction and installation of lifts - Particular applications for passenger and goods passenger lifts),
- British Standard (BS 9999:2008- Code of practice for fire safety in the design, management and use of buildings),
- Singapore Fire Safety Code -2013,
- Life Safety of National Building Code of India (IS SP 7 2005).

ISO/TR 25743:2010 [96] standard (Lifts (elevators)-Study of the Use of Lifts for Evacuation During an Emergency) that was published by BSI Standards Publication aims to highlight the main risks associated with elevators for the evacuation of building occupants. For emergencies like fire, flood, earthquake, explosion, gas leakage, numerous decision charts are given. One of the charts is given below as an example. These charts provide a detailed guidance in different emergencies whether the elevator should be used for evacuation purpose or not. These decisions are to be made by Building Management.

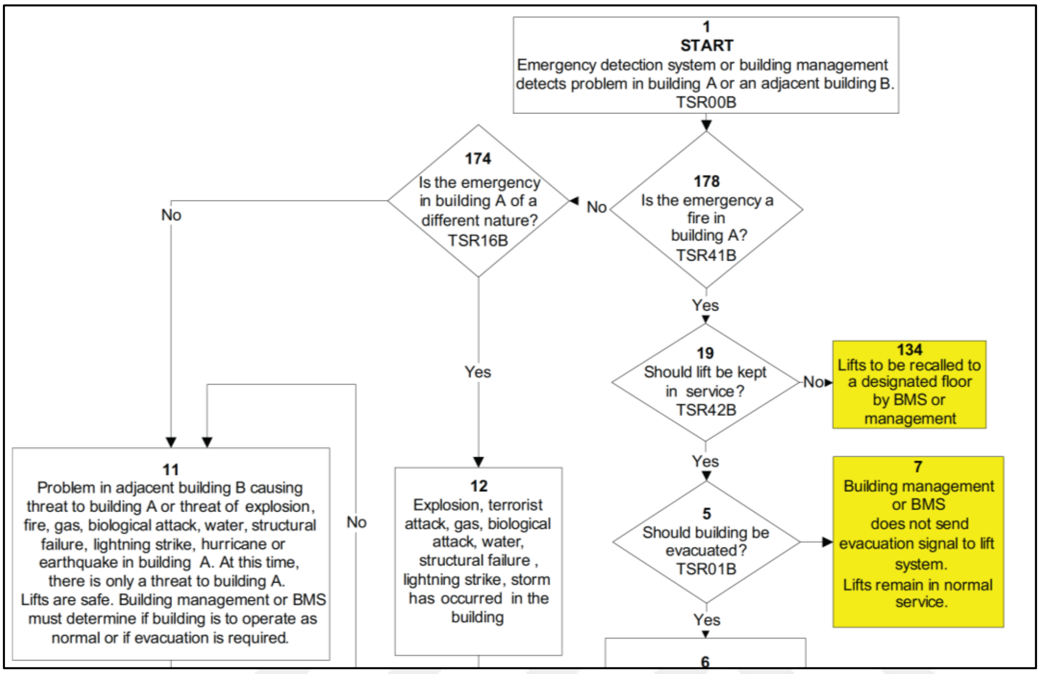

Figure 2.14. A section from ISO/TR 25743:2010 standard [96]

2.5. Elevator Related Studies for Evacuation

In the following three subsections, selected studies from the literature on elevator evacuation are reviewed.

2.5.1. Studies on normal and emergency evacuation of buildings

The reason for the preparation of this chapter is to compile studies comparing normal evacuation and emergency evacuation situations and to point out the background story of the normal evacuation.

Human factors associated with the selection of lifts/elevators or stairs in emergency and normal usage conditions (2012-Article) [97]

In the study, it is said that the elevator is used or considered to be used for evacuation purposes in countries such as Australia, China, Malaysia, UK, and USA. A high-rise fire (in Hiroshima in 1996) which 47% of the building occupants used elevator and 7% of the building occupants exit the building by using both elevators and stairs is given as an example where elevator evacuation was used in special cases in the past. In this case, elevators was not planned as a part of the evacuation procedure but used by occupants as a faster evacuation. It is mentioned that in high-rise buildings, some people may not want to wait for elevators to evacuate but choose to start descending via stairs unless it is told otherwise. Thus, it is pointed out that evacuation management should be done well.

It is mentioned that the use of elevators in normal evacuation is related to the use of elevators in emergency evacuation. So, understanding elevators usage behavior in normal evacuation is considered essential. In the study, it was determined that building occupants are at a distance from using elevators for evacuation purposes because of the warnings made by authorities. It is mentioned that only a sign that shows “elevators can be used during that evacuation” may not be enough to change the occupants’ ideas that have been settled for many years.

Human exit choice in crowded built environments: investigating underlying behavioral differences between normal egress and emergency evacuations (2016-Article) [98]

In this study, egress behavior of the occupants are investigated for both normal and emergency evacuation scenarios in Australia’s busiest rail station that accommodate about 100.000 passengers daily. Interviews were conducted with 105 people within the scope of the study. It has been investigated which criteria are effective in people's decision to exit and whether these criteria differ in normal and emergency evacuation situations. By investigating the normal evacuation situation, it is aimed to decide how to manage the crowd management of such buildings with high occupant load, especially with the increasing number of occupant on some special days. It is aimed to ensure with the right management, people can continue on their way without any blockage or congestion. This perspective is considered very important within the scope of the thesis. As a result, in people deciding which exit to use, it was observed that the closest exit was chosen for normal evacuation, but crowded exits were avoided in emergency evacuation.

2.5.2. Studies on fractional use of elevators in evacuation

In this section, studies on the fractional use of elevators during evacuation of buildings are compiled. In the given studies, occupants on each floor of the building used the elevator at a certain fraction, while the remaining occupants used the stairs. In this way, the optimum evacuation of the building was tried to be measured. The reason for the preparation of this chapter is that a similar method is used in this thesis study, and it is intended to point out the background of the method used.

Combined stairwell and elevator use during building evacuation (2013-Report-National Institute of Standards and Technology) [69]

This technical note is prepared to analyze the use of combined elevator and stairwell use during a fire emergency using Egress Simulator which is modeled by National Institutes of Standards and Technology. Stairwell evacuation, elevator evacuation and combined use of elevator and stairs are modeled with different evacuation strategies like full evacuation, phased evacuation, and zoned evacuation, to determine an optimal fraction of the occupants that should be using each evacuation component. As a result, a fraction of people using elevator is found for the most effective evacuation as given below.

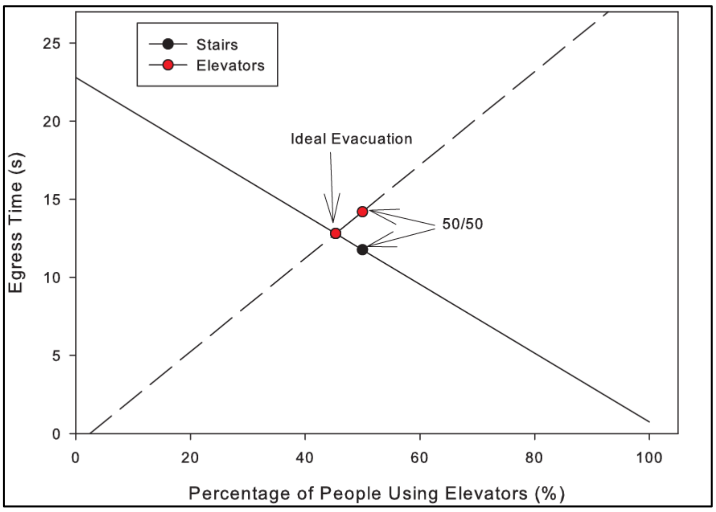

Figure 2.15. Optimum fraction of people using elevator according to the study [69]

Results of the study indicates that the total egress time, increases as a quadratic of the number of floors. Changing the speed and acceleration of the elevator has a small effect on the evacuation time of the building (this effect increases on the upper floors). Separating the elevators of the building into zones contributes positively to the evacuation process by ensuring effective use of the system. This study is found valuable in terms of measuring evacuation efficiency over the fraction of use of elevators and stairs.

<u>Cellular automaton modeling approach for optimum ultra high-rise building evacuation design (2012-Article) [72]</u>

In this article, where phased evacuation and total evacuation strategies were compared, optimum elevator usage for evacuation of ultra-high-rise buildings is analyzed using cellular automaton model. In the study, the optimum elevator usage was investigated by changing the elevator usage fraction in 0.2 intervals. As can be seen in the Figure 2.16 (left), the results indicate that the clearance time for the floors above the 40th floor is barely affected by stair user percentage. In contrast, stair user percentage did play an important role in affecting the evacuation process for other floors. The figure on the right shows that the optimum stair use percentage of the building occupants is %60 which means the shortest evacuation time was achieved when 60% of building occupants used the stairs and remaining used the elevators. The study is valuable as it shows that the effect of the elevator usage fraction on clearance time of the upper floors is less than on the lower floors.

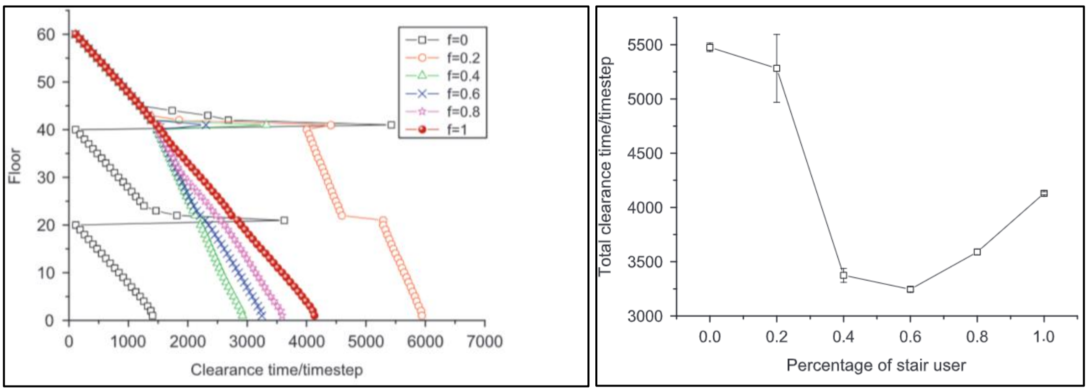

Figure 2.16. Optimum fraction of people using stairs according to the study [72]

<u>Collaborative evacuation strategy of ultra-tall towers among stairs and elevators (2016-Article) [29]</u>

In this proceeding, the building is divided in 3 part: floors 1-27 (low-rise), floors 30-48 (mid-rise), floors 50-66 (high-rise), and 3 different cases modeled.

- First case is stairs only evacuation.
- In second case, low-rise occupants uses stairs. 40% of mid-rise occupants use elevators and remaining mid-rise occupants use stairs. 70% of high-rise occupants use elevators and remaining high-rise occupants use stairs.
- In third case, low-rise occupants uses stairs. 30% of mid-rise occupants use elevators and remaining mid-rise occupants use stairs. 60% of high-rise occupants use elevators and remaining high-rise occupants use stairs.

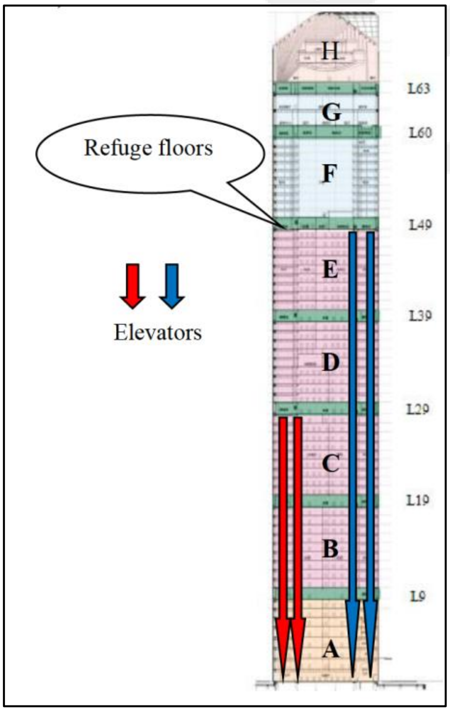

Figure 2.17. Modeled high-rise building in the study [29]

Table 2.5. The effect of different fraction of occupants using elevators on the evacuation time [29]

	Scenario	Evacuation floors	Floor the elevator stop	Potion of evacuation by elevator	Number of evacuees by elevator	Number of evacuees by stairs	Evacuation time
I	Stairs for evacuation only	Whole building	—	—	—	12010	4945
II	Collaborative evacuation	1-28F	—	0	0	6070	4285
		30-48F	29F	40	1588	2383	
		50-66F	49F	70	1373	596	
III	Collaborative evacuation	1-28F	-	0	0	6070	4171
		30-48F	29F	30	1191	2780	
		50-66F	49F	60	1181	788	

According to the data obtained, the third case gave the shortest evacuation time. It can be said that the method chosen in the study is inadequate. The result are far from finding the optimum evacuation time of the building and will give the most effective evacuation time out of the 3 cases identified.

2.5.3. Studies on the analysis of elevator usage with miscellaneous methods

In this section, studies on the use of elevators in evacuation of buildings are compiled. This section aims to give a general evaluation of the methods used to analyze the effect of the elevator on evacuation. Thus, it is aimed to show the needs of the use of elevators for evacuation and its place in the literature.

<u>Passenger traffic flow simulation in tall buildings (2000-Article-KONE) [99]</u>

In the study, a mega tall building is analyzed. It is aimed to analyze how fast can the upper part of the building can be evacuated. It has been observed that 4000 occupants on the highest 35 floors of the building can be evacuated by elevators in 31.5 minutes. It has been indicated that a 20-50 story building can be evacuated in 30 minutes via elevators and 15-30 minutes is an acceptable range for these buildings. In the study, to show the effect of elevator on evacuation duration, stair flow rate is given. It has stated that in a 1 m wide stair 60 people can descent in 1 min. This way an 88-story building with 120 occupants on each floor take 176 minutes to be evacuated. Although the information provided is valuable, the study is outdated. Nowadays, elevators can work much faster and more effectively.

Assessment of total evacuation systems for tall buildings (2013-Report-The Fire Protection Research Foundation) [65]

This report focuses on the effect of different evacuation components like stairs, elevators, sky-bridges. A model case is given with 7 strategies as given below. The model building has 50 floors that split into 3 sections: low-rise, mid-rise, high-rise as illustrated below.

- Strategy 1: Two Stairs Only
- Strategy 2: Three Stairs Only
- Strategy 3: Two Stairs and Occupant Evacuation Elevators (E1-E24)
- Strategy 4: Occupant Evacuation Elevators (E1-E24) Only
- Strategy 5: Two Stairs, Occupant Evacuation Elevators (E1-E24) and Service Elevators (sE1-sE2)
- Strategy 6: Two Stairs ,Occupant Evacuation Elevators (E1-E8, E17-E24) and Mid Rise Elevators as Express Elevators
- Strategy 7: Two Stairs, Occupant Evacuation Elevators (E1-E24) and Two Sky-bridges

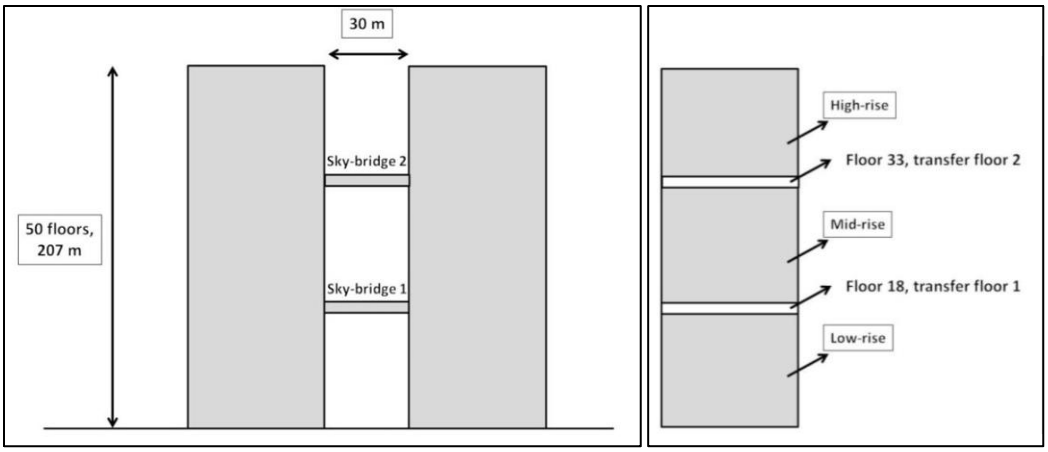

Figure 2.18. Floors of the model building in the study [65]

The study was found interesting in terms of using the terms Evacuation Elevators, Fire Service Access Elevators, Service Elevators and making this distinction.

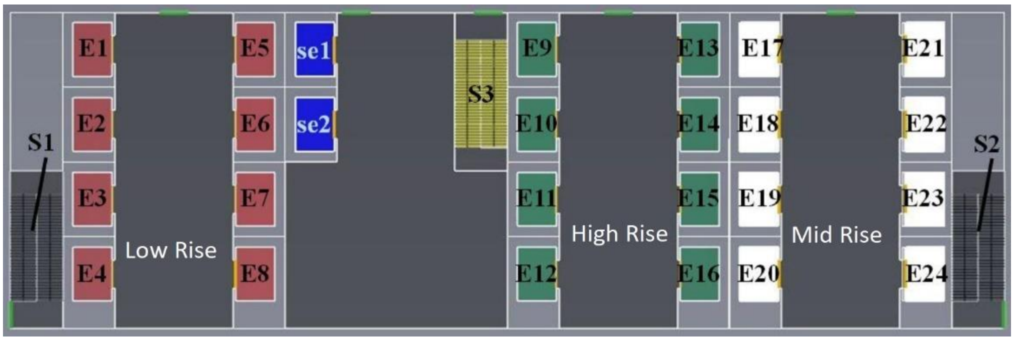

Figure 2.19. Elevator layout of the building in the study [65]

As a result, it has seen that scenarios 4 (Occupant Evacuation Elevators Only) and 7 (Two Stairs, Occupant Evacuation Elevators and Two Sky-bridges) give the most effective evacuation time. In addition, it has been reported that the results obtained may vary depending on the accepted maximum elevator waiting time in the simulation program.

Lifts used during evacuation (2013-Non Mandatory Document - Australia) [100]

This non-mandatory document was prepared by Australian Building Codes Board to provide a guidance to evacuate buildings (especially high-rise buildings) using elevators. It is stated that any means of egress carry risks. Like stairs, elevators will not be risk free during evacuations. In the event of an emergency, building occupants (especially visitors) want to leave the building by the same means they entered. This situation may lead people to the elevator first. An extensive training program is advised to manage the evacuation. These trainings will be a guide for people to understand;

- who may use the lifts?
- how may lifts be used?
- are the lifts to be used in conjunction with refuges?

A building may have three types of elevators; passenger elevators, emergency elevators and evacuation elevators. Evacuation elevators are used to evacuate the building and these elevators are equipped with safety measurements like air tightness, fire endurance, water resistance. If people to be evacuated via elevators, elevator lobbies should be isolated with fire-proof separators and occupants on every floor should be managed by wardens that designated before. These lobbies may be used as refuges so people may get in the lobbies and wait for the elevators safely. In the scenario when elevators are assigned for only some occupants (not all occupants) make the warden’s role difficult. Warden’s roles are to decide who should use the elevator first, what should be done when elevator is overloaded, contacting other floors so in case of breakdowns of elevators occupants may be leaded to stairs. The same is valid for stairs. If one of the stairs is blocked for any reason, occupants should be led to other means of egress. Also, operational approaches are proposed on the elevator’s working principle when the alarm begins. Fire, smoke and water management systems and related standards are given. Negative pressure regime is suggested for fire floors and positive pressure regime for other spaces. Power supply for elevators, emergency control center and communication systems are suggested. This document has been found valuable in terms of showing that the use of elevators has a wide place in regulations and the flexible framework that some authority and jurisdiction offer to elevator use during evacuation.

<u>The use of elevators for evacuation in fire emergencies in international buildings (2014-Report-National Institute of Standards and Technology) [95]</u>

This technical note is published by National Institute of Standards and Technology (NIST) to provide an overview of the elevator use for evacuation of high-rise buildings for especially mobility impaired occupants. In the study, 6 high-rise building across the world (Burj Khalifa, Canary Wharf, Eureka Tower, Petronas Twin Towers, Shanghai World Finance Center and Taipei 101) are introduced in terms of means of egress, evacuation procedures, fire safety measurements. Of these buildings, Burj Khalifa and Eureka Tower and Shanghai World Finance Center are designed in a way that allows elevator evacuation for fire emergencies. In the evacuation plan of Canary Wharf, evacuation by elevator is allowed for emergencies other than fire. The emergency evacuation plan of the Petronas Twin Towers was changed after the 9/11 incident. Before the incident, the use of elevators was not included in the evacuation procedure ,considering the possibility of usage of sky bridge, and continuing the evacuation from the other tower. After the incident, evacuation with the use of an elevator was added to the evacuation procedure of the building. Emergency/service elevators are used in emergency situations in Taipei 101 building, while passenger elevators are not used. The study also refers to human behavior during evacuation via elevators. The study was found valuable in terms of showing the existence of elevator use in the evacuation procedures of high-rise buildings that widely known in the world, and the changes after the September 11 attack.

