ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

A DECISION SUPPORT MODEL FOR ELEVATOR SYSTEM DESIGN IN TALL BUILDINGS

M.Sc. THESIS

Ayşe ÇOLAKOĞLU

Department of Informatics

Architectural Design Computing Programme

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Ayşe ÇOLAKOĞLU
(523111019)

Department of Informatics

Architectural Design Computing Programme

Thesis Advisor: Prof. Dr. Gülen ÇAĞDAŞ
Thesis Co-advisor: Assoc. Prof. Dr. Georg SUTER

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Ayşe ÇOLAKOĞLU
(523111019)

Bilişim Anabilim Dalı

Mimari Tasarımda Bilişim Programı

Tez Danışmanı: Prof. Dr. Gülen ÇAĞDAŞ
Eş Danışman: Doç. Dr. Georg SUTER

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Ayşe Çolakoğlu, a **M.Sc.** student of ITU **Graduate School of Science Engineering and Technology** student ID 523111019, successfully defended the **thesis** entitled “ **A DECISION SUPPORT MODEL FOR ELEVATOR SYSTEM DESIGN IN TALL BUILDINGS**”, which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Prof. Dr. Gülen ÇAĞDAŞ** Istanbul Technical University	....
Co-advisor :	**Assoc. Prof. Dr. Georg SUTER** Vienna Technical University	....
Jury Members :	**Assoc. Prof. Dr. Hakan YAMAN** Istanbul Technical University	....
	Asst. Prof. Dr. Neşe ÇAKICI ALP Kocaeli University	....
	Asst. Prof. Dr. Sema ALAÇAM Istanbul Technical University	....

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FOREWORD

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Ayşe ÇOLAKOĞLU
Architect

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ABBREVIATIONS

ADA	**:** The American Disabilities Act
ADAAG	**:** Standards for Accessible Design - Accessibility Guidelines for Buildings and Facilities
ASHRE	**:** American Society of Heating and Ventilating Engineers
AR	**:** Arrival Rate
ASHRE	**:** American Society of Heating and Ventilating Engineers
ASME	**:** American Society of Mechanical Engineers
AWT	**:** Average Waiting Time
ATT	**:** Average Travel Time
CIBSE	**:** Chartered Institution of Building Services Engineers
CTBUH	**:** Council on Tall Buildings and Urban Habitat
EN	**:** European Standards
ESN	**:** Emporis Standards
IBC	**:** International Building Code
INT	**:** Interval
ISO	**:** International Organization for Standardization
HC	**:** Handling Capacity
MRL	**:** Machine Room-Less
NEC	**:** National Electric Code
NFPA	**:** National Fire Protection Association
RTT	**:** Round Trip Time

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A DECISION SUPPORT MODEL FOR ELEVATOR SYSTEM DESIGN IN TALL BUILDINGS

SUMMARY

Especially in the last few decades, by the construction of mega tall towers, elevator systems have become a major constraint of a tall building design since it is the most important part of a vertical transportation system in buildings. Vertical transportation systems can be described as a system that contains the design of all passenger and goods circulation facilities and devices in a building, such as elevators, escalators and stairs. The vertical transportation strategy has a fundamental impact on the design of any building. In design process, number of vertical transportation elements and their locations are the preliminary decisions to specify the circulation pattern of a building that needs to provide users a comfortable means of transportation.

The most important systems for vertical transportation in buildings are elevators. The goal in elevator system design is to move a specific number of passengers from the entrance floor to their destination floors with the minimum amount of waiting and travelling time, with minimum number of elevators by providing minimum core space, cost and using the smallest amount of energy. In other words, designers need to consider several factors affect the vertical circulation design to achieve an optimal elevator system solution. Yet, making decisions to achieve an optimal vertical transportation indicates an expert knowledge or research on existing buildings.

Principally, the design of an elevator system is based on traffic analysis, which identifies the traffic requirements, elevator traffic calculations and the efficiency of an elevator system as well as the traffic control method. Traffic analysis are generally used to analyze the traffic flow of an existing or designed elevator system. Various methods and different commercial software have been developed for analyzing the elevator traffic of a building. Fundamentally, each method are using standard traffic calculations. While conventional methods are using analytical equations, advanced methods combines the analytical equations with complex computer models of simulations. With few exceptions, most of them are developed to analyze initially designed elevator systems to check the efficiency according to traffic requirements. In addition, traffic calculations are using for determining the required number of elevators in a building, based on a principle that designer picks a relevant speed and car capacity of elevators. Without any experience or expert knowledge, the decision of picking a rated speed for elevators becomes arbitrary

The aim of this research is to establish a decision support model for elevator system design in tall buildings. The model named as a decision support model as it is conceptualized for giving support to architects in the planning and conceptual design stage of a tall building that helps designer to find optimum number of elevators, their speed and capacity without having any expert knowledge or experience. The proposed model is considered as part of a comprehensive system, which determines the optimum vertical transportation system for tall buildings including elevators, escalators and stairs. In this research, the elevator system, which is the major element of a vertical transportation, is examined. In the first chapter, the purpose and scope of the thesis is explained. In the second chapter, through the literature survey, elevator system design considerations are identified from the point of different profession's objectives, since it is assumed as a multi-objective procedure. In the third chapter, traffic analysis and design methods are introduced to identify the relation between analysis methods and elevator system design process. In the last chapter, the decisions support model for elevator system design in tall buildings, is introduced. The model implemented for office buildings under 40 stories and results are tested with an existing elevator simulator called Elevate. In conclusion part, all results are evaluated and suggestions for future works are considered for future development of the model.

The model only comprise passenger elevators so; goods elevators and fire-fighter lifts are out of scope. Analytical traffic analysis method is used in the model through the conventional up-peak traffic calculations. The parameters affect the elevator system design are provided from previous field studies through literature survey and elevator kinematics are provided by lift companies. The model is implemented for tall office buildings as the traffic analysis calculations are coded for up-peak traffic conditions which is the determinant traffic pattern of an office building's elevator system. If complex analytical equations were added in the model for other types of traffic patterns, the model could also be implemented for different building uses. The model has a height limit of 40-storeys, because tall building more than 40-storeys need special solutions like sky lobby system. The model is developed using Rhinoceros 4, Grasshopper add-on. The reason of using the Grasshopper for the implementation of the model is to supply a medium for geometric relations and queries for further developments. For instance, the distance from main entry to the elevator lobby, efficiency of elevator configuration, fire regulations could be added to the model. The results of the model are transferred directly to the spreadsheet using an add-on, which connects Grasshopper to MS Office Excel file. In addition, results are tested with an existing elevator traffic simulation software called Elevate.

Key words: Tall building, elevator, elevator system design, elevator traffic analysis.

YÜKSEK BİNALARDA ASANSÖR SİSTEMİ TASARIMI İÇİN KARAR DESTEK MODELİ

ÖZET

Yüksek yapılar kentsel silüetin ve yapılı çevrenin değişmez unsurlarındandır. Gerek ölçek bakımdan, gerekse insanlar üzerinde bıraktığı görsel etki bakımında yüzyıllardır insanların daha da yükseğe çıkma arzularını artırmıştır. Tarih boyunca yüksek yapıların inşa edilmesi ise, teknolojik gelişmelere bağlı olmuştur. Modern anlamda yüksek binaların ortaya çıkışındaki en önemli gelişmelerden biri asansörlerin kullanılmasıdır. Asansör teknolojisindeki gelişmeler yüksek binaların sayısını artırırken, sayıları her geçen gün artan yüksek binaların inşaası asansör teknolojisinin sınırlarını zorlamaktadır. Özellikle son yıllarda sayıları gittikçe artan gökdelenlerde, dikey sirkülasyon sistemlerinin tasarımı daha da önemli bir yer tutmaktadır. Yüksek binaların tasarımında sirkülasyon hayati önem taşımaktır. Bu yüzden, tasarım sürecinde yatay veya düşey sirkülasyonla ilgili alınacak kararlar tasarımın önemli parçasını oluşturur. Yüksek binalarda asansör sistemi tasarımı, farklı disiplinlerden birçok etkenin göz önünde bulundurularak tasarlandığı süreçlerdir. Mimari, strüktürel, teknik, fonksiyonel birçok etken tasarıma etki eder.

Asansör sistemi tasarımı bir bina için gerekli olan asansör sayısı, asansör kapasitesi ve hızının belirlenmesinin yanı sıra asansörler için en uygun yerleşimin belirlenmesini de kapsamaktadır. Yolcu asansörlerine ek olarak binada kullanılacak servis ve yangın asansörleri de bu sistemin içerisinde yer alır. Asansör sisteminin hedefleri binanın kullanıcı trafiğini karşılamak olduğu gibi, tasarım kriterleri arasında maliyet, enerji etkinliği, bakım, güvenlik, strüktürel ve sismik faktörler de bulunmaktadır. Tüm bunlar düşünüldüğünde, tasarımcının farklı disiplinden birçok etkeni göz önünde bulundurularak bina için ideal asansör sistemini tasarlaması gerekmektedir. Fakat bu durum uzman bilgisi, deneyim veya mevcut binalar üzerinde kapsamlı bir araştırma gerektirmektedir.

Yönetmelikler, asansör tasarımına etki eden en önemli faktörlerden biridir. Binanın bulunduğu ülke ve hatta şehire göre değişen yönetmeliklerde asansör tasarımında dikkat edilmesi gereken hususlar detaylı olarak belirtilmektedir. Kullanılacak asansör tipi ve teknolojisi ise tasarıma etki eden bir diğer faktördür. Genel olarak asansörler hidrolik, elektrikli ve makine dairesiz asansörler olmak üzere üç ana grupta toplanır. Yüksek binalarda dişlisiz (gearless) olarak adlandırılan elektrikli asansörler kullanılmaktadır. Bir binada asansör sistemi tasarımında bina fonksiyonu ve kullanımı belirleyici faktördür. Binanın konut, ofis, hastane veya otel gibi farklı kullanımlarda olması ve binanın kullanıcı profili tasarlanacak asansör sistemindeki asansör sayısı, trafik yükü, sirkülasyon şeması gibi diğer faktörleri de etkiler. Bunlara ek olarak, binadaki toplam kullanıcı sayısı ve kullanıcıların katlara olan dağılımı, bina trafik analizi, asansörlerin bina içerisinde konumlandırılması ve gruplanması, kullanılacak

asansörlerin sayısı, hızı ve kapasiteleri asansör sistemi tasarımını etkileyen diğer faktörlerdir.

Asansör sistemi tasarımı temel olarak asansör trafik anaizlerine dayalıdır. Asansör trafik analizleri mevcut bir binanın yada tasarlanmış bir asansör sisteminin binanın ihtiyacı olan servis hizmetini karşılayıp karşılamayacağını test eden yöntemlerdir. Bu yöntemeler genel olarak iki şekilde uygulanmaktadır. Analitik hesaplara dayalı geleneksel yöntem olarak adlandırılan modellerde, temel matematiksel hesaplar kullanılarak binanın trafik analizleri yapılır. Diğer yöntem ise bilgisayar teknolojisinin kullanıldığı karmaşık simülasyon modelleri ile binanın trafik analizlerinin yapılmasıdır. Simülasyon modelleri temel olarak analitik yöntemlere dayansa da, analitik yöntemlerle hesaplanamayan karmaşık durumların analizinde etkili sonuçlar vermektedir. Bir binanın trafik durumu gelen yönde trafik, giden yönde trafik ve katlar arası trafik olarak sınıflandırılmaktadır. Gelen yönde trafik, sabah saatinde ofis binalarında olduğu gibi kullanıcıların asansöre binecekleri ana terminale geldikleri ve yukarı yönde hareket ettikleri trafik durumudur. Giden yönde trafik ise yine ofis binalarında olduğu gibi kullanıcıların binayı terk etmek için katlardan ana terminale doğru yaptıkları haraketi tarif eder. Katlar arası trafik ise, bina kullanıcılarının binanın katları arasında oluşturduğu aşağı ve yukarı yönde tarfiğin birleşiminden oluşmaktadır. Analitik yöntemlerde kullanılan trafik hesapları gelen yönde trafik durumunda binanın istenilen talebe cevap verebilmesine yönelik olarak tasarlanmıştır. Gelen yönde trafik ihtiyacını karşılayan binanın bütün trafik durumları için etkin olacağını varsayar. Simülasyon modelleri ise, binada oluşabilecek her trafik durumunun analizini yaparak sonuçlar üretir.

Asansörlerden sağlanması istenen servis kalitesi, binanın kullanım tipine, bütçeye ve kullanıcı profiline bağlıdır. Asansör servisinin kalitesi ise kullanıcıların istedikleri yerlere ulaştırılmasındaki hızla ölçülür. Bu da, istenen kata ulaşmada kullanıcının yolculuk boyunca asansör içerisinde geçirdiği zaman ve asansörü beklemesindeki toplam zamanla tanımlanır. Bu zaman ne kadar kısaysa, sağlanan servis de daha iyi olacaktır. Bir kişinin asansörü beklemek için geçirdiği süre bekleme aralığı olarak ifade edilir ve gelen kabinlerin ulaşmaları için geçen zaman aralığıdır. Bu zaman, her bir kabinin gidip gelme süresine ve kabin sayısına bağlıdır. Gidip gelme zamanı, bir asansörün giriş katından ayrıldıktan sonra, ortalama sayıda kullanıcıyı üst katta ortalama durağaulaştırdıktan sonra tekrar giriş katına gelmesi için geçen süredir.