Investigation of combined stairs elevators evacuation strategies for high-rise buildings based on simulation (2015-Article) [101]

This study is about the use of elevators and stairs together during evacuation of high buildings. An analysis was made on a 28-storey building. In the study, the optimum elevator usage of the building has been investigated.

The model building is a hypothetical building, and all floors are the same (elevators serve to each floor and the occupant load of each floor is the same). The article mentions that in order to analyze the elevator usage of the floors, each floor of the building must be the same, otherwise the result may be misleading. In the model building, it has been observed that the most effective evacuation can be achieved with the use of elevators in the last 2 floors, and the use of stairs on the other floors. The study was found interesting in that it proposes an evacuation method for the buildings. This method can be used in such buildings that consists of floors that are evacuated by the same elevators on each floor.

Table 2.6. Evacuation times in cases [101]

Occupant evacuation times in cases A1, A2 and A3 (Unit: s).

	0	13	12–13	11–13	10–13	9–13	8–13	7–13	6–13	5–13	4–13	3–13	2–13
Case A1	279	262	261	393	513	627	735	839	936	1037	1114	1219	1291
Case A2	782	710	653	687	870	1061	1259	1419	1603	1763	1929	2036	2201
Case A3	1107	1026	930	1060	1373	1688	1970	2271	2553	2806	3035	3289	3481
	Stairs only	Only last floor elevator	Only last 2 floors elevator	Only last 3 floors elevator	Only last 4 floors elevator	Only last 5 floors elevator	Only last 6 floors elevator	Only last 7 floors elevator	Only last 8 floors elevator	Only last 9 floors elevator	Only last 10 floors elevator	Only last 11 floors elevator	Elevators only

State-of-the-art high-rise building emergency evacuation behavior (2021-Article) [71]

In this review study on the evacuation of high buildings, the positive and negative aspects of vertical evacuation components like stairs and elevators, are given. It is inevitable that the stairs will be blocked as a result of the use of the stairs by all the occupants of the building. In addition, the stairs are difficult to use for the elderly, disabled, sick and children. Also, there is fatigue effect when going down from high-rise buildings. On the other side, the use of an elevator is a component that can accelerate the evacuation, although it is not allowed by most authorities for emergency evacuation. The compilation for human speed on stairs is valuable.

It is mentioned that the use of elevators for evacuation purposes has become widespread in recent years and that institutions such as International Code Council and National Fire Protection association allow the use of elevators for evacuation purposes. It is also said that there have been many successful elevator evacuations in the past. The most prominent of these is the WTC attack. After the WTC 1 building was hit, thousands of people in the WTC2 building were able to save their lives by using elevators. It is mentioned that the opening and closing times of the elevators take much longer than the occupant’s entering the elevator so the main attention should be given to the opening and closing time. It is recommended that the refuge floors be used not only as places for the elderly or patients to wait to be rescued, but also as rest stops for healthy people to evacuate the building. This review article is valuable in terms of providing comprehensive information on many current issues on the evacuation of high-rise buildings.

Event driven modeling of elevator assisted evacuation in ultra high-rise buildings (2017-Article) [102]

In this study, which was carried out on a model building with 60 floors and 2 refuge floors, elevator assisted evacuation was analyzed. The model set up propose that elevators will switch to emergency mode when an emergency occurs in the building. Switching to emergency mode, the elevator firstly carries the passengers in it to the ground floor. It then only takes calls from the refuge floors into account. It is proposed that the people in the building should go down to the refuge floors and continue downwards with the elevator or by the stairs. In this way, it is aimed to shorten the evacuation time with the effective use of the elevators.

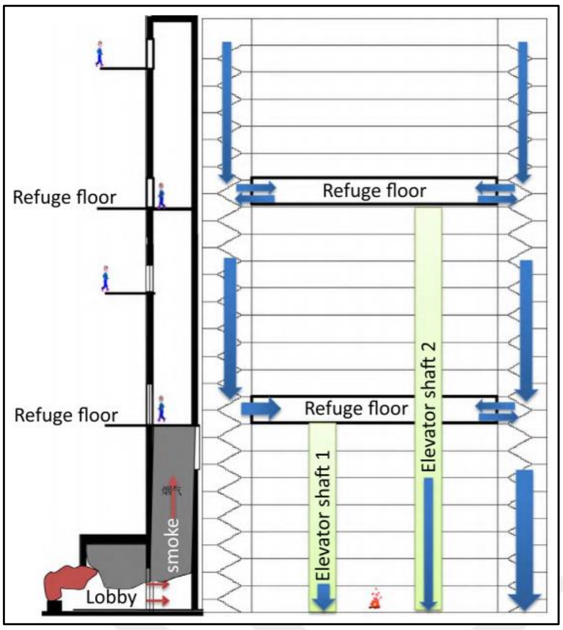

Figure 2.20. Representative emergency mode for elevators [102]

The study is found valuable because of the proposed model of evacuation using the elevator through the refuge floor, which is one of the most logical proposals for evacuation of high-rise buildings by elevators.

Performance evaluation of refuge floors in combination with egress components in high-rise buildings (2018-Article) [73]

In this study, 12 different scenarios are analyzed with 3 main evacuation components: stairs, elevators, and refuge floors. As a result, it has been observed that 1 refuge floor, 6 evacuation elevators and 3 stairs provide the most effective evacuation in those scenarios.

The study analyzed elements such as the location of stairs, the number and working principle of elevators, and the planning principles of refuge floors in the design of high-rise buildings. According to the results found on the building modeled within the scope of the study, the optimum evacuation time was obtained by planning 1 refuge floor, 6 evacuation elevators and 3 stairs for a 40-storey building.

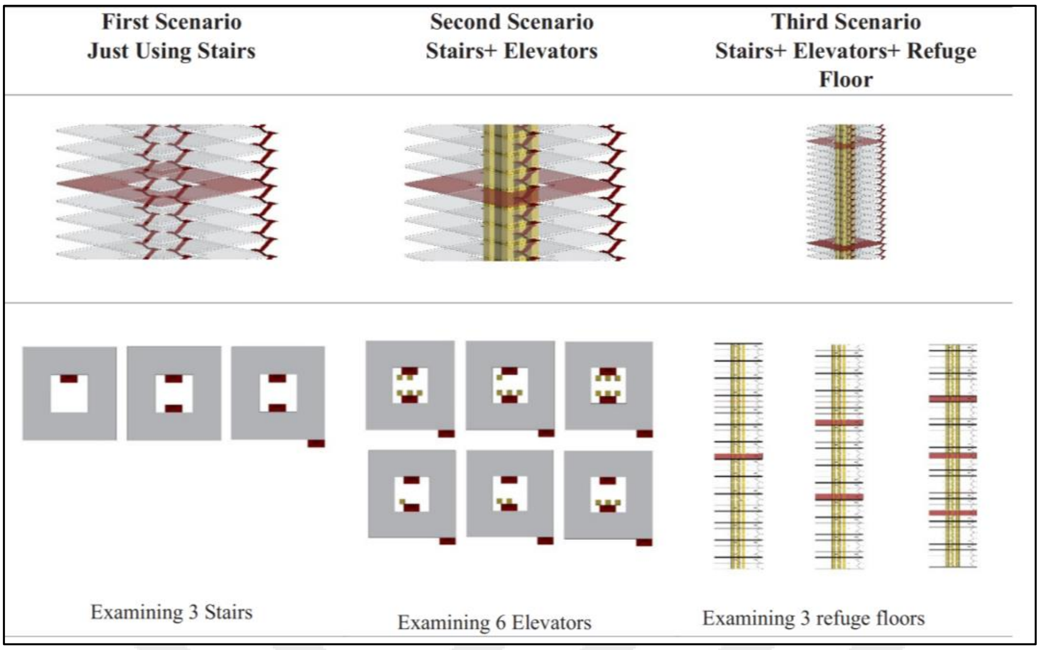

Figure 2.21. Three scenarios modeled within the study [73]

<u>Modelling and finding optimal evacuation strategy for tall buildings (2019-Article) [103]</u>

In the study, the optimum evacuation strategy was investigated by modeling a 56-storey building with 2 refuge floors and one evacuation elevator on each of these refuge floors. According to the model, building occupants will first descend from the floor they are on to the refuge floor by stairs and then they choose to continue by elevator or stairs. The results indicate that evacuation of 5400 occupants (100 occupants on each floor) takes about 1 hour.

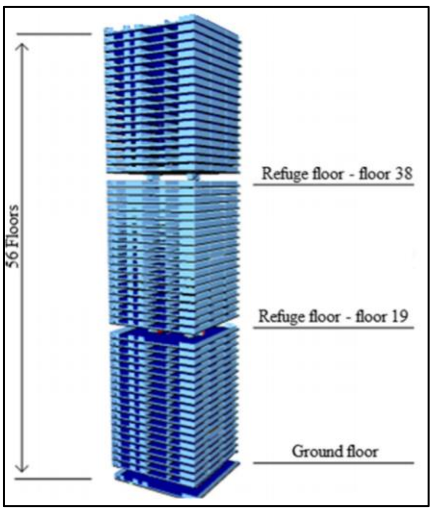

Figure 2.22. Modeled building [103]

The study was found valuable in terms of the proposal for elevator evacuation over the refuge floors, which is a logical model that can be used in elevator assisted evacuation of high-rise.

3. MODELING PROCEDURES

This section consists of the introduction of modeling procedures of 2 case buildings (İş Tower and Mersin Metropol) selected within the scope of the study. Simulation study was carried out on these buildings. Two case buildings were modeled within Pathfinder software. This model has a microscopic perspective. In other words, it allows the building occupants to be modeled with separate parameters and can calculate the paths of these occupants separately. Interface of the program is given below in Figure 3.1. As can be seen in the image, the buildings were modeled in 3D with floors, elevators, stairs, and occupants.

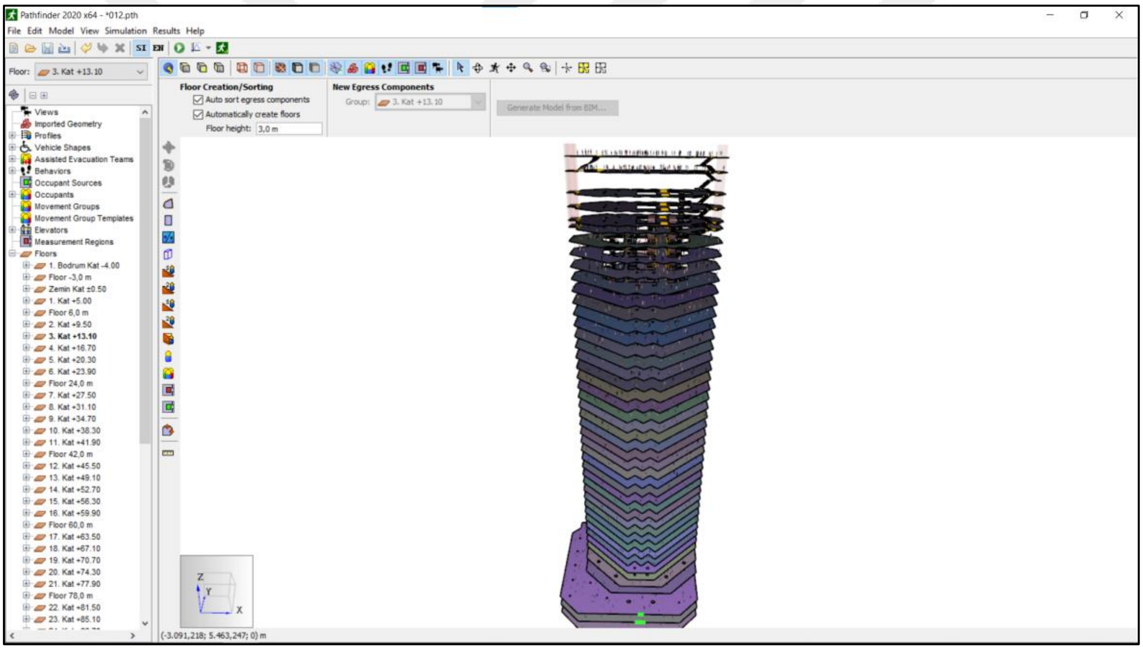

Figure 3.1. Interface of Pathfinder software

Both buildings' plan s are publicly published in [104] as scanned documents. The plans were redrawn in the CAD environment by the author. Building floors are modeled according to the plans of the building. Figure 3.2 shows the floor plans of the building. Each floor is attached to another floor with either a stair or elevator. Each occupant is defined to a floor. Exits of the building are defined according to the building plans. Once the simulation is started, the software is directing each occupant to the exits with closest and fastest path.

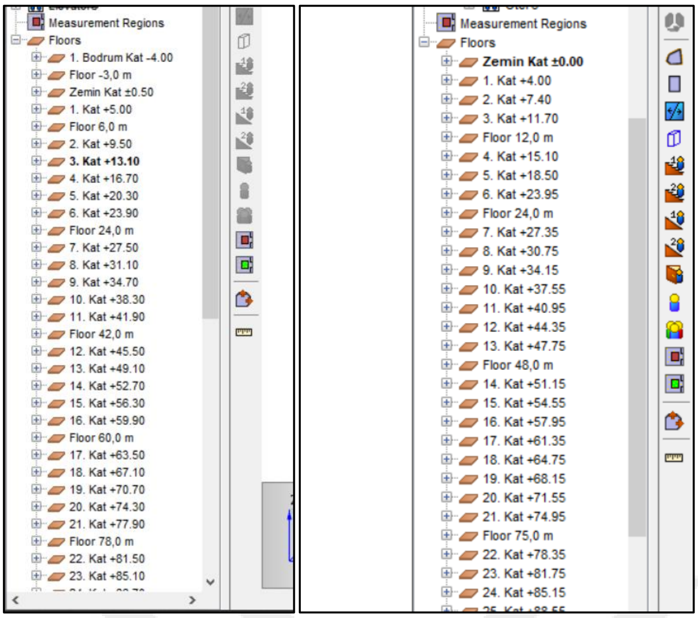

Figure 3.2. Floors of İş Tower and Mersin Metropol Building respectively

Since Pathfinder software is a microscopic simulation model, the program is able to assign a different behavior, walking speed, acceleration, and 3D models to each individual. In the modeling procedure of the thesis, each individual is considered same as the purpose of the thesis is not to analyze individual behavior during evacuation. Occupants are defined with 1.19 m/s walking speed (can be seen in Figure 3.3). This value is the default walking speed of the program, and the value is backed up with academic researches. More detail on this can be found on verification and validation documents [105] of the program.

The occupants of the buildings can be programmed to use or not use some evacuation components like stairs, elevators, escalators, ramps as can be seen in the Figure 3.4. This feature has been used extensively in the modeling of the 5 scenarios. For example, in scenario 1, "Use Stairs" option was selected as "All" because all building occupants were evacuated by stairs. And "Use Elevators" option is selected as "None". Thus, all occupants were evacuated using the stairs. In scenario 2, 25% of the occupants on each floor are programmed to use the elevators and the remaining 75% to use the stairs. Which occupants will use the stairs and which occupants will use the elevator is provided by the occupant profiles that created as can be seen in Figure 3.4. Occupants defined to use the elevator and occupants defined to use stairs are randomly distributed to each floor.

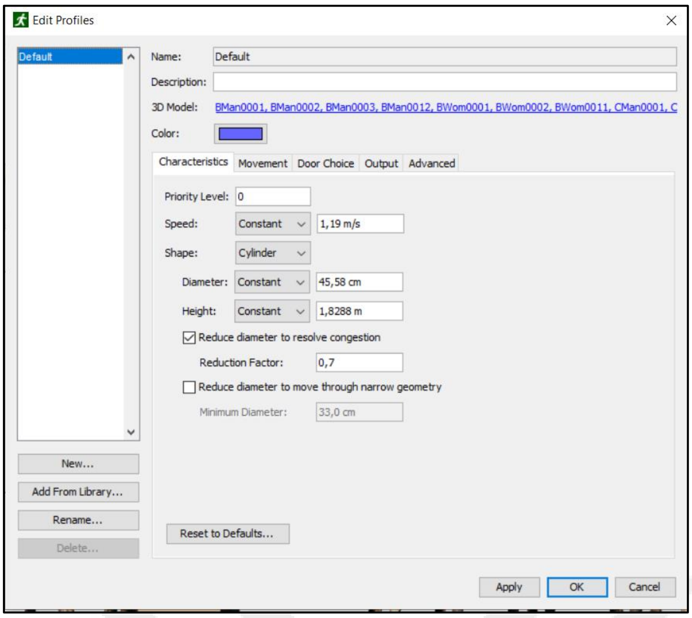

Figure 3.3. Occupant profiles of the buildings

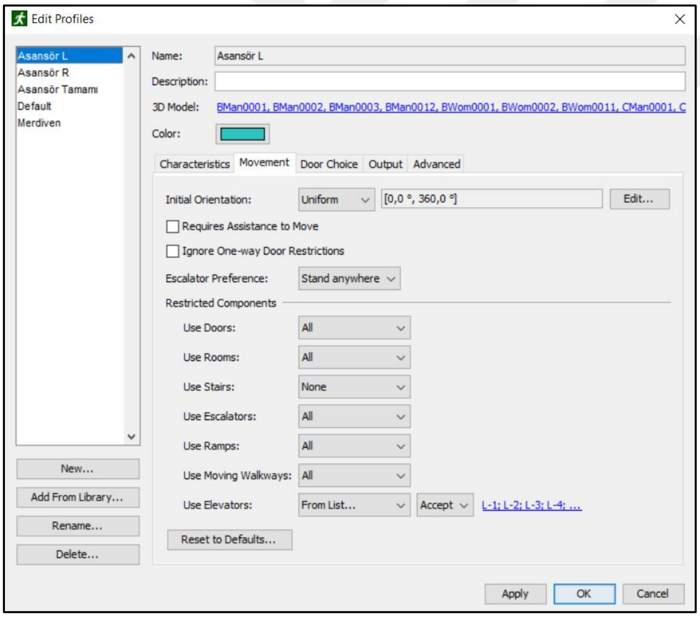

Figure 3.4. Occupants' movement properties

Occupant properties in the ribbon menu of the software is given in Figure 3.5. As can be seen, characteristics of each occupant like profile or behavior can be defined separately.

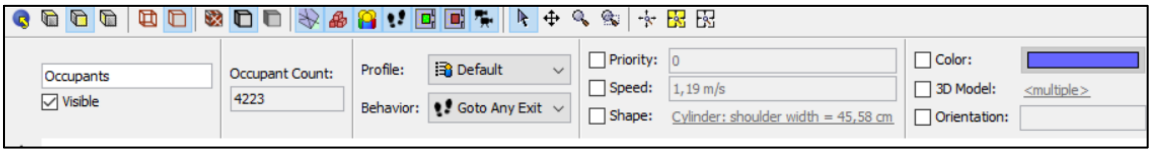

Figure 3.5. Occupant properties in the ribbon menu

Table 3.1. Five different scenarios modeled within the scope of the thesis

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Evacuation Type	Stairwell Evacuation	Combined Stairwell and Elevator Evacuation			Elevator Evacuation
Fraction of Occupants Using Elevators	%0	%25	%50	%75	%100
Fraction of Occupants Using Stairs	%100	%75	%50	%25	%0
Given in Section	4	6			5

5 scenarios are modeled for both case buildings. The modeled scenarios can be seen in Table 3.1. İş Tower and Mersin Metropol Building are introduced in detail with building parameters, stairwell parameters, elevator parameters and building population in sections 3.1 and 3.2.

3.1. İş Tower

In the following four subsections, the parameters used in the modeling of İş Tower are given.

3.1.1. Building parameters of İş Tower

İş Towers are located in the Levent district of Beşiktaş/Istanbul province. It was the Turkey's tallest building till 2011. 3 high-rise buildings placed in the complex are Tower 1, Tower 2, and Tower 3. This thesis focuses on Tower 1 only. In this thesis, "İş Tower" is used for "İş Tower 1".

The floor plans of the building are given in Figure 3.6 - Figure 3.13. The building has 43 floors above the ground floor. In addition, there are 6 basement floors under the ground floor. In the building, the 1st basement floor, ground floor and 1st floors constitute a large complex that unites 3 towers. This part of the building was excluded from the study. The entrance of the building is on the 1st basement floor. There are 2 main, and 2 side entrance of the building as can be seen in Figure 3.6. The entire building is used as an office. The standard floor height in the building is 3.6 m.

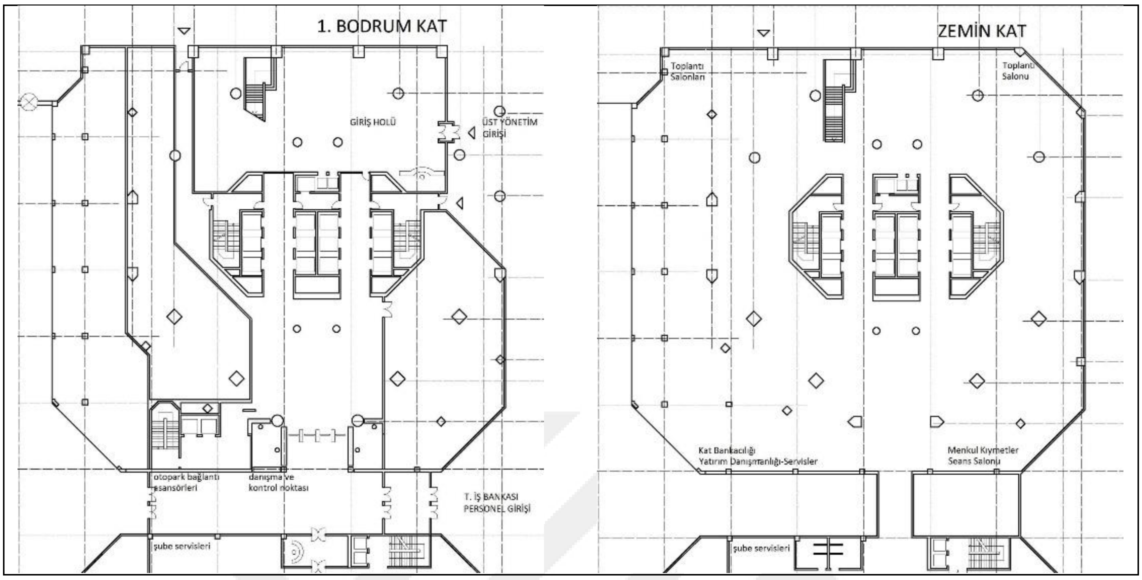

Figure 3.6. First basement (entrance floor) and ground floor plans of İş Tower

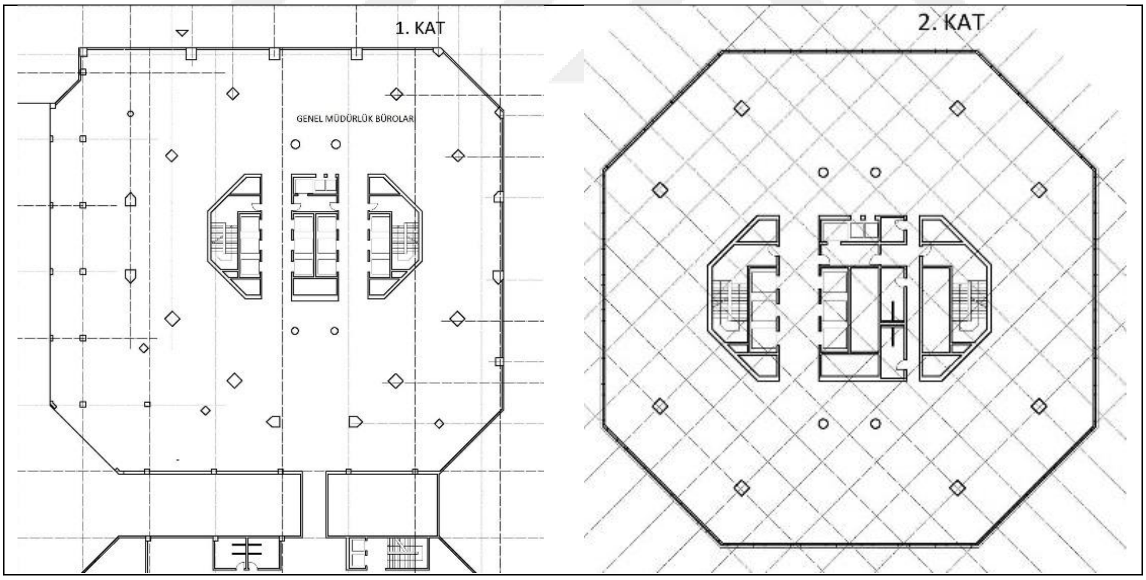

Figure 3.7. First and second floor plans of İş Tower

As can be seen in Figure 3.6 and Figure 3.7, 1st basement floor, ground floor and 1st floors are connected to Tower 2 and Tower 3. Mechanical floors are located on 4,5,39,40,41 floors.

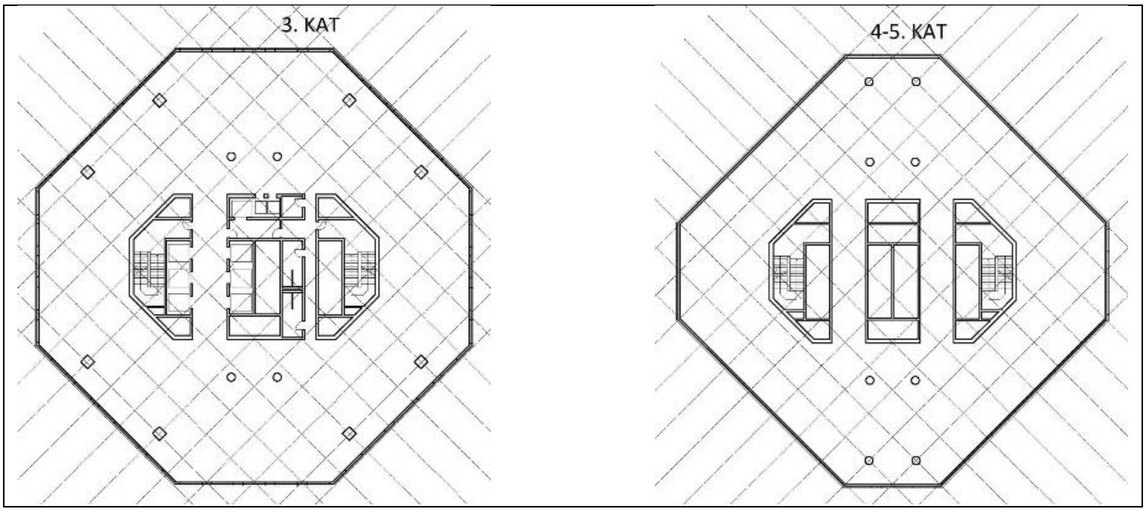

Figure 3.8.Third to fifth floor plans of İş Tower

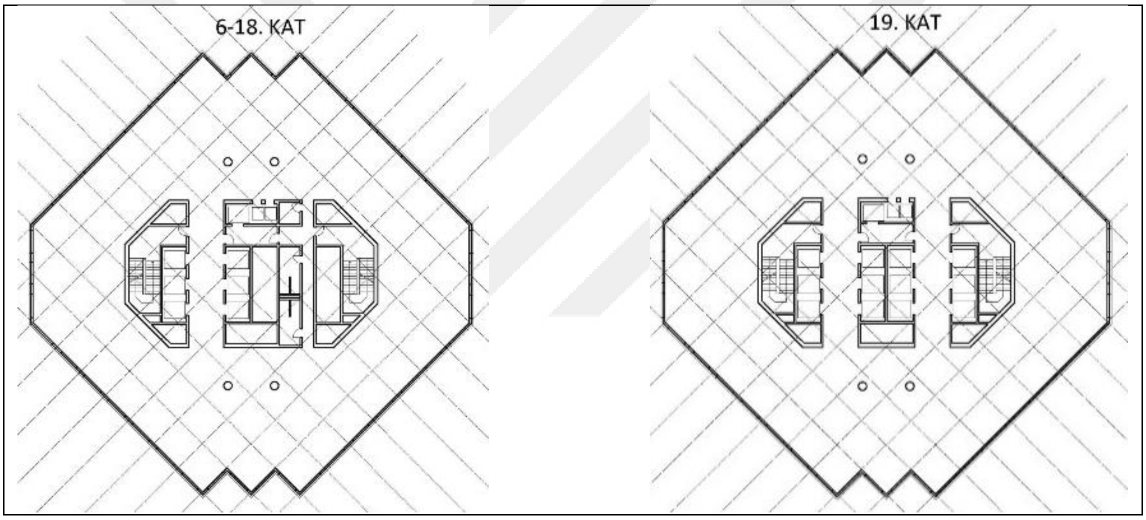

Figure 3.9. Sixth to nineteenth floor plans of İş Tower

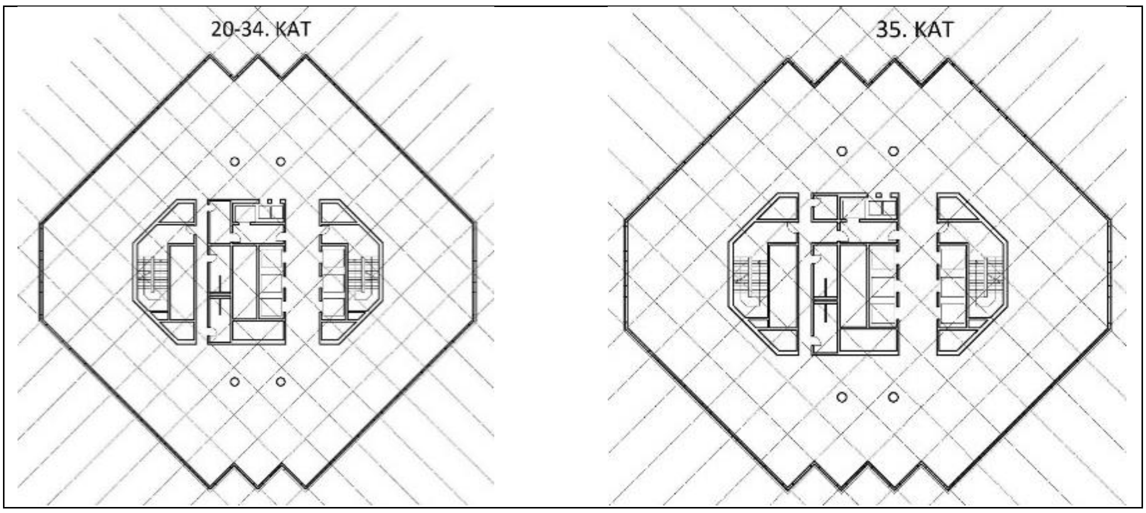

Figure 3.10. Twentieth to thirty-fifth floor plans of İş Tower

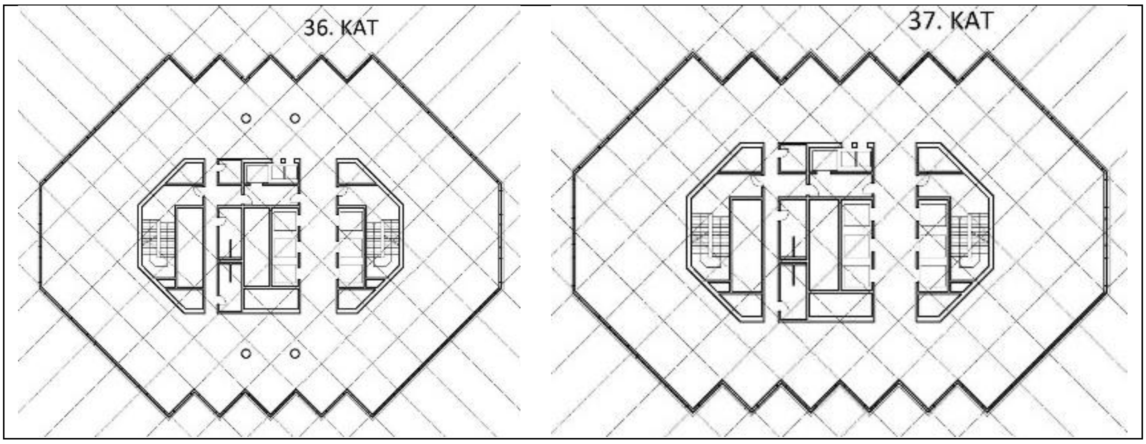

Figure 3.11. Thirty-sixth and thirty seventh floor plans of İş Tower

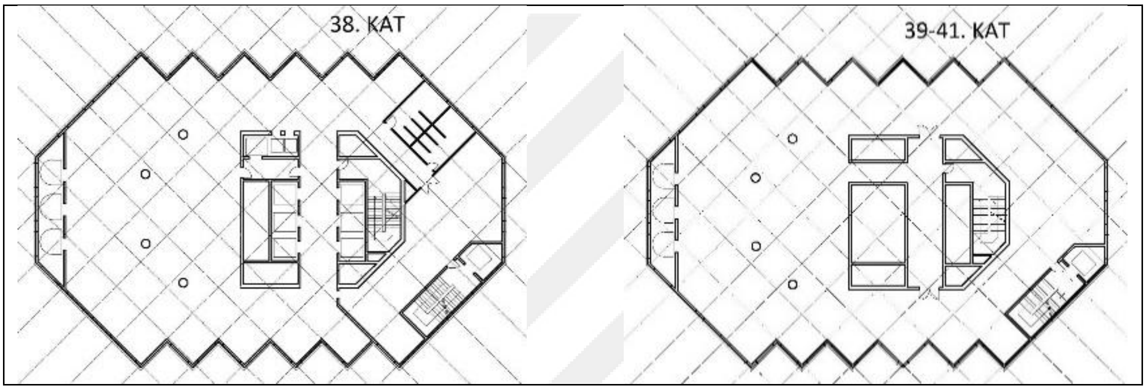

Figure 3.12. Thirty-eighth to forty-first floor plans of İş Tower

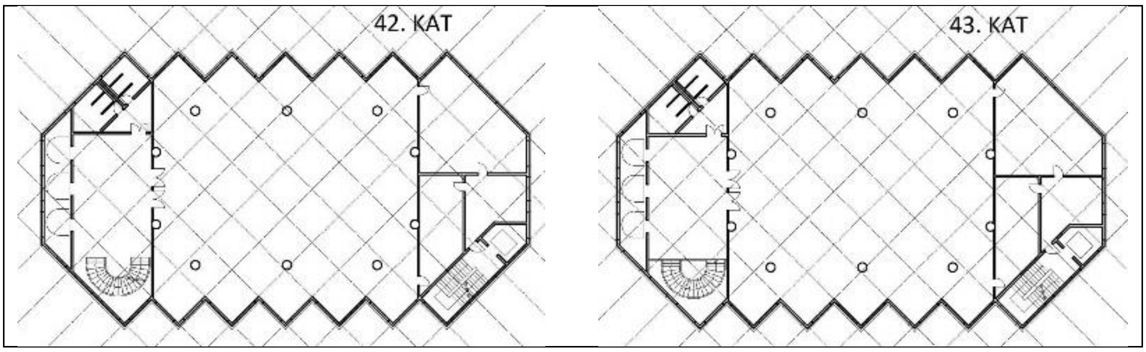

Figure 3.13. Forty-second and forty-third floor plans of İş Tower

3.1.2. Stairwell parameters of İş Tower

As can be seen in the Figure 3.14, there are 2 stairwells in the building. These two stairs are symmetrical copies of each other. The floor height (3.6 m) is divided into 24 steps. In this case, the riser height is 15 cm, and the tread length is 30 cm. It can be said that the stair steps are designed for a comfortable use. The stair width is 145 cm. Stair parameters of İş Tower can be seen in Figure 3.15. The doors of the stairwells are 90 cm wide. In the building, the elevator lobby is also used as the entrance to the stairwell. While the stair that shares elevator lobby (left stair in the Figure 3.14), has a 360 cm corridor width, the other stair has only a 120 cm corridor. This makes one of the stairs hard to reach in the crowd and it creates an ineffective evacuation environment.

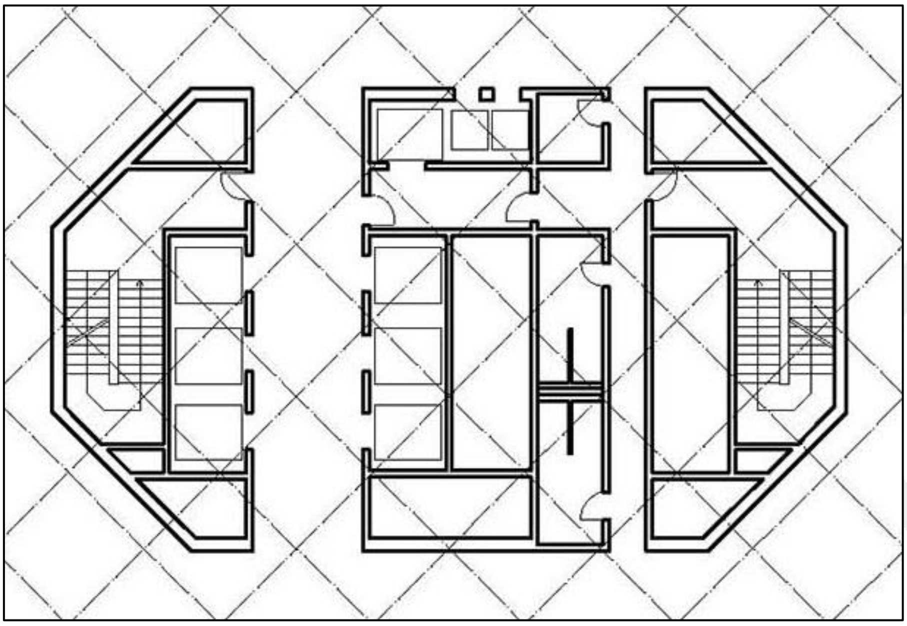

Figure 3.14. Core plan of İş Tower (19. floor)

As can be seen in Figure 3.15, each staircase can be named separately, and the riser height and tread depth can be determined. A certain person capacity can be determined for the stair. stair capacity is left as the default. Each stair can be operated in one direction. Thus, reverse flow can be prevented. This feature was not used in the thesis. In addition, separate occupant profiles for each stair can be used.

Figure 3.15. Stair properties of İş Tower

3.1.3. Elevator parameters of İş Tower

Elevators of the building are separated for lower floors and upper floors in the building. Figure 3.16 shows elevator distribution of the building. Both elevator groups (blue and orange) can be used for the 1st basement floor, ground floor and 1st floors. The elevators shown in blue, serve up to the 19th floor, while the elevators shown in orange serve from the 19th floor to the 38th floor. The elevators shown in green are available from the 39th floor to the 43rd floor. Elevators are grouped as given in Figure 3.17 and Table 3.2.

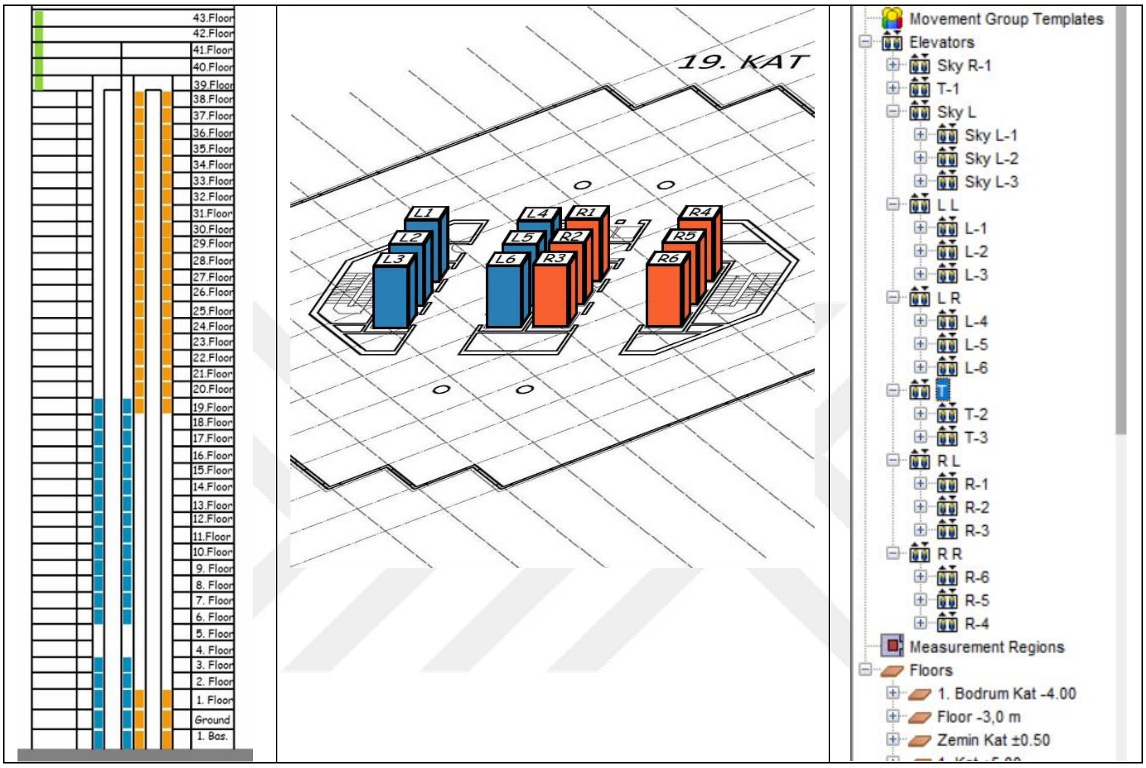

Figure 3.16. Elevator layout of İş Tower

Figure 3.16 (middle) shows 12 elevators in the building. As can be seen in Table 3.2 there are 5 groups of elevators in the building. R-1, R-2, R-3 elevators are named as R-L group. R-4, R-5, R-6 elevators are named as R-R group. L-1, L-2, L-3 elevators are named as L-L group. L-4, L-5, L-6 elevators are named as L-R group. Sky-1, Sky-2, Sky-3 elevators shown in green in Figure 3.16 are named as Sky-L group. As can be seen in Table 3.2, there are a total of 16 elevators in the building. Elevators in a group operate in relation to each other. When a call is made to an elevator group from any floor, the system sends the elevator that is closest or that is already moving in that direction. As can be seen in Figure 3.17, person capacity of the elevators are 11 person. Open and close delays are 3 seconds. Discharge floor and initial floors are 1st basement floor (entrance floor). Occupants touch the call button in a distance of 0.5 m.