Bu çalışma kapsamında, yüksek binalarda asansör tasarımı için kullanılabilecek bir karar destek modeli geliştirilmesi amaçlanmıştır. Modelin karar destek olarak adlandırılmasındaki neden, geliştirilen modelin özellikle erken tasarım aşamasında kullanıcıya herhangi bir uzman bilgisi veya araştırma gerektirmeksizin tasarlayacağı bina için en etkin asansör sistemi tasarımını elde etmesinde yardımcı olmasının amaçlanmasıdır. Böylece tasarımcı, tasarımın ilerleyen aşamalarında yanlış hesaplamış asansör sayısına bağlı olarak yaşayacağı sorunların önüne geçmiş olacak ve deneme yanılma yöntemine başvurmadan tasarımın ilk aşamalarından itibaren bilinçli bir dikey sirkülasyon şeması oluşturmuş olacaktır. Tezin ilk bölümünde, çalışmanın amacı, kapsamı ve izlenilen yöntem açıklanmıştır. Tezin ikinci bölümünde, asansör sistemi tasarımına etki eden faktörler literatür taraması yapılarak incelenmiştir. Tezin üçüncü bölümünde ise, asansör trafik hesapları ve analiz yöntemleri incelenerek, analiz yöntemleri ve tasarım süreci arasındaki ilişki irdelenmiştir. Bu bölümde incelenen analiz yöntemleri geliştirilen model için temel oluşturmuştur. Tezin dördüncü bölümünde, yüksek binalar için geliştirilen asansör sistemi karar destek modeli tanıtılmış ve 40 kattan az ofis binaları için modelin

uygulanması gösterilmiştir. Elde edilen sonuçlar mevcut asansör trafik analiz simülasyonu olan Elevate programı ile test edilmiştir. Tezin sonuç bölümünde, tez sürecinde yapılan araştırmalarla ilgili genel bir çerçeve oluşturularak, uygulanan modelin sonuçları değerlendirilmiş ve modelin ileriye yönelik çalışmalardaki hedefleri tanımlanmıştır.

Tez kapsamında geliştirilen karar destek modeli yolcu asansörlerini kapsamaktadır, yük asansörleri ve acil durum asansörleri modele dahil edilmemiştir. Bina trafik analizleri için geleneksel analiz hesaplarına dayanan analitik trafik analiz yöntemi kullanılmıştır. Asansör sistemi tasarımına etki eden parametreler ise yapılan literatür araştırmaları sonucu elde edilmiş, asansör teknik verileri ise çeşitli asansör firmalarından elde edilerek modele dahil edilmiştir. Geliştirilen model, uygulama olarak yüksek ofis binaları için test edilmiştir. Bunun nedeni, modelde kullanılan analitik trafik analiz yönteminin ofis binalarında görülen kullanıcı trafiğini baz alan matematiksel hesaplar içermesidir. Model kapsamına daha karmaşık matematiksel formüller eklendiğinde ise model farklı bina kullanımları ve farklı kullanıcı trafik örüntüleri için de uygulanabilmektedir. Modelin uygulamasına 40 katın üzerindeki binalar dahil edilmemiştir. 40 kat üzerindeki yüksek binalar için gökyüzü lobileri gibi farklı tasarım çözümlerine ihtiyaç duyulmaktadır. Bu çözümler ise daha karmaşık formüllerin modele dahil edilmesini gerektirmektedir. Modelin uygulaması Rhinoceros 4, Grasshopper eklentisi kullanılarak geliştirilmiştir. Bu programın tercih edilmesindeki neden, ileriye yönelik çalışmalarda modele geometrik ilişkilerin de dahil edilebilmesidir. Modelin ürettiği sonuçlar ise, Grasshopper ve Ms Office Excel bağlantısı kuran bir eklenti aracılığı ile kullanıcıya tablo olarak sunulmaktadır. Modelin geçerliliğinin test edilebilmesi için üretilen sonuçlar ticari bir simülasyon yazılımı olan Elevate programında simüle edilerek sonuç bölümünde değerlendirilmiştir.

Anahtar kelimeler: Yüksek binalar, asansör, asansör sistemi tasarımı, asansör trafik analizi.

1. INTRODUCTION

Tall building is an integral part of a built environment as well being the dominant element of an urban skyline. Due to its scale and visual impact, tall building has been tempting people for years and increasing their desire to rise higher. Historically, the development of tall buildings has been dependent on technological advancements. One of the most important innovations that leads to an evolution in tall building development is elevator. Advancements in elevator technology and increase in number of building floors multiplied the use of elevators in buildings. Thereby, buildings have required elaborately designed elevator systems over time. Especially in the last few decades, by the construction of mega tall towers, elevator systems have become a major constraint of a tall building design since it is the most important part of a vertical transportation system in buildings.

The design of an elevator system for tall buildings involves multidisciplinary considerations in terms of architectural, functional and technical requirements. Initially, elevators are installed into buildings to transport building occupants and visitors vertically, so the main goal in elevator planning is to provide effective vertical circulation. The design of an elevator system comprises the selection of the number, speed and capacity of the lifts, as well as, the selection of the most appropriate elevator configuration. Elevator system also needs to satisfy specific requirements of building traffic performance criteria in addition to cost, energy efficiency, safety, structural and seismic considerations. In other words, designers need to consider several factors affect the vertical circulation design to achieve an optimal elevator system solution.

In the computational field, various methods and different types of software have been developed for analyzing the elevator system of a building. Fundamentally, each method are using passenger traffic calculations. While conventional methods are using analytical equations, advanced methods combines the analytical equations with complex computer models of simulations. With few exceptions, most of them are developed to analyze existing or initially designed elevator system to check the system's efficiency according to standard traffic requirements. Besides, their performance criteria is mostly related with the total travel time of an elevator, average passenger waiting times and handling capacity of an elevator. Deficiency of architectural performance criteria is another problematic point of the existing models.

In tall building design process generally, architects are the main decision maker for the building conception. Especially in the conceptual design phase, decisions on building circulation, both horizontal and vertical, plays an important role, as it is the lifeblood of a tall building. Making decisions to achieve an optimal vertical transportation indicates an expert knowledge or research on existing buildings' elevator systems for a new building design. For this demand, sometimes, elevator specialist are participating into the conceptual design stage. Otherwise, designers may have problems at further design steps in case of the determined core dimensions or the number of elevators are not satisfy the building needs and consequently, the designer may needs to change the vertical transportation system design decisions by trial and error method.

The intent of the research is to propose a decision support model for elevator system design in tall buildings. The model is conceptualized for giving support to architects in the planning and conceptual design stage of a tall building that helps to find optimum number of passenger elevators, their speed, capacity and their dimensions without having any expert knowledge or experience. In addition, the model establish a method for splitting a building into zones to optimize the number of elevators and the core space needed. The proposed model is considered as part of a comprehensive system, which determines the optimum vertical transportation for tall buildings including elevators, escalators and stairs. In this research, elevator system, which is the major element of a vertical transportation of a building, is examined.

The model only comprise passenger elevators so, goods elevators and fire-fighter lifts are out of scope. In addition, the model is implemented for tall office buildings as the traffic analysis calculations are coded for up-peak traffic conditions which is the determinant traffic pattern of an office building elevator system. If complex analytical equations were added in the model for other types of traffic patterns, the model could also be implemented for different building uses. The model has a height limit of 40-storey, because tall building more than 40-storey need special solutions like sky lobby system. Since, the calculations of sky lobby system are more complex than other solutions, the model implemented for office buildings under 40-storey.

Analytical traffic analysis method is used in the model and conventional up-peak traffic calculations are combined with Al Sharif's inverse calculation method. The inverse method is used to find the number of passengers will be in elevator car in any round trip journey of the elevator, and then this number is used in standard up-peak traffic calculations. The parameters affect the elevator system design are provided from previous field studies through literature survey and elevator kinematics are provided by lift companies. Analytical traffic calculations are coded using Rhinoceros-Grasshopper that is used as a medium to make both parametric and geometric queries. The reason of using the Grasshopper for the implementation of the model is to supply a medium for geometric relations and queries for further developments. For instance, the distance from main entry to the elevator lobby, efficiency of elevator configuration, fire regulations could be added to the model. As an output, the model produces number of elevators, their capacity and speed for a given project. If it is needed model also, propose a zoning policy besides, the elevators, their speed and capacity for each zone. Eventually, all results are transferring into a spreadsheet as a final documentation.

2. ELEVATOR SYSTEM DESIGN IN TALL BUILDINGS

2.1 Tall Building as a Building Type

Tall buildings are prominent elements of a built environment. They have a significant impact on their surroundings as they are integrally, connected with the city. In modern meaning, tall building has revealed as a response to the economic, industrial and social changes of the nineteenth century. Growing economies in the world and raise in the population caused a rapid urbanization. Especially the demand for the office spaces on limited and expensive lands required vertical transformation of horizontal expansion. Thus, tall buildings provided to accommodate more people in the same area. Besides the necessity to find a solution to increasing population, the series of technologic advancements have provided the progress of a new building typology (Frampton, 1992). Since it is the most visible element of an urban skyline, it has become a symbolic figure of the modern city over time.

It is important to define what constitutes a tall building. There is no widely accepted definition of a tall building as definitions are changing according to building codes of the country, region, state, or city where the building is located. Although some definitions are stated in terms of number of floors, some are dependent on total height of a building. Council on Tall Buildings and Urban Habitat discusses the term tall building as "the building that exhibits some element of tallness in one or more of the categories indicated as followed; height relative to context, proportion and tall building technology". It is supposed that, the tallness of a building changes with regard to the context in which the building exists. Thus, the 14-storey building may considered as a tall building within the urban context that typically formed by low-rise buildings. To be categorized as tall, the building also needs to have a special vertical transportation technology or contains technologies which may be attributed as being a product of tall like structural wind bracing (CTBUH, 2014)

The term of high-rise also refers to a tall building. Emporis Standards (ESN 18727) indicates, “A high-rise building is a structure whose architectural height is between 35 and 100 meters. A structure is automatically, listed as a high-rise when it has a minimum of 12 floors. If it has fewer than 40 floors and the height is unknown, it is also classified automatically as a high-rise”. From the fire safety perspective, tall building is a building that extends the maximum reach of available fire-fighting equipment. National Fire Protection Association Life Safety Code NFPA (2012) defines a high-rise building as a building more than 75 feet (23 meters) in height, measured from the lowest level of fire department vehicle access to the floor of the highest occupied story. The American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE, 1989) defines high-rises as buildings in which the height is over three times the width, whereas structural engineers define high-rises as buildings influenced primarily by wind loads.

Primarily, all definitions are related with the height of a building that have a specific impact on design. The general description is offered by Ali and Armstrong (1995), stating that it is a "building whose height creates different conditions in the design, construction and operation from those that exist in common buildings of a certain region and period". They also suggest a threshold for a numerical description. Any building could be considered as tall building over 50 meters (165 feet) in height; as “super-tall” building over 300 meters (984 feet) in height, and as “mega-tall” over 600 meters (1,968 feet) in height.

Like other buildings, tall building design process is a complex problem solving procedure taking into account many inputs and variables from different disciplines such as program requirements, environmental performance, construction, aesthetic concerns and budget. The process from the conceptual design to the final output, involves great number of information and multidisciplinary agents (Zisko, 2008). In the conceptual design phase, architects and engineers create various alternatives to use as a basis for further development in detail design. Therefore, the early phase of design is the vital part of the entire process. Several key design criteria must be considered when designing a tall building. Building area efficiency, the wind and earthquake forces, building height-to-width aspect ratio, floor-to-floor height, interior layout, exterior wall, foundation systems, fire safety, construction methods, and budget constraints (Gane, 2011).

2.2 Review of Elevator System Design

Elevator system is the major component of a vertical transportation system in buildings. Vertical transportation systems can be described as a system that contains the design of all passenger and goods circulation facilities and devices in a building, such as elevators, escalators and stairs. The vertical transportation strategy has a fundamental impact on the design of any building. In design process, number of vertical transportation elements and their locations are the preliminary decisions to specify the circulation pattern of a building that needs to provide users a comfortable means of transportation. In addition, configuration of vertical transportation system limits the building design in terms of the space it covers in the plan layout. Hence, the design of vertical transportation systems should be planned carefully from the early stages of the design process.

Undoubtedly, the most important systems for vertical transportation in buildings are elevators. The goal in elevator system design is to move a specific number of passengers from the entrance floor to their destination floors with the minimum amount of waiting and travelling time, with minimum number of elevators by providing minimum core space, cost and using the smallest amount of energy (Al-Sharif & Al-Adhem, 2013a). The design of elevator systems for tall buildings involves multidisciplinary considerations in terms of architectural, functional and technical. As the building gets higher, the design of a system becomes more crucial. Accordingly, designers need to consider several factors affect the elevator system design to achieve an optimal solution.