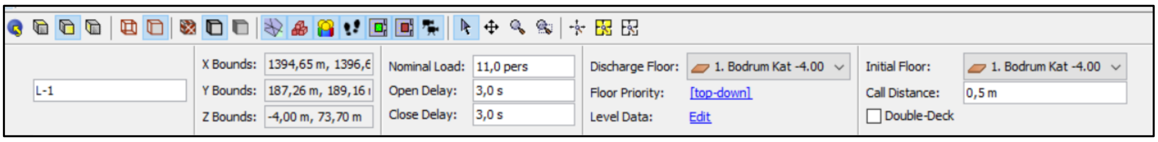

Figure 3.17. Elevator properties of İş Tower in ribbon menu

Table 3.2 shows parameters assigned to the elevators in the building. These parameters are acceleration (m/s²), maximum velocity (m/s), open + close time (s), capacity (person), open delay (s) and close delay, (s).

Table 3.2. Elevator parameters of İş Tower

Group Node	Sky L				L L			L R			R L			R R		
Elevators	**Sky L-1**	**Sky L-2**	**Sky L-3**	**Sky R-1**	**L-1**	**L-2**	**L-3**	**L-4**	**L-5**	**L-6**	**R-1**	**R-2**	**R-3**	**R-4**	**R-5**	**R-6**
Acceleration	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²
Max. Velocity	2,5 m/s	2,5 m/s	2,5 m/s	2,5 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s
Open+Close Time	7,0 s	7,0 s	7,0 s	7,0 s	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s
Capacity	15 person	15 person	15 person	11 person	11 person	11 person	11 person	11 person	11 person	11 person	11 person	11 person	11 person	11 person	11 person	11 person
Open Delay	5,0 s	5,0 s	5,0 s	5,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s
Close Delay	5,0 s	5,0 s	5,0 s	5,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s

3.1.4. Building population of İş Tower

Occupant load calculation of the building according to NFPA 101, IBC (International Building Code) and Turkey's Regulation on Fire Protection is given in Table 3.3. As can be seen in the table, 5900 people according to Turkey's Regulation on Fire Protection and 4223 people according to IBC and NFPA 101 are calculated. The building is modeled according to NFPA results. In this scenario, 4223 people were loaded into the building in the simulation.

Table 3.3. Occupant load calculation of İş Tower

Floors	Gross Area (m²)	Round Occupant Load (BYKHY)	Round Occupant Load (NFPA)	Round Occupant Load (IBC)
1. Basement Floor	2549,2	255	183	183
Ground Floor	2684,9	269	192	192
1. Floor	2684,9	269	192	192
2. Floor	1801,5	181	129	129
3. Floor	1635,0	164	117	117
4. Floor	Mechanical Floors			
5. Floor				
6. Floor	1404,0	141	101	101
…	…	…	…	…
…	…	…	…	…
34. Floor	1404,0	141	101	101
35. Floor	1330,0	133	95	95
36. Floor	1231,0	124	88	88
37. Floor	1108,5	111	80	80
38. Floor	1108,5	111	80	80

Table 3.3. (continued) Occupant load calculation of İş Tower

39. Floor	Mechanical Floors			
40. Floor				
41. Floor				
42. Floor	961,0	97	69	69
43. Floor	961,0	97	69	69
Total Occupant Load		5900	4223	4223

3.2. Mersin Metropol Building

In the following four subsections, the parameters used in the modeling of Mersin Metropol Building are given.

3.2.1. Building parameters of Mersin Metropol Building

Mersin Metropol Building was designed by Cengiz Bektaş as Turkey's tallest building and remain so until 2000. The floor plans of the building are given in Figure 18-Figure 23. The building has 47 floors above the ground floor. In addition, there are 2 basement floors under the ground floor. The building was designed with a commercial complex. This complex has 6 floors above the ground floor. Commercial complex and the high-rise building are connected at some points. These transitions were modeled as an exit of Mersin Metropol Building since the occupants can leave the high-rise buildings from these points. Only the high-rise part of the building was modeled. The entrance of the building is on the ground floor as can be seen in Figure 3.18. In addition, destination floors can be reached through the elevators separated by these lobbies. And standard floor height in the building is 3.4 m.

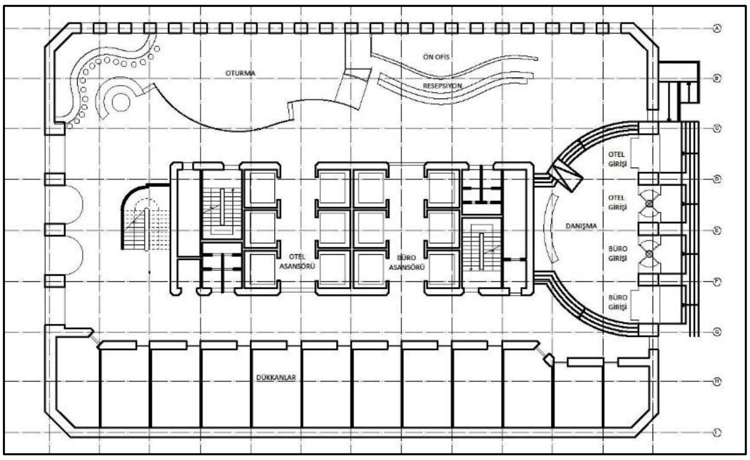

Figure 3.18. Ground floor plan of Mersin Metropol Building

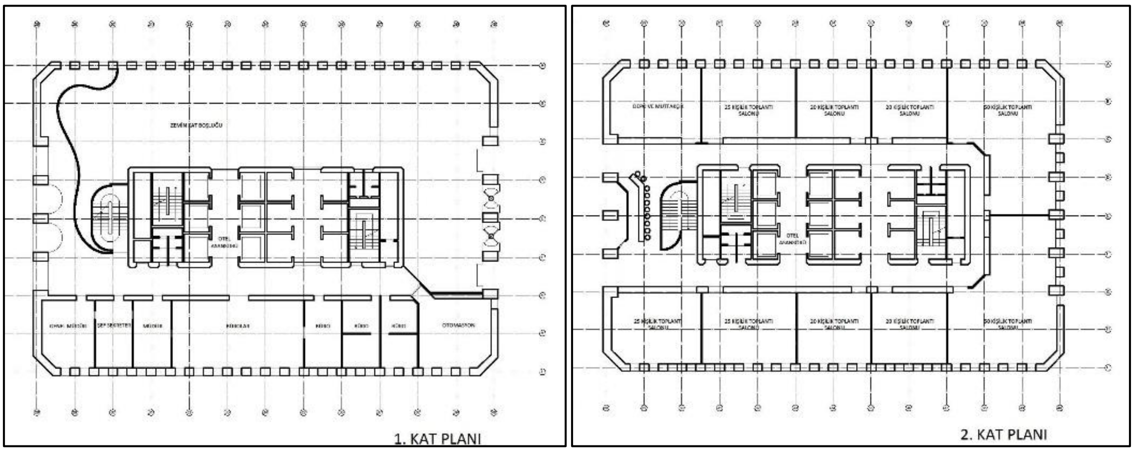

Figure 3.19. First and second floor plans of Mersin Metropol Building

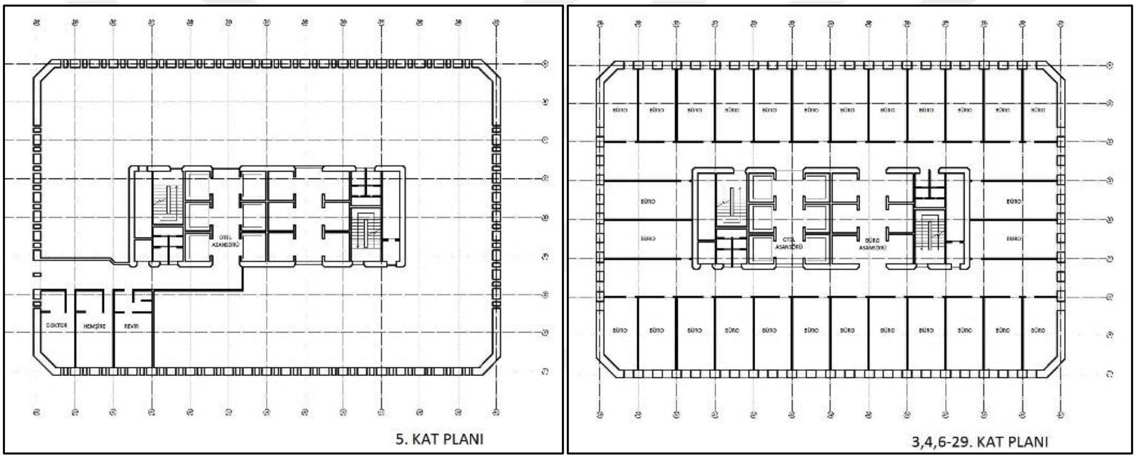

Figure 3.20. Third to twenty-ninetieth floor plans of Mersin Metropol Building

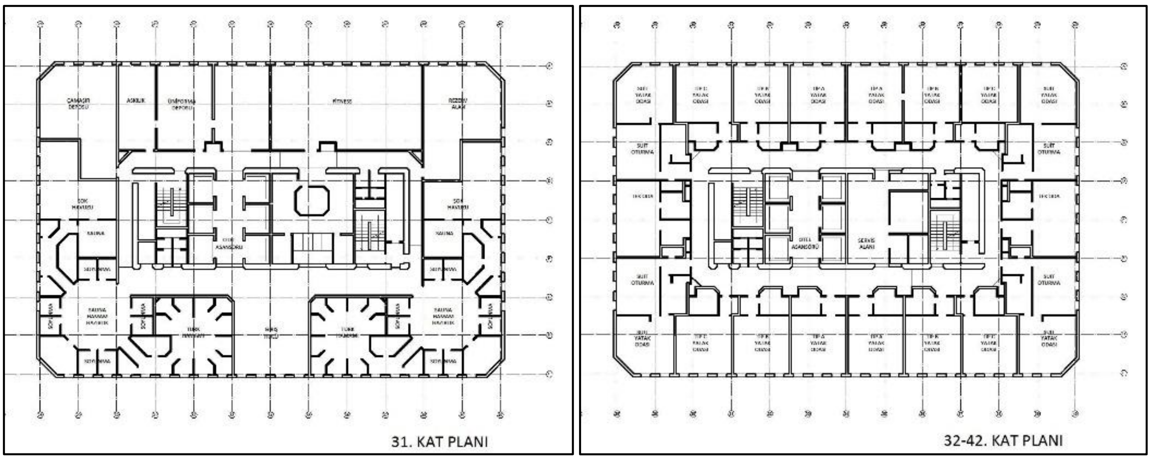

Figure 3.21. Thirty-first to forty-second and forty-fifth floor plans of Mersin Metropol Building

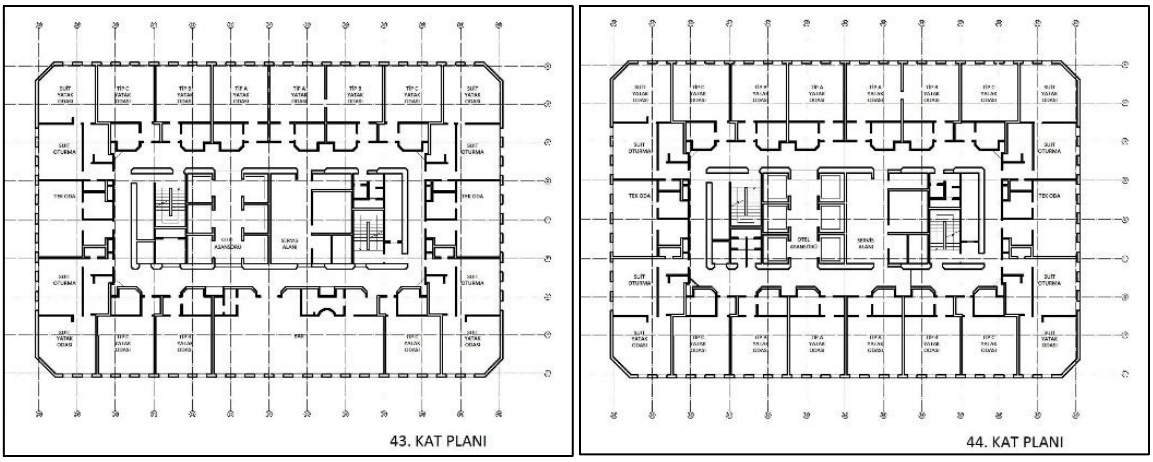

Figure 3.22. Forty-third and forty-fourth floor plans of Mersin Metropol Building

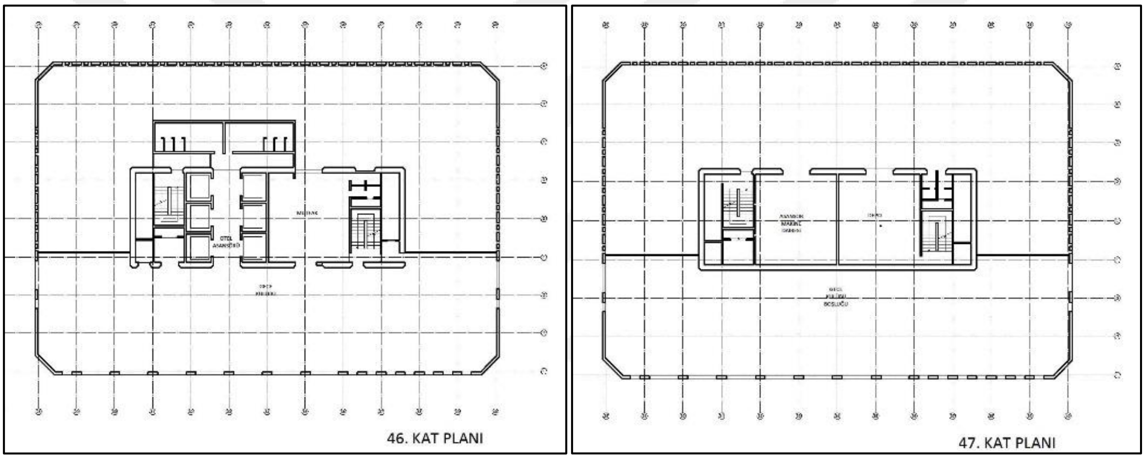

Figure 3.23. Forty-sixth and forty-seventh floor plans of Mersin Metropol Building

As can be seen from the images the ground floor of the building consists of the lobby, reception, and shops. The hotel management and lobby gallery are located on the 1st floor. There are meeting rooms on the 2nd floor. Mechanical floors are located on the 5,30,46,47. floors. The building's 3,4 and 7-29. floors are office floors. 31-46. floors are reserved for the hotel. The hotel's sauna, Turkish bath and fitness room are located on the 31st floor. And a night club is placed on the 46th floor.

3.2.2. Stairwell parameters of Mersin Metropol Building

As can be seen in the Figure 3.24, there are 2 stairwells in the building. These two stairs are symmetrical copies of each other. The floor height (3.4 m) is divided into 20 steps. In this case, the riser height is 17 cm, and the tread length is 30 cm. The stair width is 125 cm. It can be said that İş Tower has more comfortable stairs than Mersin Metropol Building in terms of tread length and riser height. Also, stair width of the Mersin Metropol is narrower. The doors of the stairwells are 105 cm wide. In the building, the elevator lobbies and stairwell entrances are separated which is a positive factor because it may prevent congestion. Stair properties of Mersin Metropol Building is given in Figure 3.25.

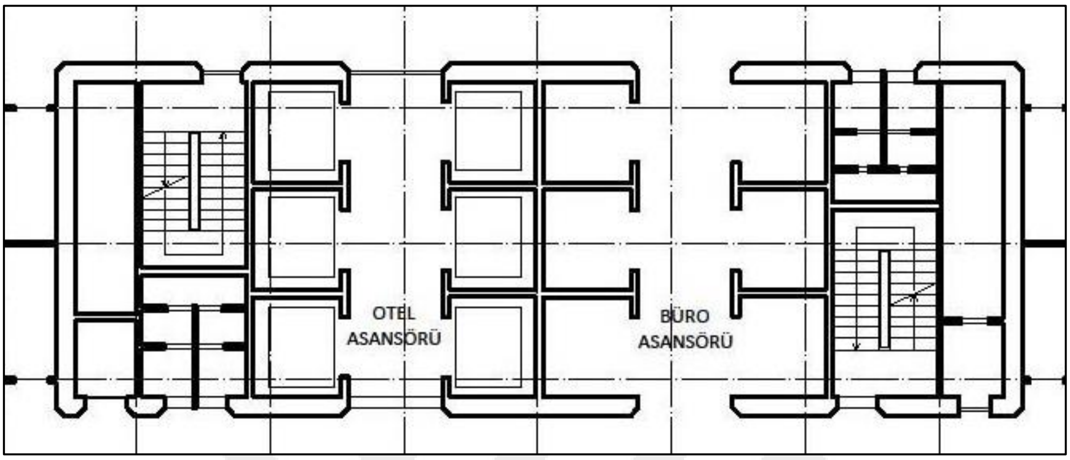

Figure 3.24. Core plan of Mersin Metropol Building (19. floor)

Figure 3.25. Stair properties of Mersin Metropol Building

3.2.3. Elevator parameters of Mersin Metropol Building

Elevators of the building are separated for hotel floors and office floors in the building. Figure 3.26 shows elevator distribution of the building. Both elevator groups (blue and orange) can be used for ground floor, 5. floor and 30. floors. The elevators shown in blue serve up to the 30. floor, while the elevators shown in orange serve from the 30. floor to the 46. floors.

Figure 3.26 shows 12 elevators in the building. The elevators shown in orange serve the hotel floors, while the elevators shown in blue serve the office floors. As can be seen in Table 3.4, there are 4 groups of elevators in the building. R-1, R-2, R-3 elevators are named as R-L group. R-4, R-5, R-6 elevators are named as R-R group. L-1, L-2, L-3 elevators are named as L-L group. L-4, L-5, L-6 elevators are named as L-R group.

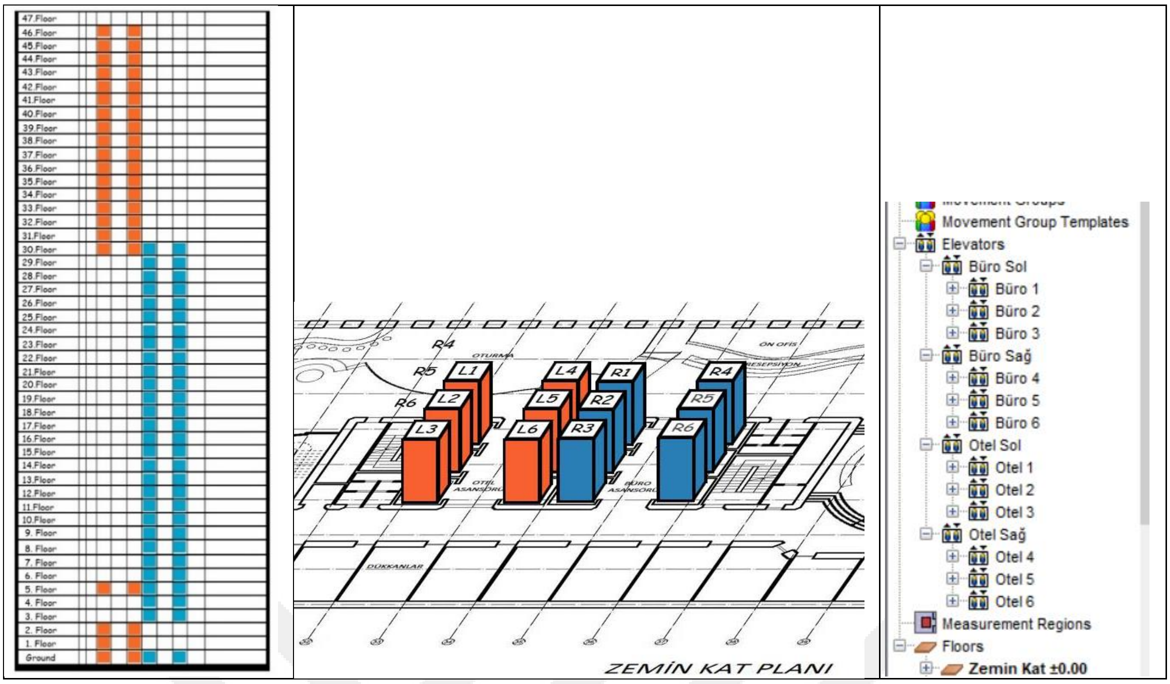

Figure 3.26. Elevator layout of Mersin Metropol Building

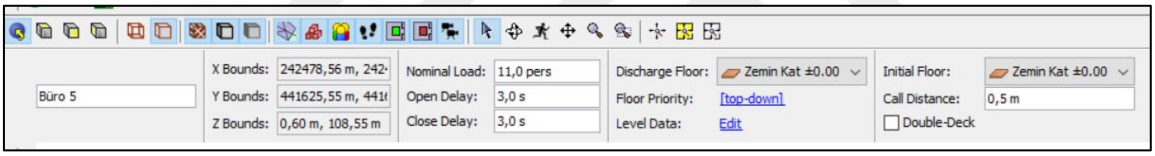

Figure 3.27. Elevator properties of Mersin Metropol Building

Figure 3.27 shows elevator parameters of Mersin Metropol Buildings in ribbon menu of Pathfinder software. Elevators have a capacity of 11 person and open/close delay of 3 seconds. Discharge and initial floors of Mersin Metropol Building is ground floor. Elevators have a top-down priority. This means elevators collect all calls and starts to respond to them starting from the top.