2.2.1 Elevator technology

The invention of the elevator safety device by Elisha G. Otis in 1854, is seen as one of the crucial technical advances that made possible the birth of the tall building, and thus the modern metropolis (Markon, Kita, Kise, & Bartz-Beielstein, 2006). There are four types of elevators according to their drives: hydraulic, machine room-less, geared traction and gear-less traction elevators (**Figure 2.1**). Each type of elevator has specific characteristics that make it appropriate for a particular building or usage application. The four types of elevators commonly used are discussed below (Popp, J. 2009). Comparison of four elevator types are displayed in **Table 2.1**.

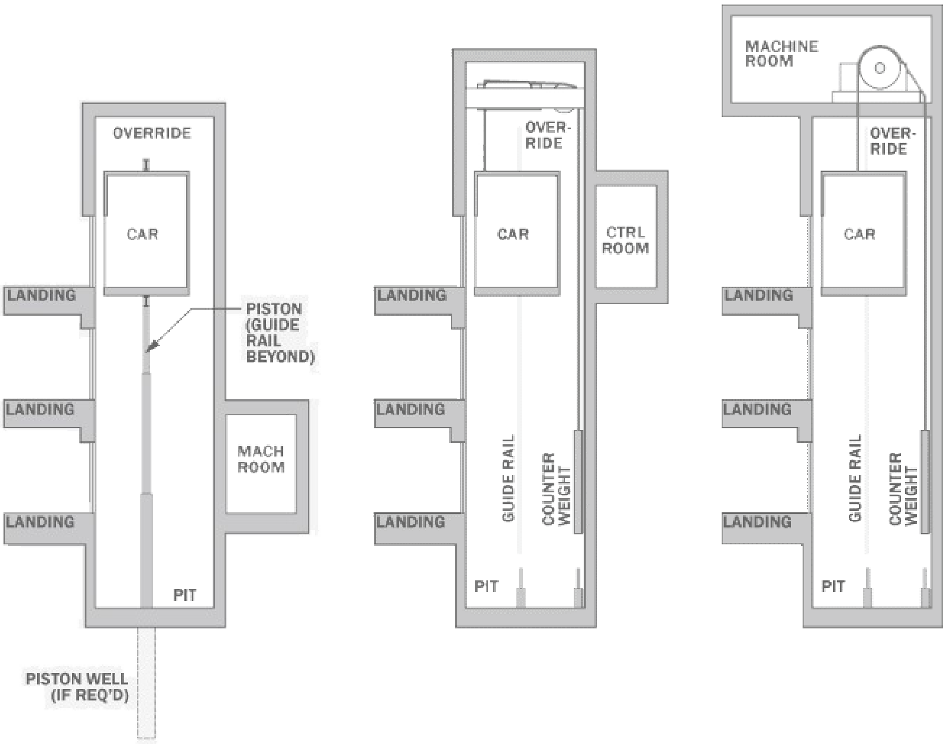


Figure 2.1 : Types of elevators; hydraulic, machine-room-less, traction (http://www.archtoolbox.com/).

Hydraulic elevators:

Hydraulic elevators are supported by a piston at the bottom of the elevator that pushes the elevator up. There are three different versions: conventional, hole-less and roped. They are not as energy efficient as traction lifts, as they use a pump to push the lift up. They are used for low-rise applications of 2-8 stories and travel at a maximum speed of 1 m/s. The machine room for hydraulic elevators is located at the lowest level adjacent to the elevator shaft.

Hydraulic elevators have a low initial cost and their ongoing maintenance costs are lower compared to the other elevator types. However, hydraulic elevators use more energy than other types of elevators because the electric motor works against gravity as it forces hydraulic fluid into the piston.

Machine-room-less (MRL) elevators:

Machine-room-less elevators are traction elevators that do not have a dedicated machine room above the elevator shaft. The machine sits in the override space and is accessed from the top of the elevator cab when maintenance or repairs are required. The control boxes are located in a control room that is adjacent to the elevator shaft on the highest landing and within around 45 meters of the machine.

Machine-room-less elevators have a maximum travel distance of up to 150 meters and can travel at speeds up to 2.5 m/s. MRL elevators are comparable to geared traction elevators in terms of initial and maintenance costs, but they have relatively low energy consumption compared to geared elevators.

Geared traction elevators:

Traction elevators are lifted by ropes, which pass over a wheel attached to an electric motor above the elevator shaft. Geared traction elevators are capable of travel speeds up to 2.5 m/s. The maximum travel distance for a geared traction elevator is around 150 meters. Geared traction elevators are middle of the road in terms of initial cost, ongoing maintenance costs, and energy consumption.

Gear-less traction elevators:

Gear-less Traction Elevators have the wheel attached directly to the motor. Gear-less traction elevators are used in high-use buildings of 12 to more than 100 stories and generally operate at speeds of 2.5 m/s to 10 m/s so they are the only choice for high-rise applications. Gear-less traction elevators have a high initial cost, medium ongoing maintenance costs, and use energy a bit more efficiently than geared traction elevators.

Table 2.1 : Comparison of elevator types, adapted from (Popp, J. 2009).

Hydraulic	(MRLs)	Geared Traction	Gearless Traction
Low rise, 2 - 5 floors	Low to mid rise, 5 - 15 floors	Low to mid rise, 5 - 15 floors	High rise, 12 - 100+ floors
0.5 - 0.75 m/s	1.0 - 2.5m/s	0.5 - 1.8 m/s	2.5 - 10 m/s
Low initial cost	Moderate cost	Moderate cost	High initial cost
Low cost to maintain	Higher cost to maintain	Higher cost to maintain	Highest cost to maintain
High energy use	Energy efficient	Medium energy use	Energy efficient
Slow speed	Higher speed	Higher speed	Highest speed
No loads on building structure	Imposes all equipment loads on building structure at 2.5 m/s only	Imposes all equipment loads on building structure	Imposes all equipment loads on building structure

2.2.2 Codes and standards

Elevator system of a building is pertaining to the elevator safety code and the building code, which may typically be international, national, state, regional or city based. Besides that, it must also comply with standards relating to earthquake resilience, fire standards, electrical wiring rules and so forth. In the United States, the ASME

A17.1/CSA B44-07 code deals strictly with elevators, escalators, and other forms of vertical and horizontal transportation. In addition, elevator code requirements are found in the National Electric Code (NEC), the National Fire Protection Association Code (NFPA-72E, NFPA 101, and NFPA 5000).

Some of the standards that affect vertical transportation design, installation, and operation are listed below. Detailed list can be found in CIBSE Guide D - Transportation Systems in Buildings.

- ASME (American Society of Mechanical Engineers) A17.1 - Safety Code for Elevators and Escalators, A17.7 - Performance-Based Safety Code for Elevators and Escalators,
- EN 81 (European Standards),
- ISO 4190-1:2010 - Lift (Elevator) installation,
- ICC IBC (International Building Code),
- NFPA (National Fire Protection Association) 5000: Building Construction and Safety Code,
- ADA (The American Disabilities Act),
- ADAAG (Standards for Accessible Design - Accessibility Guidelines for Buildings and Facilities).

2.3 Elevator System Design Considerations

After the rise in number and height of buildings in early 1900s, the quantity, size, speed, and location of elevators were questioned. The first approach to elevatoring a building was "Joe Doe has two elevators in his building and seems to be getting by all right. Since my building is twice as big, give me two twice the size." In the latter buildings people had to wait twice as long for service as those in Joe Doe's building and soon the elevator system design emerged as a special design discipline (Strakosch & Caporale, 2010). By the increase in number of building heights due to the technologic advancements in elevator technology, calculating the elevator needs of a building had been more complex. "The four decades between 1945-1985 have seen the acceptance of automatic cars, the introduction of better traffic and control systems, and the inclusion of the digital computer equipment "(Barney, 2003).

Due to its multidisciplinary nature, elevator system design comprises various factors affect the design process. The design of elevator systems for buildings involves the selection of the number, speed and capacity of the lifts required. It also involves the selection of the most appropriate configuration in terms of zoning, group control algorithm and the use of special elevator technologies (Al-Sharif & Seeley, 2010b). In this section, the design parameters of an elevator system and performance criterion are explained.

2.3.1 Design parameters

To design an effective elevator system, it is important to identify the design objectives. Parker and Wood (2013), indicate the design objectives of elevator system design as:

- Effective circulation;
- Minimum cost;
- Life safety;
- Security;
- Energy efficiency.

The aim of an elevator system is to provide comfortable means of transportation. The circulation pattern of a building effects the success or failure of a building as a place to work, live or receive a service (CIBSE, 2005). Total budget stated by the project developer is the main constraint of an elevator system design. The cost of an elevator system consists of build and maintenance costs. According to the budget, the elevator devices and technologies would be selected varies. Another purpose related with cost is occupied floor area of the building. The floor area consists of elevator shaft space and the lobby space, which is the waiting area for passengers. Especially in tall buildings, larger elevator shafts are needed, as the number of elevators are more. The more area occupied by elevators, reduce the rentable area which means more cost.

Life safety of an elevator system mostly restricted by the codes that electrical, structural and seismic regulations are indicated in. Life safety, also include the fire safety regulations. Another design target of an elevator system is to propose the safety of its occupants and visitors of the building. Especially, in mixed-use buildings, the elevators should be accessible by separate elevator lobbies in addition, for garage and basement usages special solutions should be produced. Likewise, the energy consumption is an important task for elevator systems. Types of elevator drivers, their speed and number are all effecting the energy usage of the elevator system. The reduced number of stops, shafts and slow speed decrease the energy consumption.

The design process of the elevator system comprises four distinct activities (Al-Sharif & Seeley, 2010a):

1. Identifying the number, speed and capacity of the lifts within a specific group.
2. Identifying the number of group of lifts and their arrangement within the building. For each group, the floors, which will be served by each group of lifts, are also identified (referred to as a zone).
3. Identifying the group control algorithm that will allocate the landing calls to each of the lifts in a certain group (e.g. conventional group control).
4. Identifying the need for special lifts like double decker lifts where appropriate.

General design parameters crucial for elevator system design can be summarized as type and use of building, number of floors above the main entrance, size of population and its distribution through the floors, building traffic, elevator arrangements, elevator number, speed and capacity.

Type and use of the building:

While designing an elevator system in any building, the most important criteria is the use of the building. According to building type, the need of elevatoring varies. For instance, an office building has different design criteria in terms of passenger demands, traffic planning and service level of elevatoring. As an example, some of parameters changing according to use of building type are showed in the table 2.2.

While designing an elevator system, the first step is defining the types of users due to the use of building. The office building has mainly two types of users; employees and visitors who is the daily users of the office building. If the office building has one tenant, it is likely to have fix working hours so, the passenger traffic mostly have the constant values. However, if it has multiple tenants, the working hours, visitors' capacity and number of employees may differs. For a different building function, there are several factors affect the elevator system design comparing to an office building. For instance, the hospital building totally has different pattern of visitors. Deciding the spatial relationship between location of elevators and clinic services and the size of elevators are the substantial part of a design process. As a result, each building function indicates its own parameters while designing the required elevator system.

Table 2.2 : Example of design factors according to building type (Ong, 2004).

Key Factors	Types of Building		
	Office Building	**Hotel**	**Apartment**
Population	Floor areas	Number of rooms	Number of bedrooms
Traffic Conditions	Morning up: normally prime determinant Noon: two-way Evening down	Morning down Evening two-way: normally prime determination	Two-way
Quality of Service	30 sec intervals 20-25 sec waiting times 150 sec system service time	35-45 sec intervals 25-30 sec waiting time 180 sec system service time	45,0 sec intervals 30-60 sec waiting time 260 sec system service time
Quantity of Service	10% - 15% up handling capacity	6% - 9% two-way handling capacity	5% two way handling capacity

Number of floors above the main entrance:

In some instances, total height of a building is accepted as design criteria. However, the total height is insufficient to specify the number of floors and inter-floor distances. In addition, in elevator traffic analysis, calculations are made by using the number of floors above the main entrance. Regarding to elevator safety rules and structural restrictions, elevators have a limited travel distances. Generally, the limit is 15-20 storey. Tall building that is more than 20-storey need special solutions like zoning which is dividing building as it comprises two buildings. Moreover, the number of floors effects the building traffic calculation that is significant in elevator planning.

Size of population and its distribution through the floors:

Before starting an elevator system design, detailed study must be made of how people will arrive at the building, occupy that building, and move about the building. “Basic factors in elevatoring a building include the number of occupants and visitors, their distribution by floors, and the times and rates of arrival, departure, and movements” (Strakosch & Caporale, 2010). The size of the intended population should be obtained. If the population numbers are not available, total population should be estimated using floor areas. The number of people occupying the usable area will vary according to;

- the purpose of the building (residential, commercial or institutional);
- the quality of the accommodation (prestigious, standard, speculative);

- the type of occupancy (for office buildings single/multiple tenanted) (CIBSE, 2005).

Traffic planning:

To decide the right number, type and speed of elevators, building traffic must be designed in a detailed way. Traffic analysis study varies according to the type and usage of the building. Building traffic contains the specification of traffic patterns within a building by using traffic analysis methods. For example, an office building typically requires more elevators than an apartment building due to heavier loads and traffic. The most important parameters used in traffic planning is handling capacity of an elevator system and interval. Traffic analysis and design methods are discussed in chapter three.

Elevator arrangements:

In a modern multi-storey building, the appropriate selection of the position of the elevator system is very important for the efficient vertical transportation of the building's occupants. The users of the system should reach it easily and, after landing to the floor of their demand, they should walk to the space they want with the fewest movements (Markos & Dentsoras, 2010). Elevators should be accessible and centrally located (**Figure 2.2**). Experience has shown that the walking distance from the elevators to the farthest office or suite should not exceed 60 m, with a preferred maximum distance of about 45 m (CIBSE, 2005). The fire safety regulations are also effect the positioning of elevators.

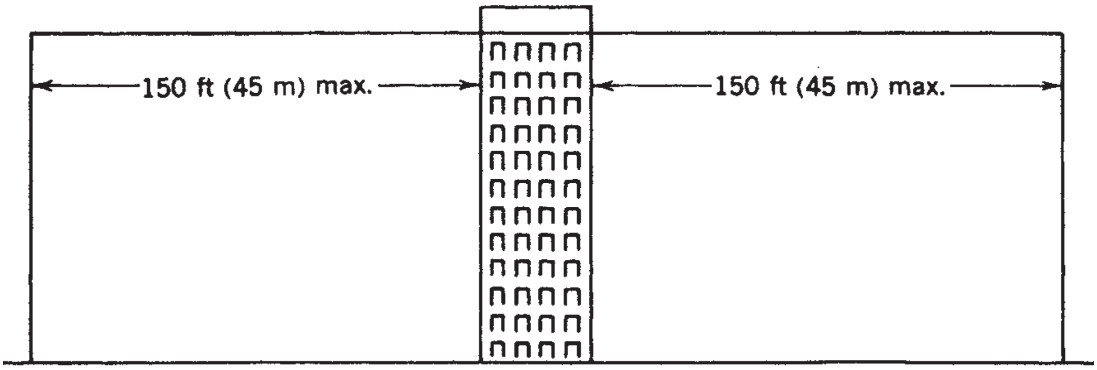


Figure 2.2 : The maximum distance people have to walk to an elevator on any floor (Strakosch and Caporale, 2010).

If a building requires more than one passenger elevator, all the passenger elevators should be grouped (**Figure 2.3**). As a rule, elevators should be arranged to minimize walking distance between cars. Elevator grouping in plan layout helps to decide the total area that is required to occupy elevators and elevator lobbies.

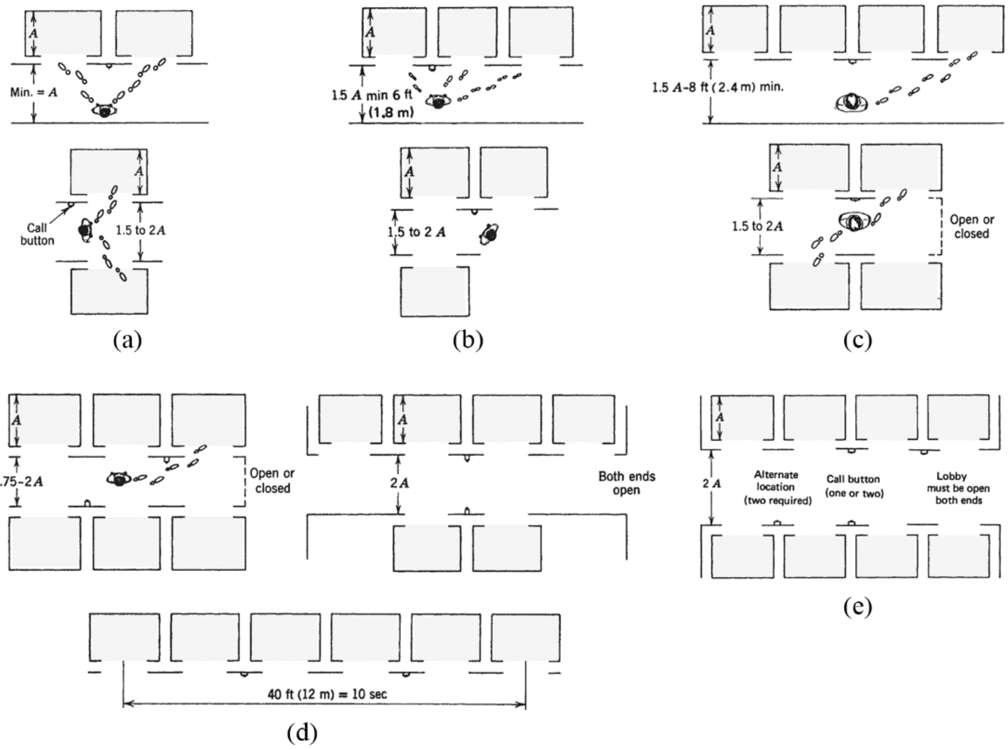


Figure 2.3 : Elevator grouping; two-car (a), three-car (b), four-car (c), six-car (d), eight-car (e) arrangement, adapted from (Strakosch & Caporale, 2010).

Elevator number, speed and capacity:

The selection of the number of elevators, their sizes and speeds is mostly related with the budget, the building space available and the passenger service level (Siikonen, 1997). The design of an elevator system aims to minimize the elevator number, speed and capacity. As, the number of elevators determine the performance of the system, it is the most demanding part of the process. After, the number of elevators selected, the detailed traffic analysis should be made to check the efficiency of vertical transportation performance of the building.

2.3.2 Performance criteria

Each building is unique, and the optimum solution is project specific. There could be over a hundred different possible configurations for one building's elevators, and each will have its advantages and disadvantages compared with the others. To decide the efficiency of a designed system, performance criteria should be satisfied.

The first requirement for good elevator service the elevator system must be designed to provide average waiting time of less than 30 sec in commercial buildings and less than 60 sec in residential buildings. The second requirement is to provide sufficient quantity of elevator service for the maximum passenger arrival or departure rate expected within a maximum peak traffic period. The third requirement of good elevator service, therefore, is to design the system so that a person will not be required to ride a car longer than a reasonable time (Barney, 2003).

2.4 Designing Tall Building Elevator System

Tall building challenges in elevator system planning:

- A wider variety of elevator configurations is possible for high-rise construction than low-rise.
- It is very hard to make subsequent changes in the design process as the minor changes effects the whole design.
- Various control systems are available.

2.4.1 Solutions for tall building challenges

Zoning:

As the building height and floor plan size increase, more elevators are needed. Elevator zoning is required for usability of space that becomes available on the upper floors after the lower zone elevator drops off. Zoning is a method to divide the building where a lift or group of lifts is constrained to serve a designated set of floors (**Figure 2.4**). A rule of thumb is to serve a maximum of 15–16 floors with a lift or a group of lifts.

There are two forms of zoning: stacked and interleaved. An interleaved zone is where the whole building is served by lifts, which are arranged to serve either the even floors or the odd floors (**Figure 2.5**). This has been a common practice in public housing and has been used in some office buildings. A stacked zone building is where a tall building is divided into horizontal layers, in effect, stacking several buildings on top of each other, with a common `footprint' in order to save ground space. It is a recommended practice for office and institutional buildings (Barney, 2003). When zoning the building, a general rule of thumb is to split the building population in the ratio of 60% for the lower zone and 40% for the upper zone to make up for the extra travel requirement for the upper zone and attempt to equalize the interval and the number of elevator for both zones. This rule of thumb is used for deciding on the zoning cut-off point.

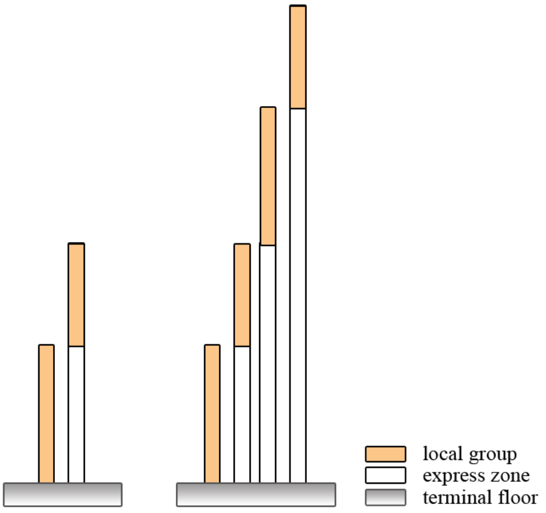


Figure 2.4 : Zoning and stacking of building, adapted from (Siikonen, 1997).

Although the number of available elevators in each group is reduced, the increase in waiting interval is generally more than offset by the reduction in travel time, owing to a much lower probable stop curve. An added advantage is that the cars will be less crowded because of the separation of low-rise and high-rise traffic. The low-rise/high-rise configuration opens additional rental areas on the upper floors above the low-rise hoist ways.

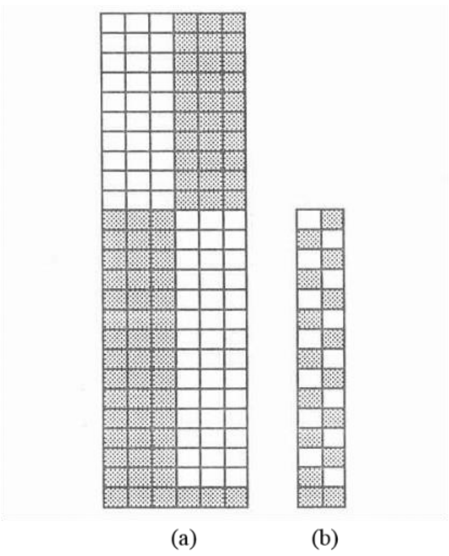


Figure 2.5 : (a) Stacked and (b) interleaved zones (Barney, 2003).

Sky lobby:

Sky lobby design is a method generally used in buildings higher than 50 stories as well the mixed-used buildings. The aim is to divide the building with separate lobbies at different levels. The sky lobby concept has been a successful approach to the office–apartment combination. A separate lobby is located on the lowest apartment floor and connected to the street by shuttle elevators (**Figure 2.6**). Apartment tenants ride these elevators to the sky lobby and change to the local elevator, which takes them to their floors.

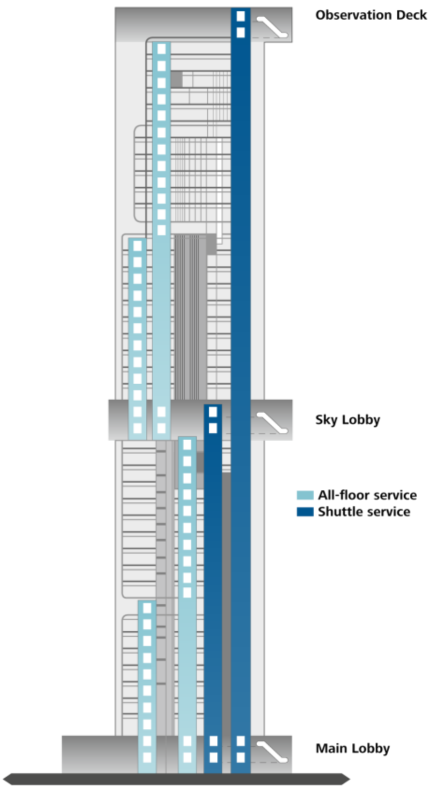


Figure 2.6 : Sky lobby system (http://www.schindler.com/tr/internet/tr/ulasim secenekleri/urunler/asansorler.html).

Shuttle elevators:

Generally, shuttle elevators are using to provide express transportation between sky lobbies (**Figure 2.7**). They are calculating as two stop elevators and provide passenger to reach upper floors without stopping at the lower parts of the building. Shuttle lifts are usually quite large and fast and provide an excellent service to the sky lobby. In order to reduce the travel time high-speed elevators are used as shuttle elevators. Their main disadvantage is that the passengers must change lifts mid journey, hence increasing their total journey time.

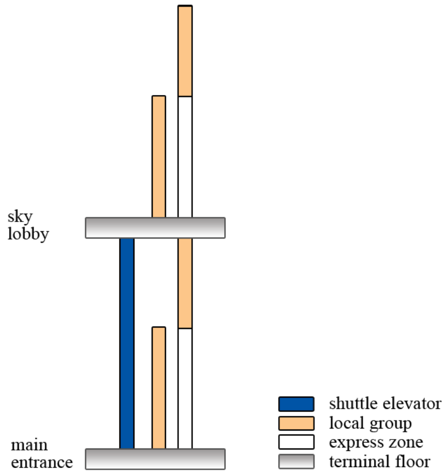


Figure 2.7 : Shuttle elevators, adapted from (Siikonen, 1997).

Double deck elevators:

Another approach to reducing the space required by elevators in taller buildings is the use of multi-deck or compartment elevators. Here the upper and lower decks of each elevator are loaded simultaneously with passengers destined for the odd-numbered floors entering the bottom deck and those for the even-numbered floors entering the upper deck.

Lobbies for double-deck elevators require special considerations. They can be designed with either the upper or lower deck at ground level and must have both escalator and shuttle elevator service between the lobbies (**Figure 2.8**). Both lobbies should be equally attractive, and clearly visible signs should be provided to guide visitors to the proper elevator entrance level for the destination floors sought.