Table 3.4. Elevator parameters of Mersin Metropol Building

Group Node	**L L**			**L R**			**R L**			**R R**		
Elevators	**L-1**	**L-2**	**L-3**	**L-4**	**L-5**	**L-6**	**R-1**	**R-2**	**R-3**	**R-4**	**R-5**	**R-6**
Acceleration	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²	1,2 m/s²
Max. Velocity	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s	6,0 m/s
Open+Close Time	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s	4,0 s
Capacity	11 person	11 person	11 person	11 person	11 person	11 person	11 person	11 person	11 person	11 person	11 person	11 person
Open Delay	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s
Close Delay	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s	3,0 s

3.2.4. Building population of Mersin Metropol Building

Occupant load calculation of the building according to NFPA 101, IBC and Turkey's Regulation on Fire Protection is given in Table 3.5. As can be seen in the table, 5533 people according to Turkey's Regulation on Fire Protection and 4752 people according to IBC and NFPA 101 are calculated. The building is modeled according to NFPA results. In this case, 4752 people were loaded into the building in the simulation. As seen in Table 5.3, certain floors of the building have much higher occupant load. These floors are 31. (Turkish bath, sauna, fitness room etc.) and 46. floors (night club).

Table 3.5. Occupant load calculation of Mersin Metropol Building

Floors	Function	Gross Area (m^2)	Occupant Load (BYKHY)	Occupant Load (NFPA)	Occupant Load (IBC)
Ground Floor	Reception	628,21	210	62	62
	Shops	628,21	126	113	113
1. Floor	Office	757,66	76	55	55
2. Floor	Meeting Rooms		255	255	255
3. Floor	Office	1256,42	126	90	90
4. Floor					
5. Floor	Mechanical Floor				
6. Floor	Office	1256,42	126	90	90
…					
29. Floor					
30. Floor	Mechanical Floor				
31. Floor	Turkish Bath, Sauna…	1256,42	252	274	274
32. Floor	Hotel		63	68	68
…					
45. Floor					
46. Floor	Night Club	455,50	456	701	701
47. Floor	Mechanical Floor				
Total Occupant Load			5533	4752	4752

4. RESULTS AND DISCUSSION

The simulation data obtained after modeling İş Tower and Mersin Metropol Building on the Pathfinder program based on the inputs given in section 3 will be examined in this section. Figure 4.1 gives the simulation results of İş Tower. As can be seen in the figure, as a result of the modeling of İş Tower with the occupant load determined by NFPA 101, evacuation time of the building varies from 27 minutes to 52 minutes in 5 scenarios modeled.

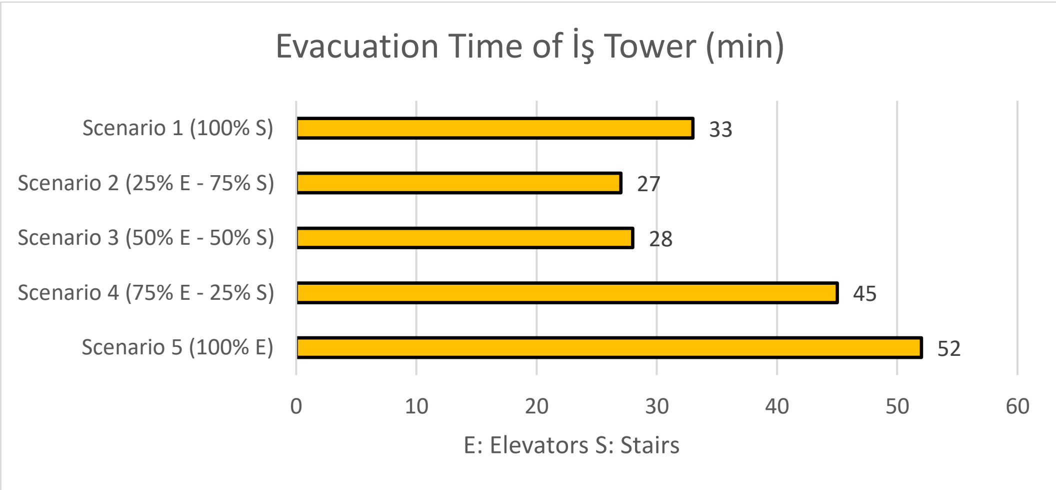

Figure 4.1. Evacuation time of İş Tower

As can be seen in Figure 4.1, the most effective elevator usage fraction in the evacuation of İş Tower is 0.25. In other words, the most effective evacuation was achieved by evacuating 25% of the building occupants by elevator and the remaining 75% by stairs. In addition, for İş Tower, it is seen that the evacuation time is shorter in Scenario 1, where only stairs are used, compared to Scenario 5, where only elevators are used. In this case, it is seen that the stairs in the building provide more effective evacuation than the elevators, that is, the handling capacity of the stairs is higher than the handling capacity of the elevators.

Figure 4.2 gives the simulation results of Mersin Metropol Building. As can be seen in the figure, as a result of the modeling of Mersin Metropol Building with the occupant load determined by NFPA 101, the evacuation time of the building varies from 29 minutes to 49 minutes in 5 scenarios modeled.

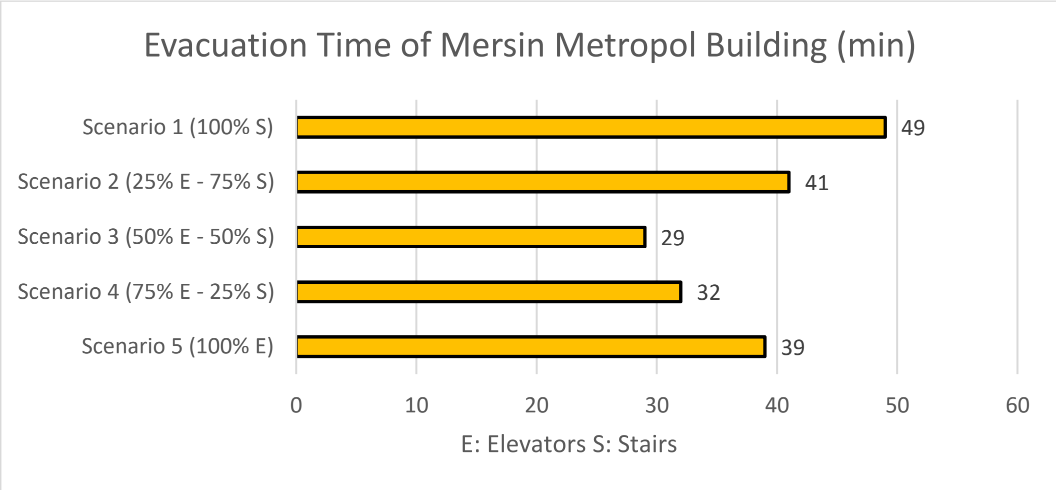

Figure 4.2. Evacuation time of Mersin Metropol Building

As can be seen in Figure 4.2, the most effective elevator usage fraction in the evacuation of Mersin Metropol Building is 0.50. In other words, the most effective evacuation was achieved by evacuating 50% of the building occupants by elevator and the remaining 50% by stairs. In addition, for Mersin Metropol Building, it is seen that the evacuation time is shorter in Scenario 5, where only elevators are used, compared to Scenario 1, where only stairs are used. In this case, it is seen that the elevators in the building provide more effective evacuation than the stairs, that is, the handling capacity of the elevators is higher than the handling capacity of the stairs. The data obtained as a result of the simulations of 5 scenarios modeled and the reasons behind these results are given in detail in the following subsections 4.1, 4.2, and 4.3.

4.1. Stairwell Evacuation Simulation for Two Cases (Scenario 1 (%100S))

The two case buildings are modeled in Pathfinder program and calculated occupant load is defined. Figure 4.3 shows front and side views of the modeled buildings. Mechanical floors as can be seen in the figure, are empty. The Turkish bath, sauna floor (31st floor), and nightclub floor (46th floor) in Mersin Metropol Building stand out with their high occupant load. In İş Tower, on the other hand, a more homogeneous distribution of occupants is observed between floors.

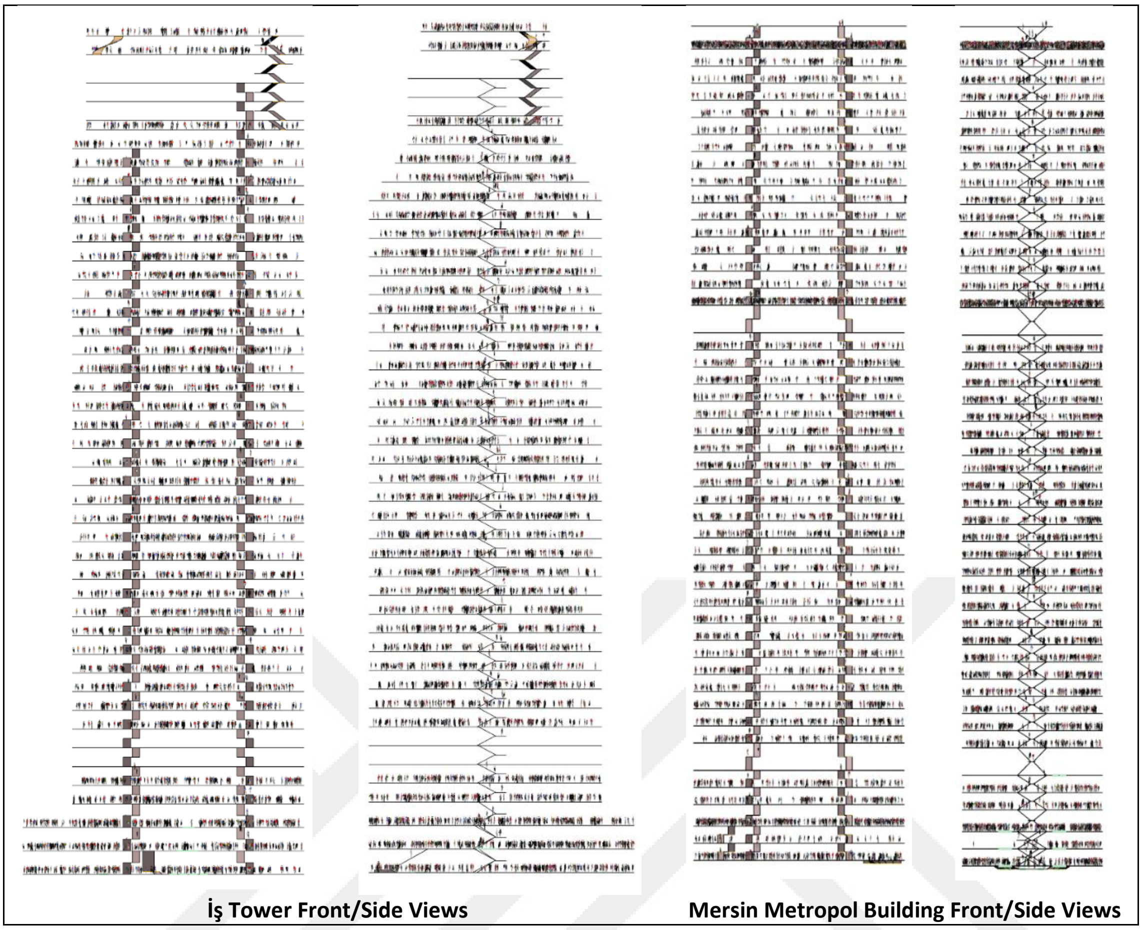

Figure 4.3. Models of İş Tower and Mersin Metropol Buildings

In Figure 4.4, a floor plan (20-34th floors) of İş Tower is seen on the building model. The blue lines on the plan show the paths occupants follow during the evacuation. As can be seen in the figure, the two stairs of the building can be reached by two corridors of different widths. The right one is designed wider (360 cm) since it reaches both elevators and stairs. However, the other corridor is narrower (120 cm) as it only leads to the stairwell. In this case, it becomes difficult to reach the stair on the left. Therefore, the program directs more occupants to the stair on the right, as more people can enter the stair on the right in a shorter time. This situation causes the stairs on the left to be not used effectively enough, thus; the building cannot be evacuated effectively.

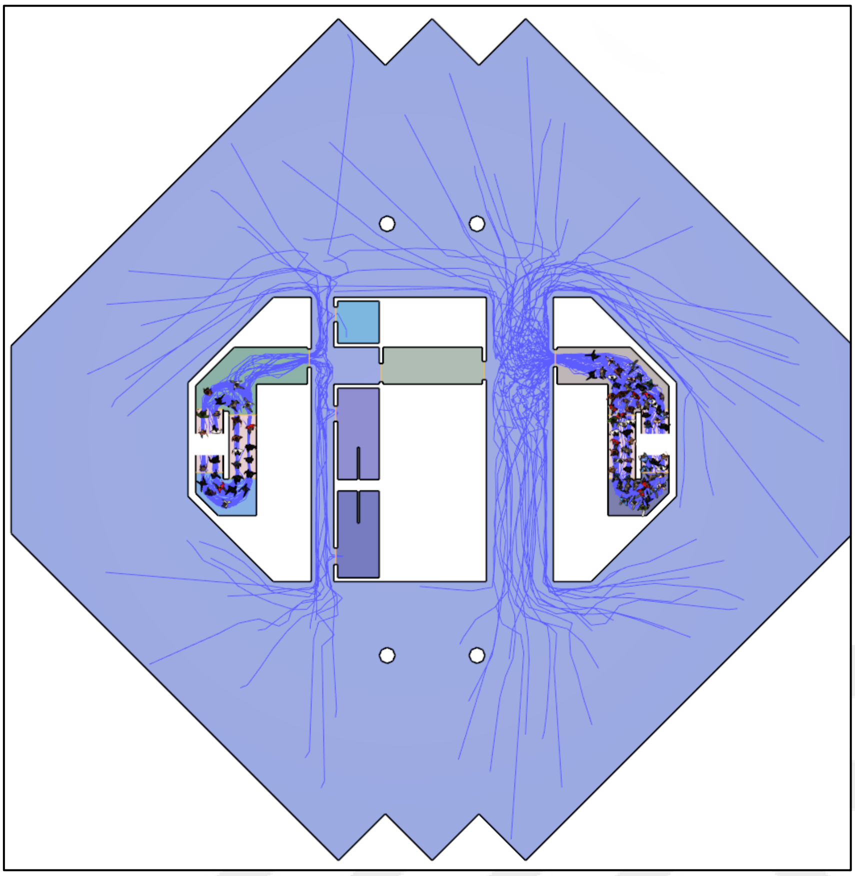

Figure 4.4. Occupant paths of İş Tower

Figure 4.5 is a perspective from the İş Tower building model. The occupant load in the building has been calculated separately for NFPA, IBC and Turkey's Regulation on Fire Protection. In the model of the building, the internationally valid NFPA calculation was used. The defined occupant load (4223 people) made according to the NFPA calculation seems to be too much for an office. In addition, the occupant load increases even more in the calculation made according to Turkey's Regulation on Fire Protection (5900 people).

A floor plan from the model of Mersin Metropol Building is given in Figure 4.6. The blue lines in the figure show the path followed by the building occupants during the evacuation. When the plans of Mersin Metropol Building and İş Tower are compared, the first difference encountered is the width of the corridors leading to the stairwells. These corridors are planned wider in Mersin Metropol Building. Therefore, it is possible to reach the stairwell more easily. However, although the corridor leading to the stairs of the Mersin Metropolitan Building (250 cm) is wider than the corridor of the İş Tower (120 cm), the stair width of the Mersin Metropolitan Building (125 cm) is planned narrower than İş Tower (145 cm). In this case, even if the stairs can be reached more easily, the stairwell will have less handling capacity for people in Mersin Metropol Building.

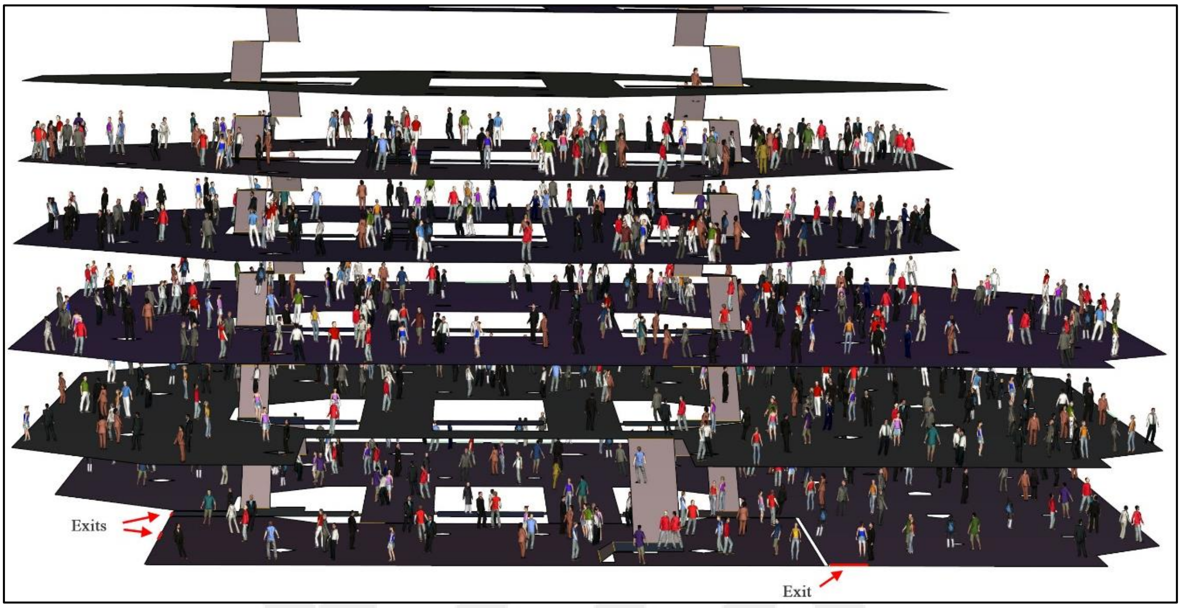

Figure 4.5. A perspective from the model of İş Tower

Figure 4.7 shows a perspective from the model of Mersin Metropol Building. The occupant load in the building has been calculated separately for NFPA, IBC and Turkey's Regulation on Fire Protection. In the model of the building, the internationally valid NFPA calculation was used. The defined occupant load (4752 people) made according to the NFPA calculation seems to be too much for this building. In addition, the occupant load increases even more in the calculation made according to Turkey's Regulation on Fire Protection (5533 people).

As a result of the simulation studies of the buildings given above, evacuation times and graphics for scenario 1 are given below. Figure 4.8 shows the number of occupants in the building/evacuation time of Mersin Metropol Building and İş Tower. In the graph below, it can be seen that the evacuation time of Mersin Metropol Building is 49 minutes while evacuation time of İş Tower is 33 minutes.