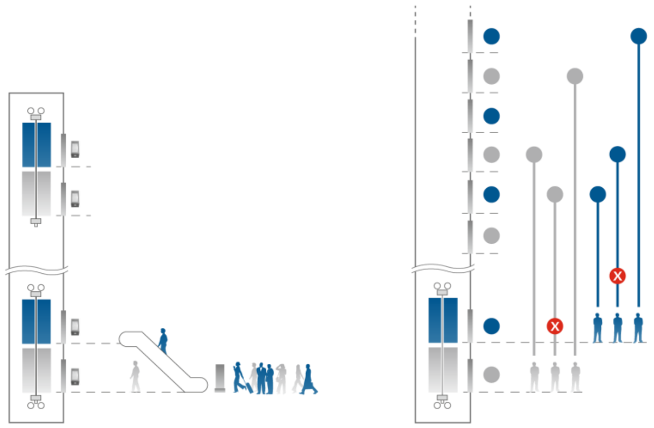


Figure 2.8 : Double deck elevator system
(http://www.schindler.com/tr/internet/tr/ulasim-secenekleri/urunler/asansorler.html).

Twin lift:

The twin lift concept involves the operation of two separate elevator cars within one shaft. The elevators use the same tracks and elevator shaft, but have separate cars, drives and control systems (**Figure 2.9**). The upper car generally serves destinations in the top half of the building and the lower car the bottom half – with destination control. The lower car can only let on passengers at the main entrance level once the upper car has departed, and is required to wait below the main entrance level whenever the upper car needs to return to that level.

Twin lifts are ideal for situations in:

- Tall buildings with high peak demand
- Buildings with large elevator groups
- Buildings with a lot of between-floor traffic flows

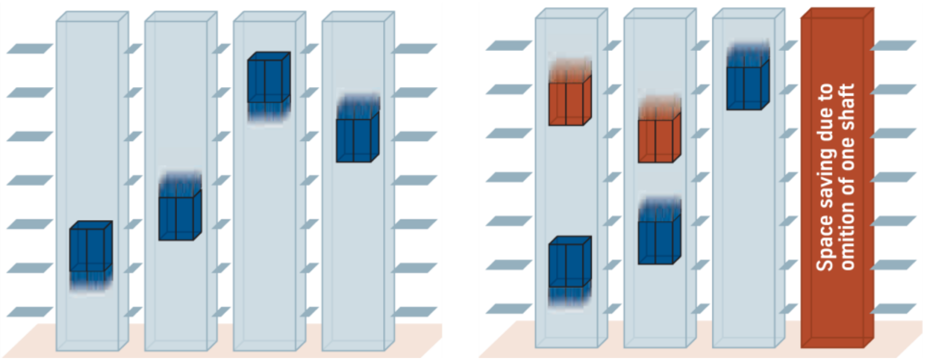


Figure 2.9 : Illustration of a twin lift (http://www.thyssenkrupp-asansor.com.tr/).

Control algorithms:

Conventional elevator controls allow users to indicate their chosen direction of travel by means of up and down buttons. Cars are filled in the same order that user requests are received. Destination control algorithm is the concept that destinations are selected by users when calling the elevator (**Figure 2.10, Figure 2.11**). This allows the control system to cluster destinations for each car using dynamic zoning, thus significantly reducing the travel time and the number of stops.

Destination control is ideal for situations in:

- High-rise buildings where large dynamic zones can be defined,
- Large elevator groups where multiple dynamic zones can be defined,
- Buildings with high peak demand.

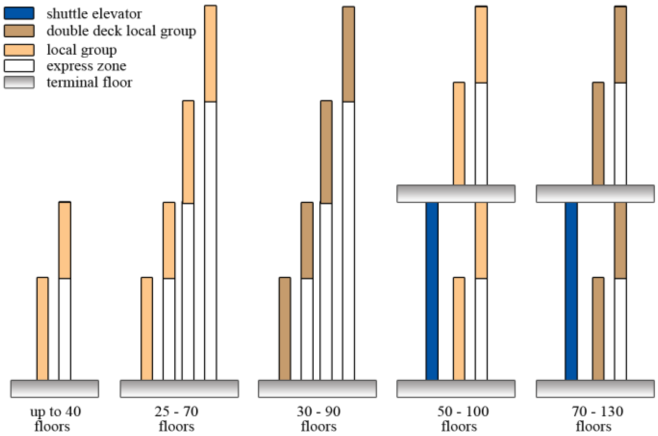


Figure 2.10 : Zoning and stacking of tall buildings as a function of building height with conventional control, adapted from (De Jong, 2008).

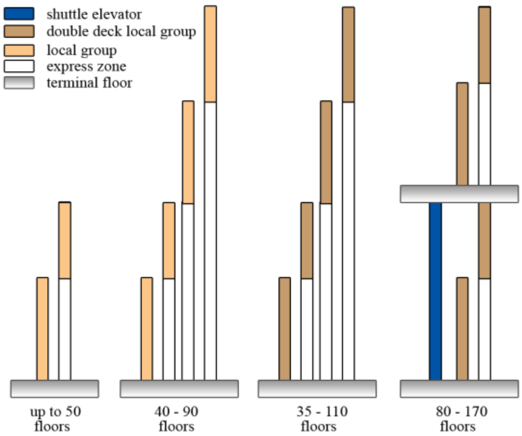


Figure 2.11 : Zoning and stacking of tall buildings as a function of building height with destination control systems, adapted from (De Jong, 2008).

2.4.2 Case studies

World Trade Centre

The Twin Towers of World Trade center in New York was completed in 1973 and was destroyed in in the terrorist attacks of September 11, 2001. The two 110-story office towers were designed by the architect Minoru Yamasaki. The design of the buildings was brought a significant innovation to the tall building design. Before the WTC, architects were hesitant to build higher than 80 stories, largely due to the elevator problem (Klerks, 2011).

The WTC design team proposed a completely different system for the huge towers. Instead of building enough elevators to move everybody from the ground floor to their destination, they decided to split the trip to the upper floors between multiple elevators. If people wanted to get from the ground to the top floor, they would need to jump from elevator to elevator. Each tower also had a single express elevator that went all the way to the top. The one in the South Tower went to the observation deck, that in the North Tower to the Windows on the World restaurant.

The towers had a square plan, approximately 207 feet (63 m) in dimension on each side and approximately 416 meters height (**Figure 2.12**). Essentially, each tower functioned as three buildings stacked on top of one another. The system turned out to be a great success with 99 elevators total per tower, each serving only specific floors, occupants could get around quickly and easily. Most super skyscrapers built after the WTC used the same basic system. First, passengers would take an express elevator from the main lobby directly to a sky-lobby on the 78th floor. From there, they could go to their destination floor directly. To keep things orderly, all the 55-person elevators had doors on each side you would enter on one side, move to the front, and exit on the other side. (http://en.wikipedia.org/wiki/Construction_of_the_World_Trade_Center).

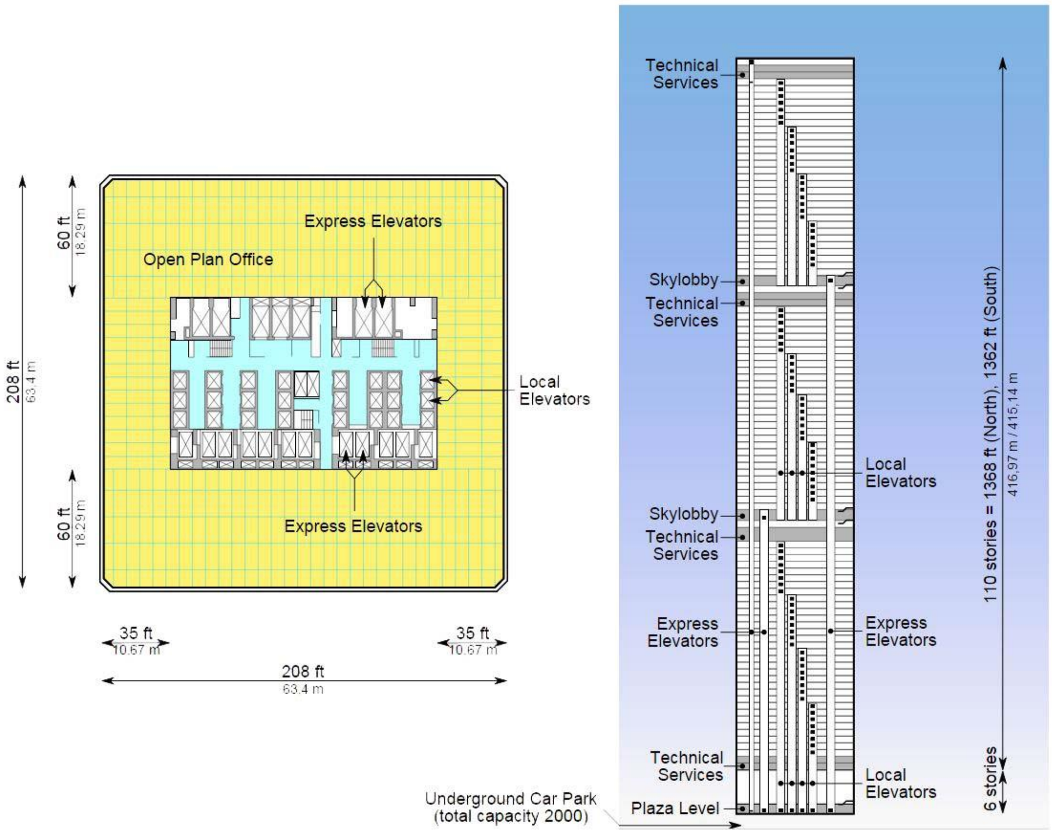


Figure 2.12 : Plan layout and section of World Trade Centre (http://en.wikipedia.org/wiki/Constructionof_the_World_Trade_Center).

The success of this system lay in its economy of space. Local elevators for the lower, middle, and upper zones of the building sat one atop the other in the same shafts. In addition, since the express elevators to the sky lobbies traveled no farther than the 44th and 78th floors, respectively, the higher one ascended in the building, the less space had to be given over to elevator shafts.

Taipei 101

The building was the world's tallest in 2004, and remained such until the opening of Burj Khalifa in Dubai in 2010. Taipei 101 was designed by C.Y. Lee & partners. The construction started in 1999 and finished in 2004. Taipei 101 comprises 101 floors above ground and 5 floors underground (**Figure 2.13**).

The tower has two shuttle elevators for public access to the observation deck on the 89th floor. With full loads, the ascent speed reaches a maximum of 16.8 m/s or nearly 60 km/h. This speed was recorded as a Guinness World Record on December 16, 2004. Descent speeds measure 10.0 m/s or 37 km/h (23 mph). Taipei 101's 60.6 km/h elevators run from the ground to the 89th floor in only 39 seconds and from the top floor to the ground in only 48 seconds.

The office block (floors 9 through 84) is accessed as though it were made up of three individual building segments each of 112 m stacked one on top of the other. Transportation to and from the sky lobbies on the 35th and 59th floors is provided by ten high-speed, double-deck elevators (weighing 4,080 kg and holding up to twenty-seven passengers per car) that shuttle their passengers non-stop to their transfer levels. Each of the three sub-segments is fitted with its own local double-deck elevator system (weighing 2,700 kg and holding up to eighteen passengers per car) of which four are low-rise and four are high-rise systems. The use of double-deck elevators doubles the transportation capacity per shaft, especially to and from the sky lobbies. These double-deck elevator cars also incorporate a technological innovation. The two cars are suspended independently of one another in a frame to allow for inter-dependent movement, which compensates for local floor height differences.

In addition to the public shuttle elevators to the observation deck on the 89th floor and the double-deck elevators to the sky lobbies, the Taipei 101 also houses four exclusive passenger elevators to the sky restaurant and executive club, four general-purpose goods and fire-fighting elevators, six car park elevators, eleven passenger elevators at the base for commercial purposes and fifty escalators (Mizuguchi, Nakagawa, & Fujita, 2005).

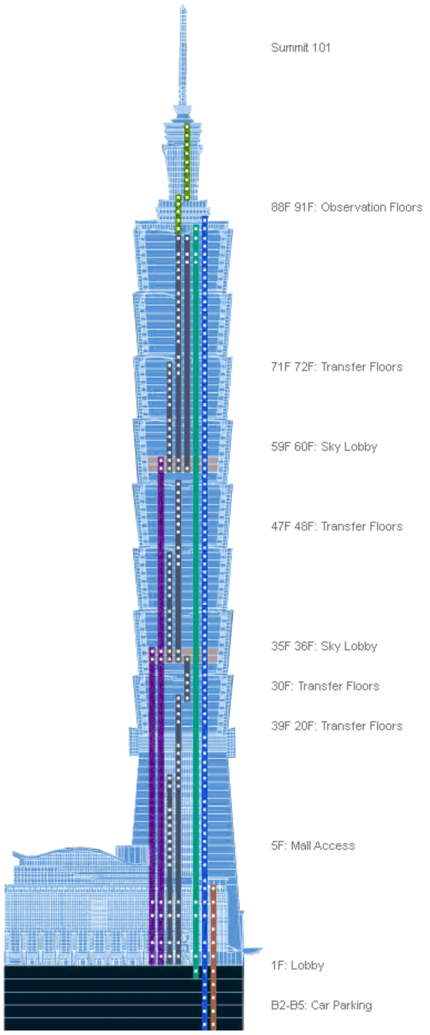


Figure 2.13 : Elevator system of Taipei 101 (http://www2.taipei-101.com.tw/).