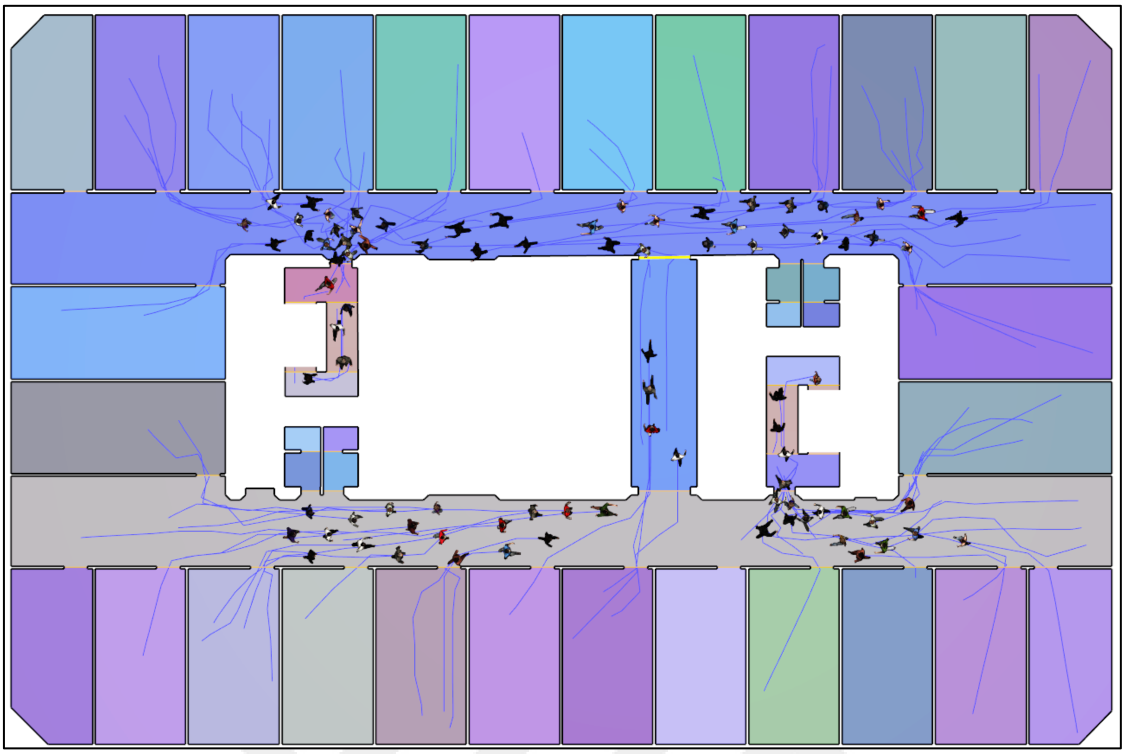

Figure 4.6. Occupant paths of Mersin Metropol Building

Figure 4.7. A perspective from the model of Mersin Metropol Building

A longer evacuation time for Mersin Metropol Building is expected because of higher occupant load. Bu if the graphic is read, it can be seen that there are elbow points where evacuation speed is changing. The first elbow point for both buildings is seen in the first 5 minutes. This elbow point is formed when people on the ground floor evacuate the building quickly in the first few minutes. For a long time thereafter, the evacuation curve remains constant. In this area, the evacuation of people in the building continues at the same speed for a long time, since the evacuation of the building is limited to the width of the stairs. In this region, the slope of the evacuation curve shows us the evacuation rate.

When the Constant Area 1 lines in the Figure 4.8 are compared for both buildings, it is observed that İş Tower evacuated more people in the same time period. In other words, the evacuation speed of İş Tower is higher in this area. The reason behind this situation may be that the width of the stairs in İş Tower is wider. The second elbow points in the figure are observed when one of the stairs of the building is emptied. After this point, the related building continues to be evacuated by only one staircase. Since the slope of the evacuation line of the İş Tower is steeper in the Constant Area 2, it is seen that İş Tower provides a faster evacuation in this process as well. However, the evacuation speed of the building is slower than in the Constant Area 1, as the evacuation continues only via one stair.

The second elbow point seen in the figure is more positive to be seen in the last moments of the building evacuation than in the first moments of the building evacuation. Because after this point, the evacuation efficiency of the building decreases. For İş Tower, the second elbow point is seen in the middle part of the evacuation, while it is seen in the last moments of the of Mersin Metropol Building. In addition, if the graph is analyzed again, approximately 1200 people in the İş Tower were evacuated with a single stair, while the last remaining 250 people in the Mersin Metropol Building were evacuated with a single stair. To summarize, although İş Tower can be evacuated faster by wider stairs, occupants cannot be evenly distributed between the stairs because one corridor that have access to left stair is narrower.

Although the normal evacuation of buildings is analyzed in this thesis, how many minutes that it takes for occupants to enter the safe area is an important criteria for safe evacuation. Figure 4.9 and Figure 4.10 show the moment when all occupants of İş Tower and Mersin Metropol Building enter the safe area (stairwell is considered safe for smoke, fire). While all occupants can enter the stairwell at the 8th minute in İş Tower, it takes 24 minutes for all occupants to enter the stairwell in Mersin Metropol Building. The reason behind this situation can be explained by the following two reasons. First of all, since the stairs of the

İş Tower are wider, the occupant capacity of the stairs is higher. In addition, since the landings of İş Tower are wider than the Mersin Metropol Building, the capacity becomes higher.

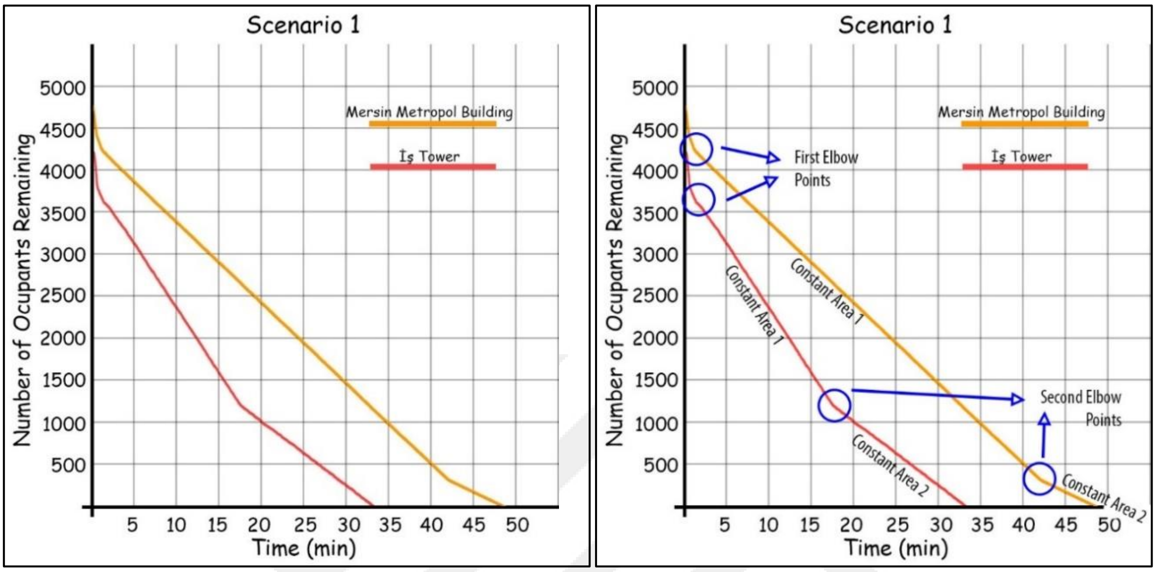

Figure 4.8. Simulation results of scenario 1

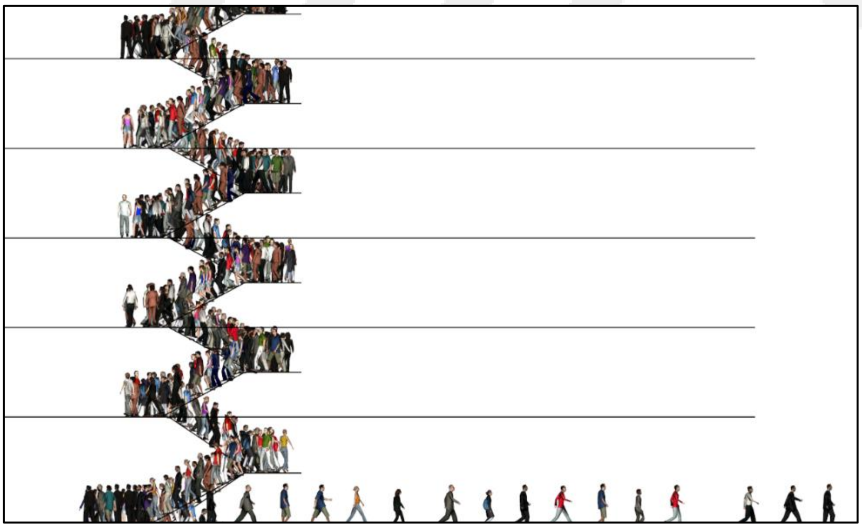

Figure 4.9. All occupants of İş Tower are in safe area in 8. minute

The second reason is the non-homogeneous occupant distribution between the floors of the Mersin Metropol Building. As mentioned before, there is a much higher occupant load on the 31st and 46th floors of the Mersin Metropol Building. In this case, it takes much longer for all occupants to enter the stairwell than at the İş Tower.

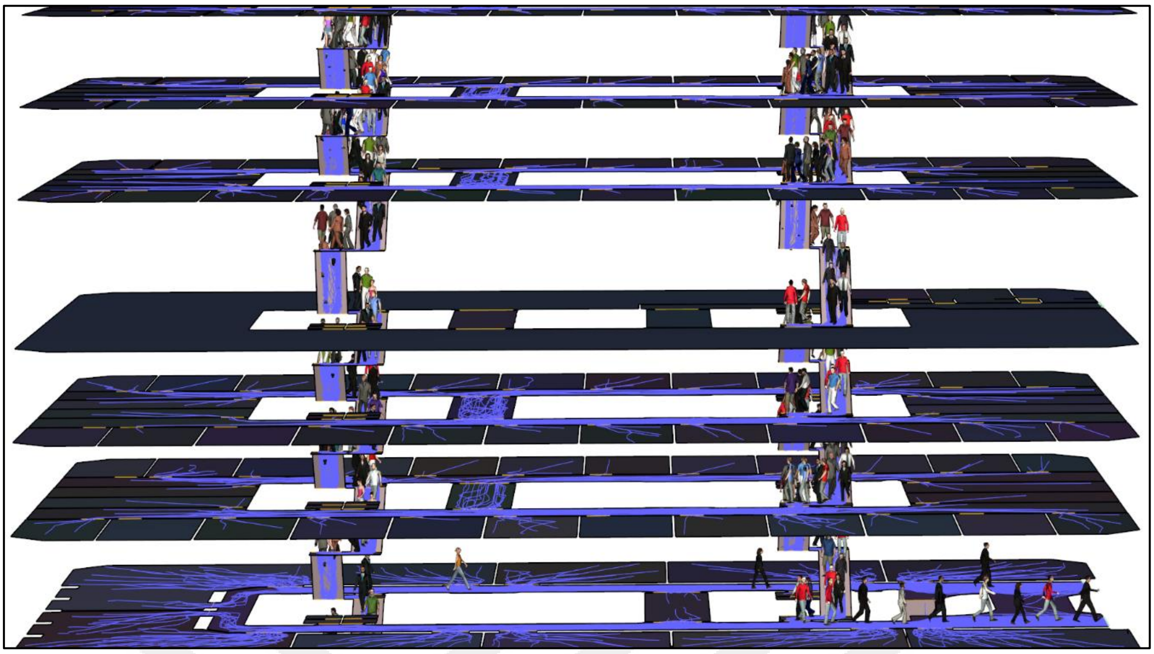

Figure 4.10. All occupants of Mersin Metropol are in safe area in 24. minute

4.2. Elevator Evacuation Simulation for Two Cases (Scenario 5 (%100E))

Scenario 5, which is the scenario where all occupants use only the elevator, is analyzed in this section. In this scenario, stairs are not used in both buildings, the building is only evacuated by elevators. The graph showing the results of scenario 5 (number of people in the building/evacuation time) is given below.

Unlike Scenario 1, fluctuations are seen in the graph below. These fluctuations occur as a result of individuals exiting the building from each elevator reaching the ground floor. Except for fluctuations, analyzes similar to Scenario 1 can be made. For both cases, during the first few minutes of the building evacuation, ground floor users evacuated the building easily and quickly. At this stage, an elbow point formed in both cases. It is observed that the evacuation speed slows down after the First Elbow Points and continues at the same speed for a long time. If Constant Area 1 lines are examined for both buildings, the evacuation speed of the buildings can be compared. The slope of these lines will give the rate of evacuation of buildings at this stage. When the slopes of the lines are compared, it is observed that the line of Mersin Metropolitan Building is slightly steeper.

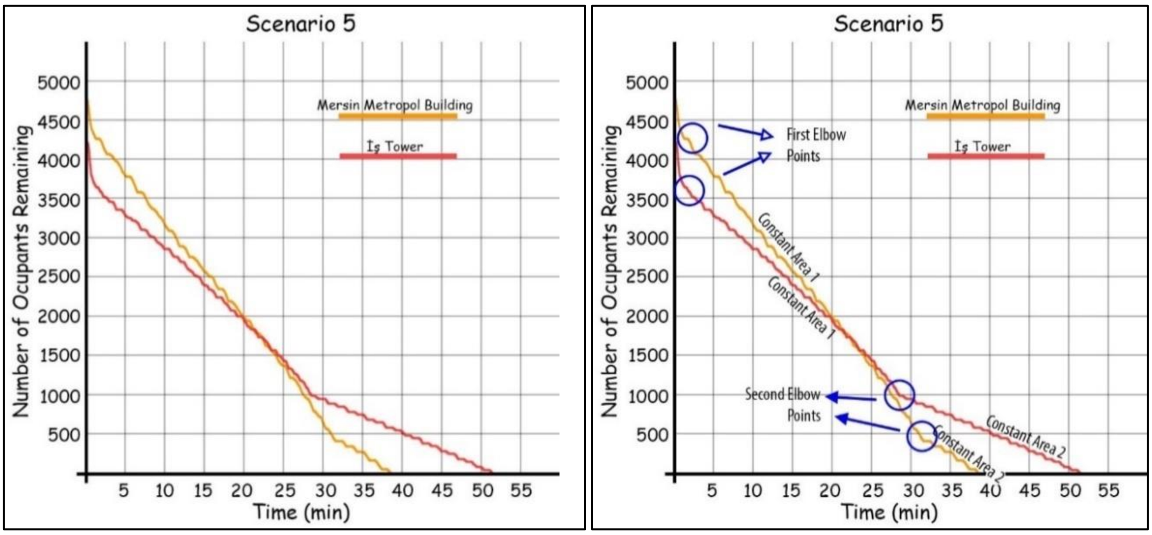

Figure 4.11. Simulation results of scenario 5

As can be seen in Figure 4.12, elevators in both buildings are separated for upper floors and lower floors. The reason why Constant Area 2 in İş Tower takes longer time is that the elevator distribution of Mersin Metropol Building is more efficient. Because, if the building floors are divided into two equal number of floors, the lower half will be evacuated quickly, while the upper part will take longer, since the Round Trip Time will take longer for upper floors. Since the elevators serving the upper half of the Mersin Metropol Building serve fewer floors than the elevators serving the lower half, a more effective evacuation has been achieved.

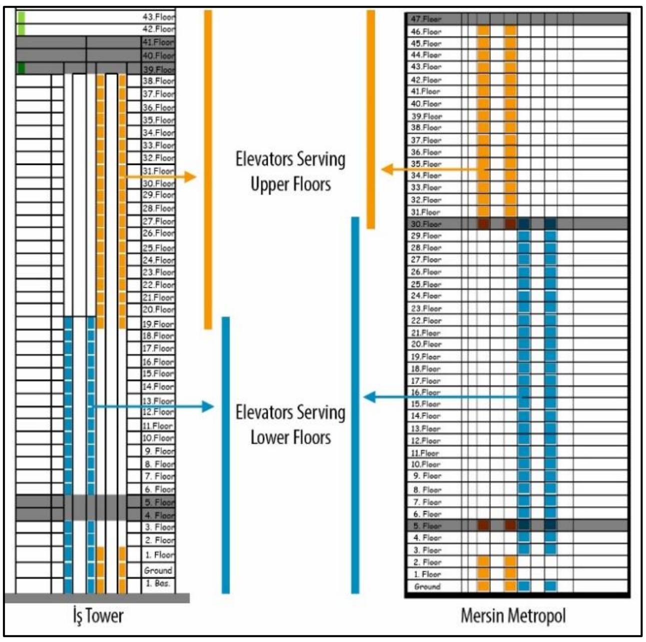

Figure 4.12. Elevator distribution for both buildings

4.3. Combined Stairwell and Elevator Evacuation Simulation for Two Cases (Scenarios 2 (%75S+%25E), 3(%50S+%50E), and 4(%25S+%75E))

In scenario 2, 75% of the building occupants on each floor use the stairs while the remaining 25% use the elevators to evacuate the building. In Scenario 2, the graph showing the simulation results (number of occupants remaining in the building/evacuation time) is given below. In order to better understand the graph, elbow points and constant areas between these points are shown on the right.

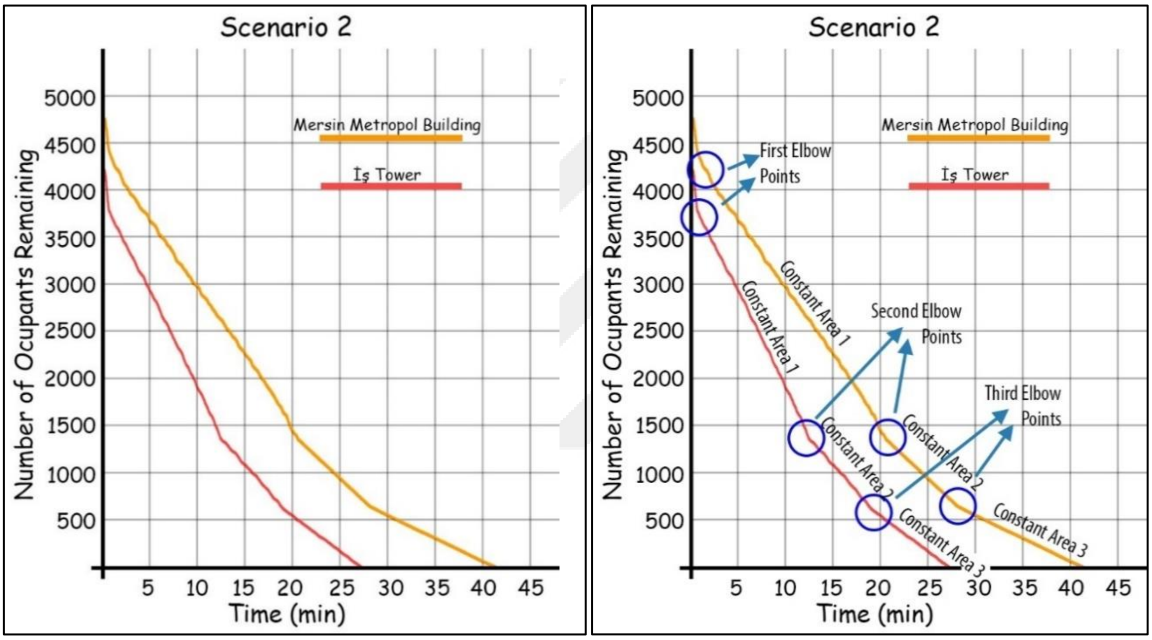

Figure 4.13. Simulation results of scenario 2

The first elbow point for both buildings is seen in the first 5 minutes when people on the ground floor evacuate the building quickly in the first few minutes. Afterwards, Constant Area 1 is observed up to the second elbow points. At the second elbow point of İş Tower, it is observed that the left staircase of the building is emptied and the elevator serving the lower floors of the building empties these floors. After this point, the evacuation of İş Tower is provided by the stairs on the right and the elevator serving the upper floors of the building. At the second elbow point of İş Tower, the elevator serving the upper floors of the building also completes the evacuation. Thus, only occupants using the right staircase remained in the building. The fact that the left staircase of the building empties quickly but the staircase on the right empties later, is related to the planning of the building. As can be seen in Figure 4.3, the last two floors of İş Tower are connected to the lower floors by only the right staircase. Occupants on these floors create more occupant load by using the stairs on the right. Also, in the upper half of the building, the right staircase is accessed by a wider corridor than that of the left staircase. Therefore, on these floors, the program canalize more people to the stair on the right. This crowd on the right stair, at the top of the building, is another factor affecting the late evacuation of the right stair.

When the simulation results of the Mersin Metropol Building are examined, it is seen that there are three Constant Areas and two Elbow Points in the evacuation of this building. At the second elbow point, it is seen that the elevators serving both the upper and lower floors of the building are emptied. After this point, only occupants using the stairs remained in the building. At the third elbow point, the stair on the right is emptied. From this point on, only those using the stairs on the left remained in the building. The reason behind this situation is that there is only one corridor on the nightclub floor, as can be seen in Figure 4.14. Thus, the occupants on the floor cannot be evenly distributed on the two stairs and there is a congestion on the left staircase.

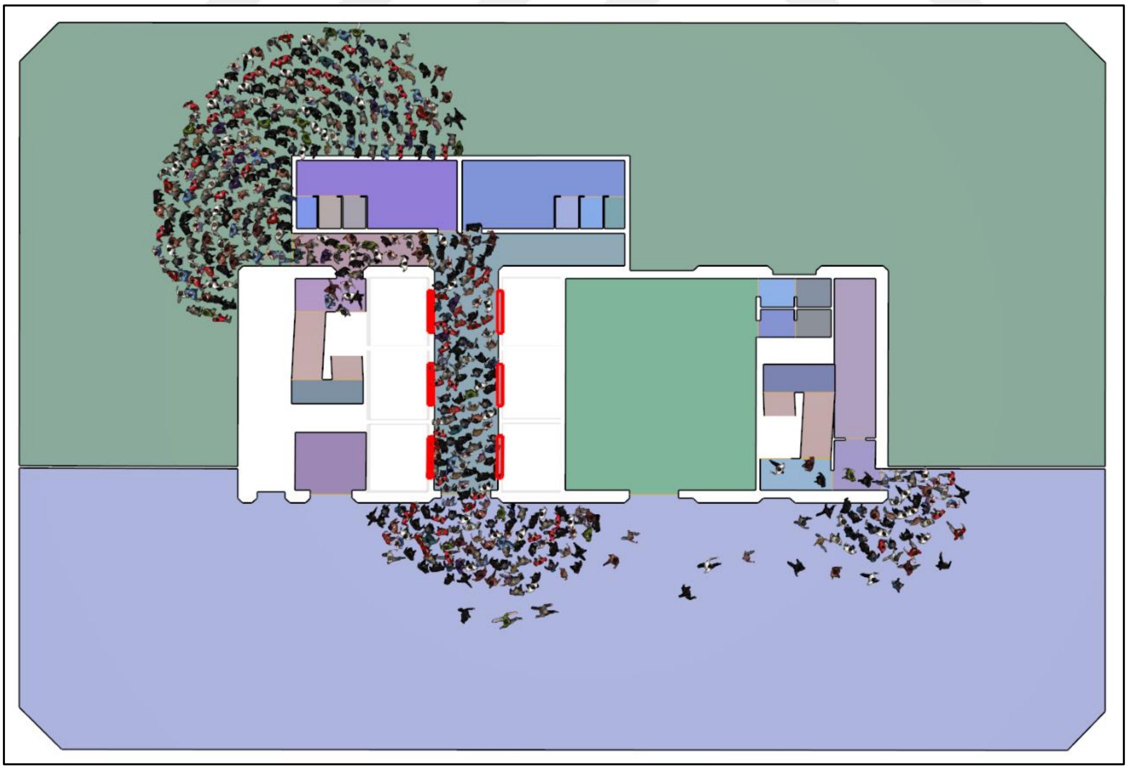

Figure 4.14. Occupants waiting elevators blocking the hall in Mersin Metropol Building (night club floor-scenario 2)

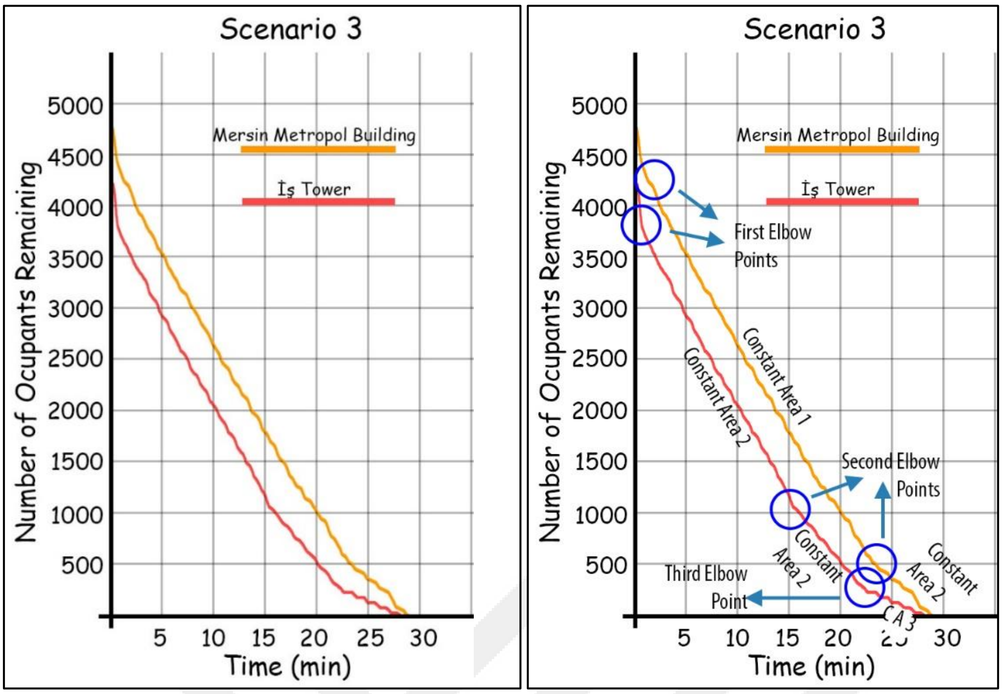

Figure 4.15. Simulation results of scenario 3

The graph showing the simulation results for scenario 3 is given above. When the graph is examined, it is seen that there are two elbow points in Mersin Metropol Building and three in İş Tower. As mentioned earlier, the first elbow points for both buildings is seen in the first 5 minutes when people on the ground floor evacuate the building quickly in the first few minutes. On the second elbow point of İş Tower, the stairs on the left and the elevator serving the lower floors of the building are emptied. At the third elbow point, the stair on the right is emptied. From this point on, only the occupants using the elevators serving the upper floors of the building remained in the building. When the results of Mersin Metropol Building are examined, it is seen that, at the second elbow point, the stairs on the right and the elevators serving the lower floors of the building are emptied. From this point on, the building evacuation continues only via the stairs on the left and the elevators serving the upper floors of the building. The reason why the left stair empties later is the planning of the nightclub floor, as discussed in Scenario 2. As a result, the evacuation time of İş Tower is 28 minutes and that of Mersin Metropol Building is 29 minutes.

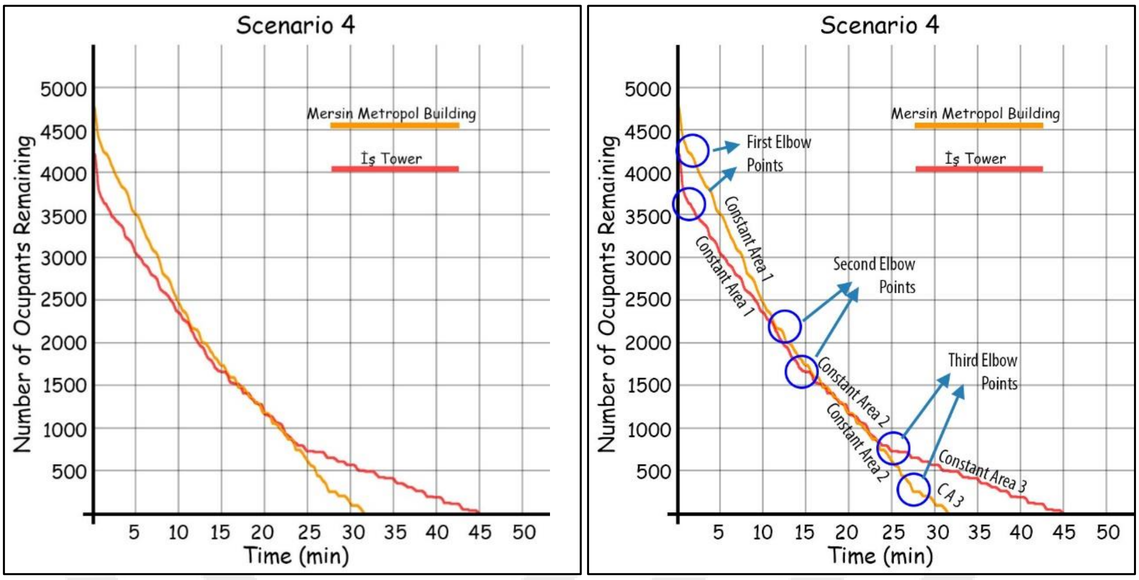

Figure 4.16. Simulation results of scenario 3

In Scenario 4, the occupants of both buildings evacuated the building by 25% using the stairs and the remaining 75% using the elevator, to be divided separately on each floor. When the graph showing the simulation results of scenario 4 above is examined, three elbow points and three constant areas are seen in the evacuation of both buildings. At the second elbow point of İş Tower, it is observed that both stairs of the building are emptied. After this point, only occupants using the elevator remained in the building. At the third elbow point, it is seen that the elevators serving the lower floors are emptied. From this point on, only people using the elevators serving the upper floors remained in the building. If the results of Mersin Metropol Building are examined, it is seen that both stairs of the building are emptied at the second elbow point. After this point, the evacuation of the building continues only through the elevators. At the third elbow point, it is observed that the elevators serving the lower floors of the building are emptied. After this point, the evacuation continues only with the elevators serving the upper floors of the building. In scenario 4, it is observed that the evacuation of the stairs ends faster than the elevators in both buildings.

Although definitions of high-rise buildings vary between countries and standards, definitions are generally concentrated around 20-30 meters limit. As the height of the building increases, the evacuation of the building becomes more difficult. With the increasing number of floors, the fatigue effect occurs. In addition, it is difficult for the elderly, disabled, sick, pregnant and children to descend from high floors by stairs. The use of elevators as a solution to this problem has been discussed for many years. Today, the use of elevators is recommended by many experts and standards and the evacuation plans of the world's important high-rise buildings are planned to include the elevator. One of the suggested methods on the use of elevators in the evacuation of high-rise buildings is the use of refuge floors. Refuge floors are recommended to be located approximately every 10-15 floors in the building and these floors can be arranged together with mechanical floors. This value is determined as a result of studies on how many floors can people get tired after descending. Some countries (e.g., China) have issued detailed regulations and restrictions on refuge floors in high-rise buildings. There is no such regulation in Turkey and there is no refuge floors in İş Tower and Mersin Metropol Building. In Figure 4.17, mechanical floors of the two case buildings is shown in red.

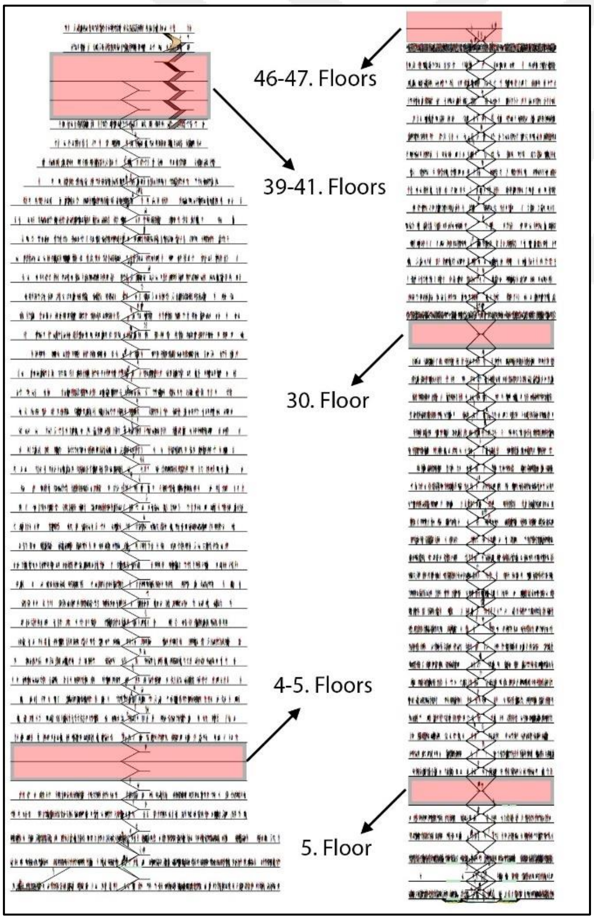

Figure 4.17. Mechanical floors (İş Tower and Mersin Metropol Building respectively)

The refuge floor should divide the building into approximately equal floors for the most useful design. For a 45-storey building, the most appropriate refuge floor design might be the 15th and 30th floors. Thus, people above the 30th floor can first descend to the 30th floor, rest in the safe area here, and continue to descend to the next refuge floor. However, as can be seen in Figure 4.17, the mechanical floors of the two case buildings were not designed in this way. As can be seen in the figure, mechanical floors of İş Tower are placed into the top and bottom of the building. As such, mechanical floors of the building are not suitable for use as refuge floors. The mechanical floors of the Mersin Metropol Building are more suitable for use as a refuge floors than the mechanical floors of the İş Tower. However, when descending from the refuge floor on the 30th floor to the 5th floor, a distance of 25 floors will be extremely tiring for people.

The architectural plan of the building is highly effective in evacuation efficiency. The plan scheme of the building should facilitate access, especially to the evacuation components like stairs, elevators, or refuge floors. As mentioned in section 3.1, one of the corridors leading to 2 stairs in İş Tower is quite narrow compared to the other. This situation prevents the use of capacity in the other stair. Thus, effective evacuation cannot be achieved. In İş Tower, the width of the corridor appears as an element that limits and restricts the use of stairs. However, in terms of the width of the stairs, İş Tower has a more positive plan compared to the Mersin Metropol Building. In addition, the stair landings in İş Tower are wider than in the other building. Thus, the handling capacity of the stairs is bigger than the Mersin Metropol Building's stairs.

One of the situations observed during the simulation studies is that the occupants of stairs and elevators blocking each other. This situation causes the people who are directed to the elevator or the stairs to be unable to go to the direction they want due to insufficient corridor width or the lack of alternative ways, thus delaying the evacuation. In particular, the elevator lobby appears to be a limiting element in this regard. When elevator lobbies with opposing elevators are designed as a corridor at the same time, people waiting for elevators block this corridor. In order to prevent this situation, elevator and stair lobbies should be designed in separate places and in such a way that they do not interfere with each other.

In high-rise buildings, the building is usually divided into certain parts and these parts are served by separate elevators. Thus, it is aimed to ensure more effective use of elevators. However, while the building is being divided, the load of the occupants using the elevators should also be considered. As can be seen in Figure 4.12, İş Tower is divided into two almost equal parts. In Mersin Metropolitan Building, on the other hand, while the upper part consists of fewer floors, the lower part includes more floors. In this case, it should not be neglected that the Round Trip Time of elevators serving the upper floors will be longer. In other words, in a building that is divided into two equal parts, the elevators serving the lower part will empty faster and effective evacuation cannot be achieved.

Distribution of building occupants to building floors has an important role in the evacuation of high-rise buildings. Floors with high occupant load should be planned as close to the ground floor as possible. Thus, these floors can be evacuated easily. This situation can be seen in the nightclub and sauna floors of Mersin Metropol Building. The building has a homogeneous distribution of occupants, except for two floors. Nightclub and sauna (Turkish bath, fitness centers) floors have a very high occupant load compared to other floors. The sauna is on the 31^{st} floor and the nightclub is on the 46^{th} floor. It is a very dangerous situation to have the place with the highest occupant load on the top floor of a high-rise building. From this point of view, İş Tower has a better design in terms of evacuation since it has a more homogeneous occupant distribution between floors.

The homogeneous occupant load distribution between floors in the building also allows building occupants to enter the safe area (stairwells) as soon as possible. While in İş Tower, all occupants can enter the staircase in 8 minutes, in the Mersin Metropolitan Building, they can barely enter in 24 minutes. Because the nightclub on the last floor has a very high occupant load and it takes a lot more for occupants to enter the stairwells.

In sections 3.1.4 and 3.2.4, the occupant load of İş Tower and Mersin Metropol Buildings has been calculated. As a result of the calculation, the occupant load of İş Tower was calculated as 4223 people according to NFPA and 5900 people according to Turkey's Regulation on Fire Protection. The occupant load of Mersin Metropol Building was calculated as 4752 people according to NFPA and 5533 people according to Turkey's Regulation on Fire Protection. Simulations are conducted based on NFPA occupant load factor. Even in this state, it is observed that the buildings are overloaded. It is out of the question that these buildings are actually loaded that much. But Turkey's Regulation on Fire Protection has taken this even further. Turkey's Regulation on Fire Protection requires calculations for occupant load even more than the widely accepted NFPA requirements, which is a controversial issue.

5. CONCLUSION

This thesis aimed to analyze the use of elevators in the normal evacuation of high-rise buildings. Normal evacuation analysis focus on measuring the evacuation efficiency of the building by excluding the emergency conditions and panic environment. In this context, analysis were carried out on two selected case buildings (İş Tower and Mersin Metropol Building). The fact that the building parameters, number of floors, the number of elevators and stairs, were being similar was effective in the selection of two buildings. The occupant loads of the buildings are defined according to the NFPA occupant load factor. Simulation method was used in the thesis and simulations were carried out with Pathfinder program, which is widely used in the literature. The evacuation efficiency of the two selected buildings was analyzed over the evacuation components.

In order to observe the effect of the elevator on the evacuation of the buildings, 5 scenarios were created for both case buildings. In these scenarios, Scenario 1 aims to analyze the complete use of stairs in the building, and Scenario 5 aims to analyze the use of elevators only. The remaining three scenarios (Scenario 2, 3 and 4) analyze the use of elevators and stairs by building occupants in 25% increments. The aim here was to analyze in which fraction of preassigned quartiles of building occupants should use elevators for the most effective evacuation. In addition, it was aimed to analyze which criteria should be considered in the design of high-rise buildings in order to shorten the evacuation times. At the end of the analysis, following research answers are obtained.

- RA 1: To reach the most effective evacuation (in preassigned quartiles of the building occupants), 25% of the occupants of İş Tower and 50% of the occupants of Mersin Metropol Building should use the elevators. Remaining occupants should use the stairs. In other words, for İş Tower, one quarter of each floor’s occupants using the elevator provide the most effective evacuation. Which of these fractions provides the fastest evacuation depends on the building's stair and elevator efficiency. While stairs work as a more efficient evacuation component in İş Tower, elevators work more efficiently in Mersin Metropol Building. In this case, the scenario in which the stairs are heavily used in İş Tower (Scenario 2 (75% stairs-25% elevator)-27 minutes) provided the fastest evacuation among 5 scenarios. For Mersin Metropol Building, the scenario where elevators are used more than in İş Tower (Scenario 3 (50% stairs-50% elevator)-29 minutes) provided the most efficient evacuation among 5 scenarios.

- RA 2: If the use of stairs and elevators is compared with the use of stairs only, it is observed that the evacuation time of the İş Tower is shortened by approximately 18% and the evacuation time of the Mersin Metropol Building is shortened by approximately 40%. When using only stairs, the evacuation time of İş Tower was 33 minutes. When 25% of the occupants on each floor were evacuated by elevator and the rest by stairs, the building was evacuated in 27 minutes. When using only stairs, the evacuation time of Mersin Metropol Building was 49 minutes. The building was evacuated in 29 minutes when 50% of the occupants of each floor were evacuated by elevator and the rest used stairs. The reason for the significant reduction in the evacuation time with the combined use of elevators and stairs in Mersin Metropol Building, compared to the scenario where only the stairs are used, is that the elevators work more efficiently than the stairs. This is due to the narrow stairways of the building and the fact that the elevator lobbies are designed separately from the corridors. Thus, people using elevators were not affected by people passing through the corridors. In addition to, elevators can operate more effectively. However, in İş Tower, the elevator lobby is located in the corridor and people passing through the corridor prevent the effective use of the elevators.
- RA 3: Design factors affecting evacuation time are, stair width, corridor width, width of elevator lobby, distribution of elevators to the floors, distribution of occupant load to the floors and the use of elevator lobbies as corridors. The effective use of the evacuation components of the building is important to achieve the most effective evacuation. If one of the stairs in the building is emptied first and the other is emptied later, one of the stairs cannot be used effectively. This situation was observed in both İş Tower and Mersin Metropol Building. This situation has been observed in all scenarios where the stairs were used as a means of egress in İş Tower. The left stair was emptied faster than the right stair. This is because, people on the highest two floors of the building can only use the stairs on the right. Thus, the occupant load of this stair increases. Another reason is that the corridor leading to the right staircase is wider than the corridor leading to the left staircase. Thus, more people can reach the right staircase and a more crowded environment is created on this stair. In this case, the stair on the right was emptied later than the stair on the left. In Mersin Metropol Building, the occupant load of the stairs on the left is greater than the one on the right. This is because

the elevator lobby is used as a corridor in the nightclub on the last floor of the building. The people on this floor are not evenly distributed between the right and left stairs. Because the elevator lobby is the only passage between two stairs and people waiting for the elevator block the elevator lobby and prevent the transition of people who want to reach the stairs. So, separate design of stair and elevator lobbies is vital for effective evacuation.

The key factor affecting this shortened evacuation time is the building plan scheme. Stair and landing widths have an important role in determining the handling capacity of the stairs and enabling people to enter to the safe area as soon as possible. Also, the width of the corridors providing access to the stairs should not be designed in a way that limit the use of stairs.

Occupant load is another significant factor in terms of evacuation. Places with high occupant load should be planned on the lower floors of the building as much as possible. Thus, it can be ensured that the high occupant load is evacuated as soon as possible. Planning the nightclub, which is the place with the highest occupant load in the Mersin Metropol Building, on the last floor of the building, makes the evacuation of the building to take longer. In İş Tower, where a more homogeneous distribution of occupant load between floors is achieved, it is possible to enter to the safe area in a shorter time compared to Mersin Metropol Building.