Burj Dubai

It is the tallest structure in the world as the height of 829.8 m. The building officially opened on 4 January 2010. The tower's architecture and engineering were performed by Skidmore, Owings and Merrill. Burj Khalifa was designed as mixed-use development that would include 30,000 homes, nine hotels, 3 hectares of parkland, at least 19 residential towers, the Dubai Mall, and the 12-hectare man-made Burj Khalifa Lake.

A total of 57 elevators and 8 escalators are installed. The building utilizes high-speed, nonstop ‘shuttle’ elevators bringing passengers to ‘sky lobby’ floors where they transfer to ‘local’ elevators serving the floors in between. The sky lobbies on the 43rd and 76th floors house swimming pools. Floors through to 108 have 900 private residential apartments (Corporate offices and suites fill most of the remaining floors, except for a 122nd, 123rd and 124th floor where the restaurant, sky lobby and an indoor and outdoor observation deck is located respectively (**Figure 2.15**). In Burj Dubai, the overall building program is organized to utilize the 'gap' floors as space for mechanical and electrical services (**Figure 2.14**).

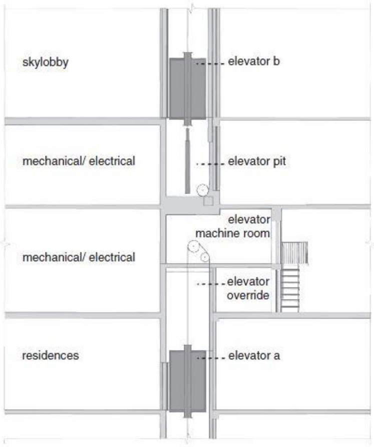


Figure 2.14 : Detail section showing the stacking of elevator groups at mechanical zones (Weismantle, Smith, & Sheriff, 2007).

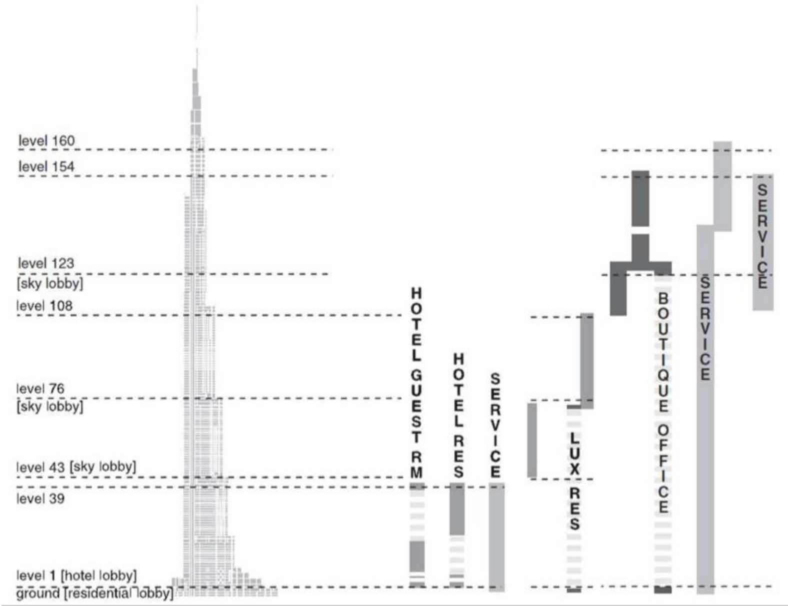


Figure 2.15 : Illustration of the elevator system of Burj Dubai (Weismantle, Smith, & Sheriff, 2007).

Burj Dubai's observatory elevators are double deck cabs with a capacity for 12-14 people each. Travelling at 10 m/s, they will have the world's longest travel distance from the lowest to highest stop. Up to Level 39, both the hotel and the lowest zone of residential service apartments are served by separate groups of local elevators with their lobbies at Level 1 and ground level, respectively. Residential sky lobbies at

Levels 43 and 76 are served by two separate groups of high-speed shuttles with lobbies at ground level. The residential floors are served by groups of three local elevators, each in standard ‘bottom-up’ configuration In the Level 123 sky lobby is served by the bottom cars of a pair of double-deck high-speed shuttle elevators. Passengers transfer to two groups of local elevators. One group goes up, serving Levels 123–154, while the other group goes down, serving Levels 123–112 (Weismantle, Smith and Sheriff, 2007).

3. ELEVATOR TRAFFIC ANALYSIS AND DESIGN

Traffic design and analysis is the major part of an elevator system design, which identifies the traffic requirements, elevator traffic calculations and the efficiency of an elevator system as well as the traffic control method. Al-Sharif and Al-Adhem (2013), define the elevator traffic design as the design process that meets the passenger traffic requirements of a building with the desired elevator system. They assign that, the outcome of an elevator traffic design involves the specification of the following four parameters:

1. Number of lifts in a group,
2. Rated speed of the lifts,
3. Rated capacity of the lifts and,
4. Group control algorithm.

Elevator traffic design is dependent on the traffic analysis. Traffic analysis is a method generally used to analyze the traffic flow of an existing or designed elevator system. However, it is also used to find the required number of elevators for a new building by using traffic calculations and target traffic performance requirements. Typically, two approaches are used in elevator traffic analysis. One approach which has been used for nearly 75 years, is calculation based on mathematical formulae. The second approach which has been used for over 30 years, is based on a digital simulation of the building, its lifts and the passenger dynamics (CIBSE, 2005). Both approaches are using to find the probable performance of the proposed design. In addition, calculations can be used to find the number of required lifts by using target performance requirements. On the other hand, in simulations there should be a proposed design, which involves the number, speed and capacity of elevators as well as other elevator kinematics.

3.1 Elevator Traffic Concepts

In elevator traffic design, there are general planning considerations which designer should take into consideration. It is important to make future projection about the use and occupancy alteration of the building. In time, the occupancy of the building may change so the elevator system should satisfy the changed conditions and maintain its performance.

The aim of an elevator traffic design, to respond a need of passenger's transportation demands with optimum vertical transportation devices, which enables the minimum travel and waiting time. Fundamentally, elevator traffic design is based on passenger demand and the time factors. To understand the elevator traffic design common concepts need to be clarified.

Arrival rate (AR%): The passenger arrivals expressed as a percentage of the building population, which will require transportation to the higher floors of a building in the busiest five minutes. In every building, there is a critical peak period, which determines elevatoring requirements. The design should provide sufficient service to meet this peak period in terms of quantity of service or the handling capacity and quality of service or the passenger waiting time.

Traffic pattern: The traffic pattern of a building depends upon the building characteristics, such as, building dimensions, building requirement, building type, public facilities and location, tenancy profile, operation time and location.

Handling capacity (HC %): The handling capacity of an elevator system is the total number of passengers that it can transport during peak traffic conditions with a specified average car loading. The handling capacity is normally calculated for a five-minute peak period and is referred to as five-minute handling capacity.

Interval (INT): It is the average time between successive arrivals of elevators in the main terminal.

Round trip time (RTT): It is the average time for a single car trip around a building, during the up-peak traffic condition. It is measured from the instant the car doors start to open at the main terminal until the instant the car doors start to reopen at the main terminal, when the car returns to the main terminal after its trip around the building.

Average travel time: (ATT): This has been defined as the time from when a responding lift begins to open its doors at the boarding floor until the doors begin to open again at the destination floor.

Passenger average waiting time (AWT): It is the average period of time, in seconds, that a passenger spends waiting for a lift, measured from the instant the passenger registers a waiting call until the instant the passenger can enter the lift.

These are the basic terms used in elevator traffic analysis. In later sections, each of them is discussed in detail. All definitions are taken from CIBSE Guide D – Transportation Systems in Buildings (2005), more definitions can be found in Appendix A.

3.2 Assessment of Passenger Demand

The passenger demand in a building depends on the arrival of passengers in the peak five minutes (the busiest five minutes of the day). Thus, the demand is measured in unit of passengers arriving in the busiest 5 minutes (300 seconds) period. In order to normalize this figure, it is usually to divide it by the total building population and express it as a percentage. This is called the arrival rate and is denoted as AR%.

In general, size of a lift system is specified by the number of passengers requesting service during the heaviest five minute of the peak traffic condition. The design should provide sufficient service to meet this peak period in terms of quantity of service or the handling capacity and quality of service or the passenger waiting time.

3.2.1 Traffic patterns

There are three types of traffic pattern:

Up-peak (Incoming) traffic**:** Incoming or up peak traffic exists when everyone arriving at a lobby floor is seeking transportation to upper floors. It is also called the morning up peak, because this traffic pattern mostly occurs in office buildings in mornings when the workers arriving to start work. The duration of the classical up-peak traffic condition is five minutes (**Figure 3.1**).

As incoming traffic provides one of the heavier traffic periods in office buildings, the required number of elevators are calculating to serve users coming in this peak period. In addition, the classical traffic analysis methods use the up peak traffic pattern in calculations to find the number of elevators required to serve a given number of people during this period.

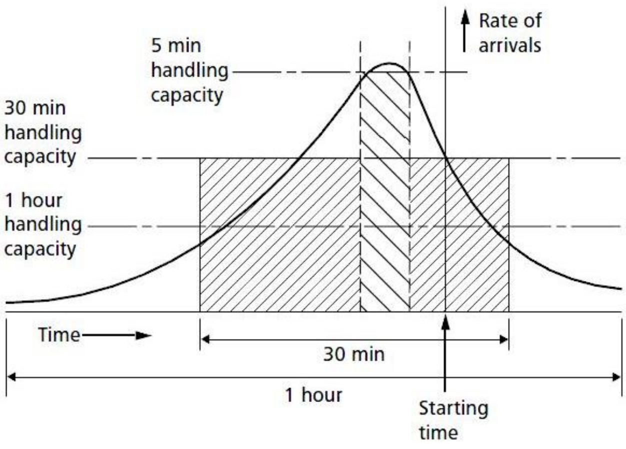


Figure 3.1 : Detail of a round trip for a single lift during up-peak traffic (CIBSE, 2005).

Down-peak (outgoing) traffic: Down peak traffic pattern occurs when most of the occupants leaving the building such as in office buildings at the end of the working day (**Figure 3.2**). This traffic patterns also called as evening down peak. The profile of the down-peak traffic is larger in size and longer in duration than the up-peak profile. But during down peak a lift car fills at 3–4 floors and to the lobby. This reduces the time taken by the car to complete a round trip and increases its handling capacity. Down peak traffic is therefore not usually taken into account in the design of the lift system. There are, however some special situations, such as theatres and movie-halls, where a down–peak analysis would produce a more acceptable system than the up–peak analysis.

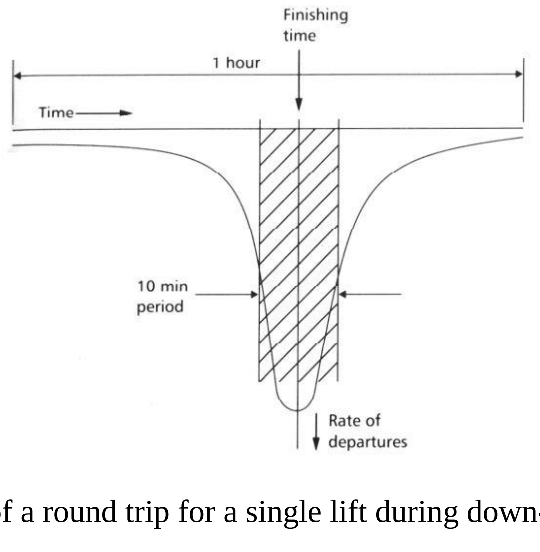


Figure 3.2 : Detail of a round trip for a single lift during down-peak traffic (CIBSE, 2005).

Inter-floor traffic: During the rest of the day, some people will be entering to a building, at the same time others are leaving, as at lunchtime (two-way lobby traffic), or people will be going from one floor to another (two-way inter-floor traffic), or there will be a combination of these traffic patterns. Two-way lobby traffic may be relatively simple; people enter an elevator at the lobby floor and leave at various stops during the up trip. The two-way inter-floor traffic trip is more complex. During an up trip, for example, an elevator makes one stop to pick up a passenger and another stop to let the passenger off. Each landing stop for a waiting passenger on a typical floor usually requires two stops of the elevator. The round-trip time is therefore long in relation to the number of passengers served (Strakosch & Caporale, 2010).

3.2.2 Estimation of population and arrival rate

Occupancy is an obvious prerequisite to the design and size of the building itself. It must be expected to perform its function to provide a living or working environment and to have an economical, physical, and functional life span. Basic factors in elevatoring a building include the number of occupants and visitors, their distribution by floors, and the times and rates of arrival, departure, and movements. We can determine the average population in a new building by calculating so many square feet of space per person. (Strakosch & Caporale, 2010).

The size of the intended population should be obtained, either from the building owner or from the proposed occupier. If the population numbers are not available, or the building is a speculative one, then an estimation must be made using floor areas. The number of people occupying the usable area will vary according to:

- The purpose of the building (residential, commercial or institutional);
- The quality of the accommodation (prestigious, standard, speculative);
- The type of occupancy (for office buildings, single/multiple tenanted).

3.2.3 Performance criteria

Two key factors affect the demand that a building's occupants will make on a lift system: the quantity of service and the quality of service required. The quantity of service factor is how many people will use the lift system over a defined period of time, it is represented by the handling capacity. The quality of service factor is how well must the lift system deal with its passengers, it is represented by passenger waiting time, and lobby queuing. Both factors are interrelated. Both factors are alos depend, amongst other things, on the type of building and its use, and on the type of occupier. This makes the design task very difficult for buildings of a speculative nature (CIBSE, 2005).

Quantity of service

The measure of the quantity of service in elevator system design is handling capacity of the system which is the percentage of the building population that the elevator system can handle in the busiest five minutes is called the handling capacity. If all passengers in the lobby are taken from the lobby within the 5 minutes, then no queues will develop. This is an important service criterion. For all passengers to be moved from the lobby in the busiest five minutes, the handling capacity of the lift system should be equal to or larger than the arrival rate in the busiest five minutes. The second requirement is to provide sufficient quantity of elevator service for the maximum passenger arrival or departure rate expected within a peak traffic period. This can be accomplished by either a platform of sufficient area to accommodate all persons waiting to ride or, alternatively, a sufficient number of smaller platforms. The alternative of more platforms is usually preferred because it reduces the waiting time.

The handling capacity only represents the quantity of service. Although all passengers arriving in the busiest five minutes had been cleared within the five minutes, this only means that the quantity of the demand has been met, but it tells us nothing about the quality of service. We can meet the same quantity of passengers to be moved from the main terminal by having a small number of large lifts, a medium number of medium lifts or a large number of small lifts. All of these arrangements can meet the required demand. However, the waiting time of the passengers in the case of the small number of large lifts will become excessive. Thus meeting the quantity is not sufficient to achieve a good system. We also need to consider the quality of service.

Quality of service

The quality of service criterion is represented by the average passenger waiting time and average travel time. Some designers use the interval of car arrivals at the main terminal as an estimation of the quality of service. Interval is part of the evaluation of handling capacity, which represents the quantity of service of a lift system.

Average waiting time (AWT) is the average period of time, in seconds that an average passenger waits for a lift measured from the instant that the passenger registers a landing call (or arrives at a landing), until the instant the passenger can enter the lift. Typically, this would be the sum of the waiting times of all the passengers divided by the total number of passengers. Frequent studies have indicated that passengers become impatient after waiting about 30 sec in a commercial building, and about 60 sec in a residential building. From these observations comes the first requirement for good elevator service: The elevator system must be designed to provide average waiting time of less than 30 seconds in commercial buildings and less than 60 seconds in residential buildings (Strakosch & Caporale, 2010).

Average travel time (ATT) is the time it takes for an elevator to run from the bottom floor to the top of the building at full speed and without any stops on the way. It defines the minimum elevator speed v for travel height h.

3.3 Traffic Design Methods

Essentially, two models are used for traffic analysis and calculations (**Table 3.1**). One model uses a calculation method based on mathematical formulae. The second model, which has been used for over 30 years, is based on a discrete digital simulation of the building, its lifts and the passenger dynamics. This simulation model allows very complex situations to be analyzed.

3.3.1 Conventional design methods

The classical approach to the lift traffic design revolves around the calculation of the round trip time. The round trip time is then divided by the target interval (usually specified by the client or the nature of the building). By dividing the calculated round trip time by the target interval, the required number of lifts are found.

Analytical equation-based calculation:

The analytical equation-based design method relies on a number of equations that have been derived with a number of assumptions. At the most basic level, the three equations for the round trip time, probable number of stops and expected highest reversal floor are based on simplifications, under a number of special conditions. If any of the assumptions above are not true, then the equations can be modified in order to cope with that. However, as conditions become more complicated, deriving the relevant equations becomes more involved.

Numerical calculation:

In order to overcome the difficulties encountered in deriving new equations for the more general cases, numerical methods can be used to find the value of the round trip time. Examples include Monte Carlo Simulation (MCS) and Markov Chain Monte Carlo (MCMC) methods. In Monte Carlo Simulation, a probability density function (pdf) and a cumulative distribution function (cdf) are generated for the entrance floor arrival percentages. Another pdf and cdf are generated for the floor population percentages. Random sampling is used to generate random origin and destination floors for each passenger using the arrival percentages cdf and the population percentages cdf, respectively. This is repeated for each of the P passengers. The individual journeys are then combined to form the full round trip and the time taken to complete the full round trip is calculated. The scenario is repeated for a large number of trials (e.g. 100,000) and the average of all the values taken.

3.3.2 Advanced design methods

Discrete event simulation:

Discrete event simulation exploits the fact that lift traffic systems are discrete by their very nature. For example, when a passenger arrives in the lobby for service, the only times of interest from a traffic design are: the passenger's arrival time; the passenger's boarding time into the lift car and the passenger's alighting time from the lift car at his/her destination. What happens between these events is of no interest from the passenger's point of view.

Discrete event simulation generates the times at which significant events take place within the system. This fact has a substantial effect on the calculation time and the complexity of the software. This is the reason why a discrete event simulator can simulate lengthy hours of lift traffic activity at a fraction of the real time.

Time-slice simulation:

Time-slice simulation uses a fixed period of time (called the time slice) as the basis for advancing the simulation. The status of the system is evaluated and updated every time slice, regardless of whether any significant events have taken place or not. This has two disadvantages:

1. The simulation takes longer to complete. As the value of the time slice is reduced, this effect becomes more pronounced.

2. Where a large value for the time slice is selected it is no longer possible to record the exact time at which a discrete event takes place.

Table 3.1 : Comparison of the four methods, adapted from (Al-Sharif and Al-Adhem, 2013).

Criterion	Simplicity	Calculation time	Convergence to final value	Ability to evaluate group control algorithms
Method				
Analytical equation-based design	Very simple	Very fast	Instant	Not practical (although some equations have been developed)
Monte Carlo simulation	Simple	Fast	Practical (but is a com-promise between accuracy and processing time)	Limited to up peak group control algorithms
Discrete event simulation	Medium level of complexity	Slow	Requires the increase of the simulation time and the number of simulations	Ideal
Time-slice simulation	Medium level of complexity	Slow	Requires the increase of the simulation time and the number of simulations	Ideal

3.4 Traffic Calculations

3.4.1 Calculation of the round trip time

The calculation of the round-trip time is the basis for the conventional elevator system design method. The round-trip time is usually calculated analytically using equation, assuming a single entrance and up-peak traffic conditions. There will be some down travelling and inter-floor traffic during the up-peak period. It is recommended that all up-peak calculations are ‘pure’ with no other traffic considered. Then the calculation can be used as a benchmark to compare different designs and different competitive offers in a tender situation (CIBSE, 2005).

Assumptions made in the derivation of the round trip time equation:

1. Passengers arrive uniformly in time;
2. All lifts load to an average of 80%. In the round trip time calculation the lifts are assumed to fill to 80% of the actual capacity.;
3. All floors are equally populated;
4. Rated speed is reached in a single floor jump and inter-floor heights are equal.

Other factors affecting RTT calculations:

Landing and car call dwell times: Typical door dwell times are 2.0–3.0 seconds for a car call stop and 3.0–4.0 seconds for a landing call stop. Where a door dwell time is longer than the assumed passenger transfer time the round trip time equation needs to be adjusted to account for this.

Lobby loading interval: The loading interval is set to be equal to the time for a reasonable number of passengers to board the car. Thus, the loading interval should be set to the time it would take for the car to become about 60% loaded. There will then be no effect on the round trip time calculation due to the loading interval

Use of traffic control algorithm: The traffic control system (dispatcher) is assumed to be ideal. During up peak the controller is programmed to bring the cars to the main terminal floor immediately after the last passenger exits from the car at the highest demanded floor (H). Up-peak performance can be boosted by traffic control techniques such as up-peak zoning, up-peak sectoring, landing call allocation and landing call allocation with up-peak sub zoning (CIBSE, 2005).

The round trip time formula (RTT):

$$\mathrm{RTT} = 2\,\mathrm{H}\,\mathrm{t_V} + (\mathrm{S}-1)(\mathrm{T}-\mathrm{t_V}) + 2\,\mathrm{P}\,\mathrm{t_P} \quad \textbf{(3.1)}$$

P: Number of passengers in the car when it leaves the ground (does not need to be an integer).

H: Highest reversal floor

S: The probable number of stops

$\mathrm{t_V}$: Time to transit two adjacent floors at rated speed (s)

T: Floor to floor cycle time (s)

$\mathrm{t_P}$: Average passenger transfer time (entry or exit) (s)

Number of passengers in the car (P):

$$\mathrm{P} = \left(\frac{\%\mathrm{CF}}{100}\right)\mathrm{CC} \quad \textbf{(3.2)}$$

CC is car capacity of the elevator.

CF is car-loading factor of elevator.

Highest reversal floor (H):

The two parameters H and S are dependent on P (the number of passengers carried in the lift), and N (the number of floors served above the main terminal floor).

$$H = N - \sum_{i=0}^{N-1} \left(\frac{i}{N}\right)^{P} \tag{3.3}$$

Average number of stops (S):

$$\mathrm{S} = \mathrm{N}\,.\left(1 - \left(1 - \frac{1}{\mathrm{N}}\right)^{\mathrm{P}}\right) \tag{3.4}$$

Single floor transit time (t_v):

This is made up of the two variables: inter-floor distance (d_f) and rated speed (v). The inter-floor distance can be taken as the average inter-floor distance and is determined as the total travel divided by the number of possible stopping floors above the main terminal floor.

There is no theoretical upper limit to lift rated speed and speeds of 17 m/s have been installed. At very high speeds, passenger comfort may be affected. Speed is limited by practical factors such as maximum sheave diameter, rope bending radius (fatigue), rope wear, safety aspects (over-travels, etc.) etc.

$$\mathrm{t_V} = \frac{\mathrm{d_f}}{\mathrm{v}} \tag{3.5}$$

Floor to floor cycle time (T):

$$T = t_f(1) + t_{sd} + t_c + t_o - t_{ad} \tag{3.6}$$

$t_f(1)$: Single floor flight time (s). The single floor flight time is the time taken from the instant that the lift doors close until the lift is level at the next adjacent floor. It is dependent on the rated speed (v), the rated acceleration (a) and the jerk (j) value.

$$t_f(1) = \left(\frac{d_f}{v} + \frac{v}{a} + \frac{a}{j}\right) \tag{3.7}$$

t_{sd}: Start delay time (s). The start delay time includes the times for the doors to lock on closure, the motor field build-up, brake release, levelling, etc.

t_c: Door closing time (s). The door closing time is the time taken from the instant the lift doors start to close until they are locked up.

t_o: Door opening time (s). The door opening time (to) is the time from the instant that the lift doors start to open at a landing, until the instant that the doors are 800 mm open at the next floor.

t_{ad}: Advance door opening time (s). An improvement in the door operating times can be achieved by overlapping the levelling operation with the first part of the opening of the doors. This is called advanced door opening.

Door operating times are dependent on door width, weight and type. The three most common standard door widths of 800, 1100 and 1300 mm. There are two basic door types: side opening and center opening.

The passenger transfer time (t_P):

The passenger transfer time is the average time a single passenger takes to enter or leave a car. The passenger transfer time can vary considerably and is affected by the shape of the car, the size and type of car entrance, environment (commercial, institutional, residential), type of passenger (age, gender, agility, purpose), car loading.

$$\mathrm{t_P} = 0.5\ (\mathrm{t_l} + \mathrm{t_u}) \qquad \textbf{(3.8)}$$

t_l: Passenger loading time (s)

t_u: Passenger unloading time (s)

Average travelling time (ATT):

This has been defined as the time from when a responding lift begins to open its doors at the boarding floor until the doors begin to open again at the destination floor. It is useful to know the average time it would take for an average passenger to reach their destination floor (assumed to be half way up the building zone being served) after their allocated lift is ready for boarding with its doors opening (CIBSE, 2005).

$$\mathrm{ATT} = 0.5\ \mathrm{H}\ \mathrm{t_V} + 0.5\ \mathrm{S}\ \mathrm{t_S} + 1.5\ \mathrm{P}\ \mathrm{t_P} \qquad \textbf{(3.9)}$$

Average waiting time (AWT):

Many lift companies state this to be half the interval. Passenger average waiting time (AWT) is the sum of all the individual passenger waiting times divided by the number of calls. Average waiting time is not dependent solely on the interval, but is also affected by the average car load and the arrival probability distribution function.

$$\mathrm{AWT} = [0.4 + (1.8 \times \mathrm{cc}\ /\ 100 - 0.77)^2]\mathrm{INT} \qquad \textbf{(3.10)}$$

It is assumed that the passenger waiting time for each passenger starts as soon as he/she arrives in the lobby and finishes when he/she starts boarding the elevator.

Calculations for zoning:

The number of floors in a zone, the number of lifts serving a zone and the length of the express jump all affect the round trip time. The round trip time equation can be adjusted by adding a time equal to the time taken to pass the unserved floors in both directions.

$$\mathrm{RTT} = 2\,\mathrm{H}\,\mathrm{t_V} + (S-1)(\mathrm{T}-\mathrm{t_V}) + 2\,\mathrm{P}\,\mathrm{t_P} + \frac{2\mathrm{d_x}}{\mathrm{v}} \quad \textbf{(3.11)}$$

where t_e is the flight time from the main terminal to the express zone terminal (sky lobby) (s).