High-rise buildings are usually divided into 2-3 vertical sections and the elevators of these sections are planned separately. This is important for the elevators to work more effectively. In order to achieve the most effective evacuation, which floors the elevators will serve should be planned carefully. However, in the planning of these sections, the occupant load of the floors and the Round Trip Time of the elevators should be considered. İş Tower is divided into two almost equal parts and elevators serving the lower and upper floors are separated. Mersin Metropol Building, on the other hand, is divided into 2 parts as approximately 1/3 (upper part - hotel section) and 2/3 of the building (lower part - office section). In İş Tower, the elevator serving the lower section emptied those floor before the elevators serving the upper section in all scenarios that elevators are used as a means of egress. A more proportional distribution is observed in Mersin Metropol Building. This is because when the building is divided into two equal parts, although the number of people that must be evacuated at the top and bottom is approximately the same, the elevators at the top have more distance to travel. Thus, the evacuation at the top is completed later. Consequently, the RTT of the elevators should also be taken into account when separating the elevators for the upper and lower sections.

Compliance with the design criteria mentioned in the planning of high-rise buildings will ensure effective evacuation of the building. In order to provide effective evacuation, both stairs and elevators of the building should serve with maximum efficiency. For this reason, the evacuation efficiency of the building will be at the highest level in a scenario which all the stairs and elevators working with maximum capacity until the end of the evacuation and they are all emptied at the same time. Achieving this situation will be possible by designing the above-mentioned design criteria.

5.1. Limitations of the Study

Limitations of the thesis are handled in this section. Modeling related and software related limitations can be named.

- The two case building were modeled according to the plans accessed on the internet. These plans were publicly available and scanned versions of original plans. The buildings may not have been built according to the plans or they may have been modified later. Both buildings are part of a complex. While modeling the buildings, only the tower parts were included in the study, and the rest of the complex was excluded. In addition, the basement floors of the buildings are also excluded. While defining the building occupants, parameters such as gender, age, health status were excluded from the study. In addition, pre-evacuation time and human behavior are also excluded from the study.

- The simulation studies carried out within the scope of the thesis were carried out through the Pathfinder program. Since the program is a package program, it has embedded assumptions. These assumptions are likely to affect the results.

5.2. Future Research

The data sets on elevators are far behind compared to the use of stairs. Human behavior in the use of elevators in an emergency needs to be researched further. Development of emergency modes for elevators to be used during evacuation is required. These modes may use a faster velocity by ignoring comfort conditions to the acceptable limit and purpose to evacuate the building faster. Experiments on the use of elevators and validations for evacuation elevators also need to be researched deeper.

REFERENCES

1. Özgen, A., Sev, A. (2000). *Çok Katlı Yüksek Yapılarda Taşıyıcı Sistemler*, İstanbul: Birsen Yayınevi Ltd. Şti., 1-45.

2. Internet: Monadnock Building. URL: https://en.wikipedia.org/wiki/Monadnock_Building, Access Date: 10.11.2020.

3. Chew, Y.L.M. (2003). *Construction Technology for Tall Buildings*. (2. Edition). Singapore, New Jersey, London, Hong Kong: Singapore University Press, World Scientific Publishing Co. Pte. Ltd., 1-20.

4. Internet: Building Foundations Fail, 1870s-1900: Technology That Changed Chicago. URL: https://www.chipublib.org/blogs/post/technology-that-changed-chicago-building-foundations-fail-1870s-1900/, Access Date: 10.11.2020.

5. Internet: Reliance Building. URL: https://en.wikipedia.org/wiki/Reliance_Building, Access Date: 18.03.2021.

6. Internet: Prudential (Guaranty) Building. URL: https://en.wikipedia.org/wiki/Prudential_(Guaranty)_Building, Access Date: 18.03.2021.

7. Internet: How elevators transformed NYC's social landscape. URL: https://nypost.com/2014/02/08/how-elevators-transformed-nycs-social-landscape/, Access Date: 10.11.2020.

8. Internet: History of Measuring Tall Buildings. URL: https://www.ctbuh.org/history/history-of-measuring-tall-buildings, Access Date 10.11.2020.

9. Internet: Home Insurance Building. URL: https://en.wikipedia.org/wiki/Home_Insurance_Building, Access Date: 18.03.2021.

10. Internet: Second Leiter Building. URL: https://en.wikipedia.org/wiki/Second_Leiter_Building, Access Date: 18.03.2021.

11. Internet: Joseph Aspdin. URL: https://en.wikipedia.org/wiki/Joseph_Aspdin, Access Date: 10.11.2020.

12. Internet: Joseph Monier. URL: https://en.wikipedia.org/wiki/Joseph_Monier, Access Date: 10.11.2020.

13. Hassanain, M.A. (2009). On the challenges of evacuation and rescue operations in high-rise buildings, *Structural Survey*, 27(2), 109-118.

14. Internet: Woolworth Building. URL: https://en.wikipedia.org/wiki/Woolworth_Building, Access Date: 23.11.2020.

15. Internet: Chrysler Building. URL: https://en.wikipedia.org/wiki/Chrysler_Building, Access Date: 23.11.2020.

16. Internet: Empire State Building. URL: https://en.wikipedia.org/wiki/Empire_State_Building, Access Date: 23.11.2020.

17. Internet: Highpoint I. URL: https://en.wikipedia.org/wiki/Highpoint_I, Access Date: 23.11.2020.

18. Internet: Lake Shore Drive Apartments. URL: https://en.wikipedia.org/wiki/860–880_Lake_Shore_Drive_Apartments, Access Date: 23.11.2020.

19. Internet: Marina City. URL: https://en.wikipedia.org/wiki/Marina_City, Access Date: 23.11.2020.

20. Internet: World Trade Center. URL: https://en.wikipedia.org/wiki/World_Trade_Center_(1973–2001), Access Date: 24.11.2020.

21. Internet: Willis Kulesi. URL: https://tr.wikipedia.org/wiki/Willis_Kulesi, Access Date: 18.03.2021.

22. Internet: CTBUH Height Criteria for Measuring & Defining Tall Buildings. URL: https://cloud.ctbuh.org/CTBUH_HeightCriteria.pdf, Access Date: 16.03.2021.

23. Internet: Tallest Buildings. URL: https://www.skyscrapercenter.com/buildings?list=tallest100-construction, Access Date: 16.03.2021.

24. Internet: Tallest Buildings. URL: https://www.skyscrapercenter.com/buildings?list=tallest100-proposed, Access Date: 16.03.2021.

25. Marriage, G. (2020). *Tall - The Design and Construction of High-rise Architecture*. New York: Routledge, 1-110.

26. Gerges, M., Mayouf, M., Rumley, P. and Moore, D. (2017). Human behaviour under fire situations in high-rise residential building. *International Journal of Building Pathology and Adaptation*, 35(1), 90-106.

27. National Fire Protection Association. (2018). *NFPA 101 - Life Safety Code*, U.S.A.

28. International Code Council. (2018). *International Building Code*.

29. Chen, J.J., Wang, X.G., Fang, Z. (2016). Collaborative Evacuation Strategy of Ultra-tall Towers among Stairs and Elevators. *Procedia Engineering*. 135, 170–174.

30. National Standard of People's Republic of China. (2014). *Code for Fire Protection Design of Buildings*, China.

31. Council of Standards Australia. (2017). *Automatic fire sprinkler systems, Part 1: General systems*, Australia.

32. Bureau of Indian Standards. (2016). *National Building Code of India - Part 4 Fire and Life Safety*, India.

33. Fire Services Department. (2012). *Codes of Practice for Minimum Fire Service Installations and Equipment and Inspection, Testing and Maintenance of Installations and Equipment*, Hong Kong.

34. Internet: Planlı Alanlar İmar Yönetmeliği. URL: https://www.mevzuat.gov.tr/mevzuat?MevzuatNo=23722&MevzuatTur=7&MevzuatTertip=5, Access Date: 08.03.2021.

35. Bouwbesluit, Netherland, (2012).

36. Architectural Institute of Japan. (2012). *Preliminary Reconnaissance Report of the 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake*. Tokyo: Springer, 1-460.

37. Code of Practice for Fire Precautions in Buildings. (2018). Singapore.

38. Internet: Emporis. URL: https://www.emporis.com/building/standard/3/high-rise-building, Access Date 17.03.2021.

39. Internet: Turkey's Regulation On Fire Protection. URL: https://www.resmigazete.gov.tr/eskiler/2007/12/20071219-2.htm. Access Date: 08.03.2021.

40. Internet: Türkiye Bina Deprem Yönetmeliği. URL:. https://www.resmigazete.gov.tr/eskiler/2018/03/20180318M1-2.htm, Access Date: 08.03.2021.

41. Internet: Elevator. URL: https://dictionary.cambridge.org/dictionary/english/elevator, Access Date: 07.01.2021.

42. Bernard, A. (2014). *Lifted - A Cultural History of the Elevator*, New York: University Press, 1-10.

43. Internet: Elevator. URL: https://en.wikipedia.org/wiki/Elevator, Access Date: 08.01.2021.

44. Internet: How A Historic Strike Paved the Way for the Automated Elevator and What Those Lessons Could Mean for Self-Driving Cars. URL: https://henrylgreenidge.medium.com/how-a-historic-strike-paved-the-way-for-the-automated-elevator-and-what-those-lessons-could-mean-a0ae49993796, Access Date: 08.01.2021.

45. Barley, G., Al-Sharif, L. (2016). *Elevator Traffic Handbook Theory and Practice*, (Second Edition), Routledge: London, 1-20.

46. Bangash, M.Y.H., Bangash, T. (2007). *Lifts, Elevators, Escalators and Moving Walkways/Travelators*, London: Taylor & Francis, 1-10.

47. Internet: Pneumatic Vs Hydraulic Elevators for Homes. URL: https://homeelevatorofhouston.com/pneumatic-vs-hydraulic-elevators-homes/, Access Date: 07.01.2021.

48. Internet: A Brief Comparison Between Pneumatic Vs Hydraulic Elevators. URL: http://www.household-decoration.com/hydraulic-elevators/, Access Date: 07.01.2021.

49. Internet: How Fast Should an Elevator Go?. URL: https://www.treehugger.com/how-fast-should-elevator-go-4858555, Access Date: 08.03.2021.

50. Internet: Mitsubishi Electric Design Reference for Elevator Installations. UEL: https://www.mitsubishielectric.com/elevator/products/basic/elevators/nexway_europe/pdf/desig_reference.pdf, Access Date: 03.08.2021.

51. CIBSE. (2010). *Transportation Systems in Buildings*, (4. Edition), Norwich.

52. Alginahi, Y., Mudassar, M., Kabir, M.N., Tayan, O. (2019). Analyzing the Crowd Evacuation Pattern of a Large Densely Populated Building, *Arabian Journal for Science and Engineering*. 44 3289–3304.

53. Kinsey, M., Gwynne, S., Kuligowski, E., Kinateder, M. (2018). Cognitive Biases Within Decision Making During Fire Evacuations, *Fire Technology*. 55(3), 1-18.

54. Kinateder, M.T., Kuligowski, E.D., Reneke, P.A., Peacock, R.D. (2014). *A Review of Risk Perception in Building Fire Evacuation*, National Institute of Standards and Technology. 1-42.

55. Proulx, G. (2007). High-Rise Office Egress: the Human Factors. *Symposium on High-Rise Building Egress Stairs*. National Research Council Canada, New York, 1-5.

56. Huo, F. Song, W. Chen, L. Liu, C. Liew, K.M., (2016). Experimental study on characteristics of pedestrian evacuation on stairs in a high-rise building, *Safety Science*. 86 165–173.

57. Kobes, M., Post, J., Helsloot, I., Vries, B. De. (2008) Fire risk of high-rise buildings based on human behavior in fires, Conference Proceedings FSHB, 1-11.

58. Gershon, R.R.M., Qureshi, K.A., Rubin, M.S., Raveis, V.H., (2007). Factors associated with high-rise evacuation: Qualitative results from the world trade center evacuation study, *Prehospital and Disaster Medicine*. 22(3),165-73.

59. Lin P., Ma J., Liu T., Ran T., Si Y., Li T., (2016). An experimental study of the “faster-is-slower” effect using mice under panic, Physica A: Statistical Mechanics and its Applications. 452, 157–166.

60. Sun Y., (2013). *Egress as Part of Fire Safety in High-rise Buildings*, Undergraduate Thesis, Delft University of Technology. Delft.

61. Fang Z.-M., Song W.-G., Li Z.-J., Tian W., Lv W., Ma J., X. Xiao. (2012). Experimental study on evacuation process in a stairwell of a high-rise building, *Building and Environment*. 47, 316–321.

62. Zhai L., (2019). *The Comparison of Total and Phased Evacuation Strategies for a High-rise Office Building*, Master of Science Thesis. University of Maryland.

63. Ronchi E., Nilsson D., (2013). Fire evacuation in high-rise buildings: a review of human behaviour and modelling research, *Fire Science Reviews*. 2(7), 1-21

64. Peacock, R. D., Hoskins, B. L., & Kuligowski, E. D. (2012). Overall and local movement speeds during fire drill evacuations in buildings up to 31 stories. *Safety Science*, 50(8), 1655–1664.

65. E. Ronchi, D. Nilsson, (2013). *Assessment of Total Evacuation Systems for Tall Buildings*, New York: Springer. 1-51.

66. Ma, J., Song, W. G., Tian, W., Lo, S. M., & Liao, G. X. (2012). Experimental study on an ultra high-rise building evacuation in China. *Safety Science,* 50(8), 1665–1674.

67. Huang, L., Chen, T., & Yuan, H. (2014). Simulation Study of Evacuation in High-rise Buildings. *Transportation Research Procedia*, 2, 518–523.

68. Haitao, C., Leilei, L., & Jiuzi, Q. (2012). Accident Cause Analysis and Evacuation Countermeasures on the High-Rise Building Fires. *Procedia Engineering*, 43, 23–27.

69. P.A. Reneke, R.D. Peacock, B.L. Hoskins. (2013). *Combined Stairwell and Elevator Use During Building Evacuation*. New York: CreateSpace Independent Publishing Platform. 1-50.

70. Nakahama, S., Ebihara, M., Sekizawa, A., Ikehata, Y., & Notake, H. (2005). An Examination of Feasibility Of Elevator Evacuation Based On Risk Assessment. *Fire Safety Science*, 8, 611–622..

71. Ding, N., Chen, T., Zhu, Y., & Lu, Y. (2021, January 1). State-of-the-art high-rise building emergency evacuation behavior. *Physica A: Statistical Mechanics and Its Applications*, 561, 125168. 1-20.

72. Ma, J., Lo, S. M., & Song, W. G. (2012). Cellular automaton modeling approach for optimum ultra high-rise building evacuation design. *Fire Safety Journal*, 54, 57–66.

73. Soltanzadeh, A., Alaghmandan, M., & Soltanzadeh, H. (2018). Performance evaluation of refuge floors in combination with egress components in high-rise buildings. *Journal of Building Engineering*, 19, 519–529.

74. E.D. Kuligowski, R.D. Peacock, B.L. Hoskins. (2019). *A Review of Building Evacuation Models*, (2. Edition), National Institute of Standarts and Technology.

75. Hurley, M. J., Gottuk, D. T., Hall, J. R., Harada, K., Kuligowski, E. D., Puchovsky, M., … WIECZOREK, C. J. (2015). SFPE Handbook of Fire Protection Engineering, New York. Springer.

76. C. M Y Ng, W. K Chow, (2006). A brief review on the time line concept in evacuation, *International Journal on Architectural Science*. 7(1), 1-13.

77. Galea, E. R., Sharp, G., Lawrence, P., & Holden, R. (2008). Approximating the Evacuation of the World Trade Center North Tower using Computer Simulation. *Journal of Fire Protection Engineering*. 18, 85–115.

78. Zhang, B., Xu, Z. S., Zhao, Q. W., & Liu, Y. Y. (2014). A study on theoretical calculation method of subway safety evacuation. *Procedia Engineering*, 71, 597–604.

79. Lovreglio, R., Kuligowski, E., Gwynne, S., & Boyce, K. (2019). A pre-evacuation database for use in egress simulations. *Fire Safety Journal*, 105, 107–128.

80. McConnell, N. C., Boyce, K. E., Shields, J., Galea, E. R., Day, R. C., & Hulse, L. M. (2010). The UK 9/11 evacuation study: Analysis of survivors' recognition and response phase in WTC1. *Fire Safety Journal*, 45(1), 21–34.

81. British Standards Institute. (2019). *BS PD 7974-6*, United Kingdom.

82. Van de Leur P., (2005). Building Evacuation, Rules and Reality, *Heron*. 50, 237–246.

83. Oven, V. A., & Cakici, N. (2009). Modelling the evacuation of a high-rise office building in Istanbul. *Fire Safety Journal*, 44(1), 1–15.

84. Proulx, G. (1995). Evacuation time and movement in apartment buildings. *Fire Safety Journal*, 24(3), 229–246.

85. Wang, S.H., Wang, W.C., Wang, K.C., & Shih, S.-Y. (2015). Applying building information modeling to support fire safety management. *Automation in Construction*, 59, 158–167.

86. Sujatmiko, W., Dipojono, H. K., Soelami, F. X. N., & Soegijanto. (2014). Performance-based Fire Safety Evacuation in High-rise Building Flats in Indonesia – A Case Study in Bandung. *Procedia Environmental Sciences*, 20, 116–125.

87. Lovreglio, R. (2018). *A Review of Augmented Reality Applications for Building Evacuation*. 17th International Conference on Computing in Civil and Building Engineering. Tampere.

88. Sosnowski, M., & Pisarek, J. (2014). Comparative analysis of evacuation modelling using different numerical models. *Prace Naukowe Akademii*. 2, 383–390.

89. Internet: Egress Estimator Software. URL: https://www.nist.gov/el/fire-research-division-73300/safety-building-occupants-building-egress, Access Date: 03.08.2021.

90. Gwynne, S., Galea, E. R., Owen, M., Lawrence, P. J., & Filippidis, L. (1999). A review of the methodologies used in the computer simulation of evacuation from the built environment. *Building and Environment*, 34(6), 741–749.

91. Wu, G.-Y., & Huang, H.-C. (2015). Modeling the emergency evacuation of the high rise building based on the control volume model. *Safety Science*, 73, 62–72.

92. Ronchi, E., Kuligowski, E., Nilsson, D., Peacock, R., & Reneke, P. (2014). Assessing the Verification and Validation of Building Fire Evacuation Models. *Fire Technology*. 52, 197–219.

93. Xing, Z., & Tang, Y. (2012). Simulation of Fire and Evacuation in High-Rise Building. *Procedia Engineering*, 45, 705–709.

94. Zhong-an, J., Mei-ling, C., & Xiao-hua, W. (2011). Experiment and Simulation Study on High-rise Student Apartment Fire Personal Evacuation in the Campus. *Procedia Engineering*, 11, 156–161.

95. Kinateder, Max T., Omori, H., & Kuligowski, E. D. (2014). *The Use of Elevators for Evacuation in Fire Emergencies in International Buildings*. National Institute of Standards and Technology.1-50.

96. International Organization for Standardization. (2010). *ISO/TR 25743:2010, Lifts (elevators)-Study of the Use of Lifts for Evacuation During an Emergency*.

97. Kinsey, M., Galea, E. R., & Lawrence, P. (2012). Human Factors Associated with the Selection of Lifts/Elevators or Stairs in Emergency and Normal Usage Conditions. *Fire Technology*, 48, 3–26.

98. Haghani, M., & Sarvi, M. (2016). Human exit choice in crowded built environments: Investigating underlying behavioural differences between normal egress and emergency evacuations. *Fire Safety Journal*, 85, 1–9.

99. Siikonen, M.-L., Susi, T., & Hakonen, H. (2001). *Passenger Traffic Flow Simulation in Tall Buildings*. Kone.

100. Australian Building Codes Board.(2013). *Handbook: Lifts Used During Evacuation*.

101. Ding, Y., Yang, L., Weng, F., Fu, Z., & Rao, P. (2015). Investigation of combined stairs elevators evacuation strategies for high rise buildings based on simulation. *Simulation Modelling Practice and Theory*, 53, 60–73.

102. Chen, J., Ma, J., & Lo, S. M. (2017). Event-driven modeling of elevator assisted evacuation in ultra high-rise buildings. *Simulation Modelling Practice and Theory*, 74, 99–116.

103. Aleksandrov, M., Cheng, C., Rajabifard, A., & Kalantari, M. (2019). Modelling and finding optimal evacuation strategy for tall buildings. *Safety Science*, 115, 247–255.

104. Internet: Salt Research. URL: https://archives.saltresearch.org/, Access Date: 09.03.2021.

105. Internet: Thunderhead Engineering. URL: https://www.thunderheadeng.com/wp-content/uploads/downloads/2014/08/verification_validation.pdf.

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