3.4.2 Deciding elevator numbers and capacity

Deciding the required number of elevators for a new building, is the most challenging part. If the building gets complicated, it becomes more crucial. Especially in big projects, elevator specialists are including to the design process. However, elevator specialist or consultant mostly use his previous experiences or case buildings to estimate the required number of elevators. By making assumptions, he analyses different alternatives using comprehensive elevator traffic analysis methods to find the best suited one.

Design parameters used in traffic calculations can be categorized in three; building characteristics, elevator characteristics and traffic requirements. Project characteristics is the major factor in elevator traffic design. Each building has its own design goals mostly designated by the project owner therefore, each has its own variables affect the elevator traffic. The other factor affecting the elevator traffic planning is elevator characteristics. The type, speed and capacity of elevators are the key parameters. Traffic requirements are performance criterion of an elevator traffic. These factors are discussed in detail, in traffic calculations section.

In elevator planning, the number, size and performance of the elevators are mostly determined by two planning parameters: the up-peak handling capacity and interval. In an elevator group with several elevators, the handling capacity may be good and the interval may be short, but the round trip time and passenger ride time inside the car may be long. Instead of the interval, more comprehensive and understandable criteria would be to use the average passenger waiting and journey times in up-peak. For the average passenger waiting time, half of the interval value and criteria could be used even though they give rough estimations of the average waiting time. By using the average journey time in elevator planning, the total time a passenger spends in an elevator system would remain short. In a high-rise building the journey time criterion sets a limit on the number of floors served by an elevator group (Siikonen, 1997).

3.5 Case Traffic Analysis and Simulation Models

Analytical lift traffic models and derived lift performance measures (e.g., round trip time, number of stops, and number of passengers per trip) are covered comprehensively in Barney and Santos (1985) and Barney (1986). The predictability of mathematical models in this context relies on the simplifying assumptions made about the passenger movement.

The DSS Elevate, developed by Peters (1998), is available in the market as a development platform for elevator control and traffic analysis (**Figure 3.3**). A zoning option for high-rise buildings is available where certain floors served by the same lift group are only accessible by these lifts. However, a limitation is that each lift group can only be analyzed separately. The impact of different lift groups on passengers cannot be simulated simultaneously. Passengers with a specific origin–destination need first to be sorted into the right lift group. When the zoning policy involves passengers changing lift groups on some floors, the pre-processing of passenger traffic has to be done manually and so will take up a lot of time.

Kone Building Traffic Simulator (BTS) is able to simulate the traffic flow of a whole building with multiple transports. It also models the behavior of various passenger types, such as adults, children and disabled people. In the BTS, any building can be specified, as well as all the transportation devices inside the building. The capability of the transportation devices to handle passenger traffic can be tested in various situations. With the BTS simulator, for instance, the evacuation of the building in an exceptional situation can be tested. The BTS interface has a building design view for constructing a specified building. The user can draw the floor shape of the building for each floor or only the floors where the building shape is changed (**Figure 3.4**). The elevator and escalator groups can be dropped in their correct positions on the floor.

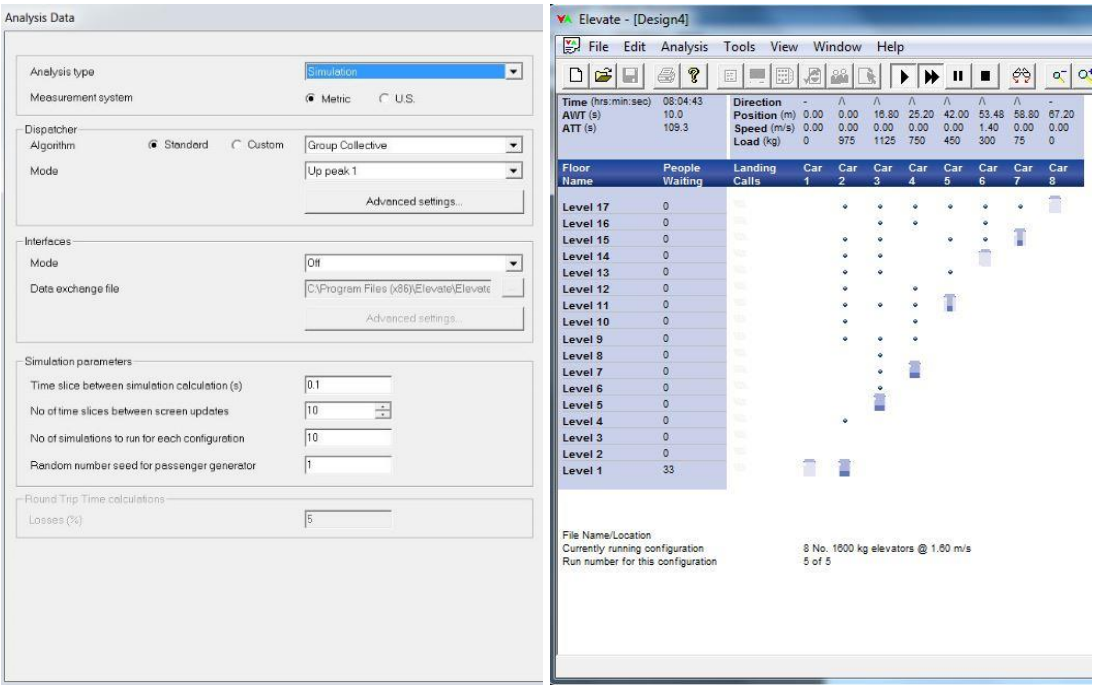


Figure 3.3 : Elevate – elevator traffic simulator interface.

In BTS, population distribution is both floor and tenant related. Passenger traffic is usually given as incoming, outgoing and inter-floor traffic components. In BTS, the traffic components are defined on a per-tenant basis, not per-elevator group. BTS defines four traffic components for each tenant: incoming, outgoing, intra-tenant and inter-tenant. The actual parameters for the building, elevators, escalators and passenger traffic are defined through a simple Microsoft Access interface. The BTS main program contains a user interface where the initial data for each simulation is defined. The simulation itself is event driven.

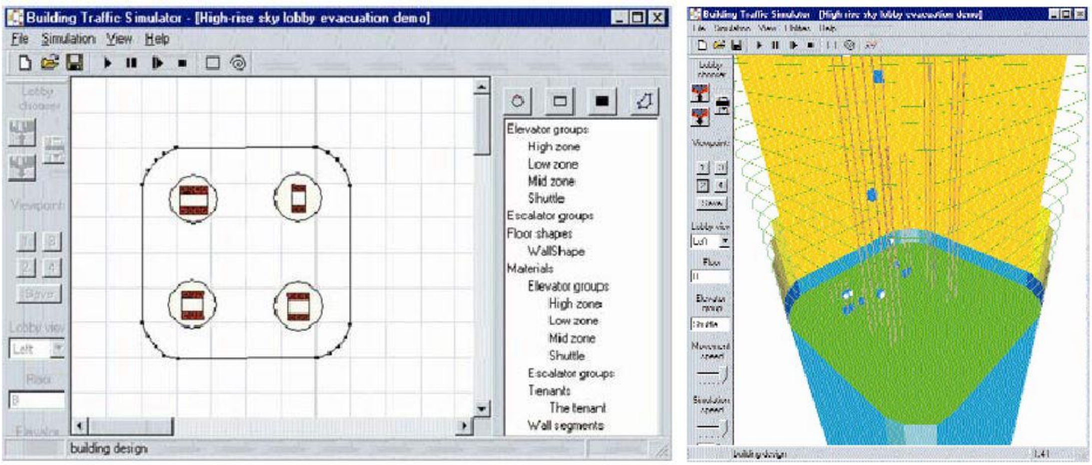


Figure 3.4 : User interface of Building Traffic Simulator (Siikonen, Susi and Hakonen, 2001).

Al-Sharif (2013), proposes an automated optimal design methodology of elevator systems using rules and graphical methods. In the method, inversed the conventional up peak analysis formulae inversed to estimate the number of passengers using a lift. The methodology starts from the calculation of expected number of passengers boarding an elevator car. Then, the round-trip time is calculated using other tools (Monte Carlo simulation) and the optimum number of elevators is calculated. The model also suggests the optimization of speed and capacity of elevators to explore the possibility of reducing the number of elevator cars. Finally, all results are transferred to the graphic called HARint plane that is presented as a graphical tool that allows the designer to visualize the solution (**Figure 3.5**). In Further unpublished work of Al Sharif (2014), he added a zoning policy for tall buildings and analysis of average trip time and average waiting time of results. However, the model only works for up peak and down peak traffic patterns as it uses round trip time calculations. In addition, the model uses total building population and equal floor-to-floor height.

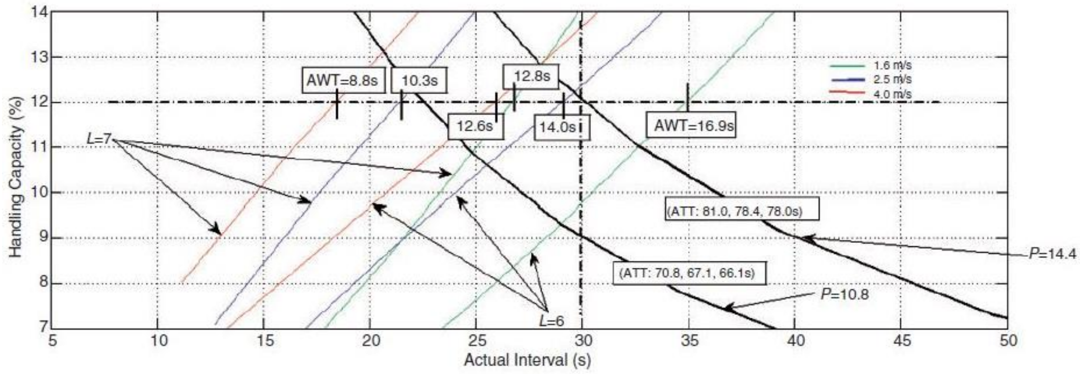


Figure 3.5 : Graphical representation of HARint plane, (Al-Sharif, 2013).

Cortes, Munuzuri and Onieva (2006), proposed a design and analysis of a tool for planning and simulating dynamic vertical transport. The objective of SimMP model is to provide not only a simulation tool but also a tool capable of helping designers in the design process of vertical transportation system. The tool allows selecting the number of cars to be installed, the kinematics group, the technical characteristics of the elevator group and of each specific car, and the optimization algorithm, among several other options accordingly with the building profile (**Figure 3.6**). The tool has a database set with adaptable configurations for several types of buildings (with diverse typologies, such as housings, professional uses, etc.), as well as different elevator technologies and functional specifications. A database for feasible traffic is also loaded. However, the user can modify or create new data for all these aspects. The system includes a set of optimization algorithms. Nevertheless, the user can design any kind of optimization algorithm according to the specifications of the dll input file, which allows the correct performance of the simulation engine. SimMP output includes graphical and text reports that allow the user to select among diverse tests for alternative configurations of the elevator group characteristics and/or the elevator controller. The tool includes an advanced configuration interface, as well as a quick start option with most of the values preselected.

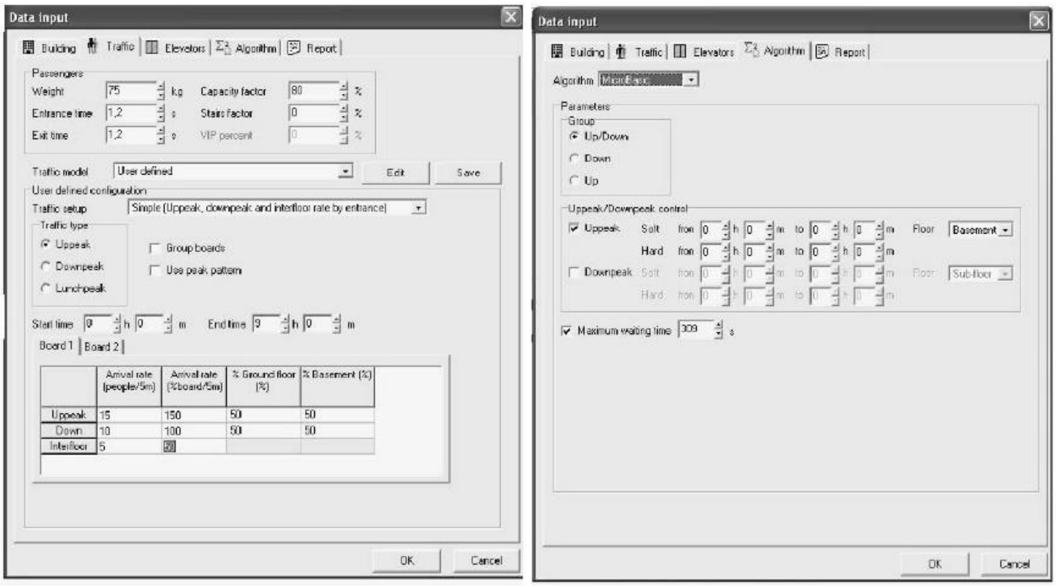


Figure 3.6 : User interface of SimMP, (Cortes, Munuzuri, & Onieva, 2006).

4. A DECISION SUPPORT MODEL FOR ELEVATOR SYSTEM DESIGN IN TALL BUILDINGS

In tall building design process generally, architects are the main decision maker for the building conception. Especially in the conceptual design phase, decisions on building circulation, both horizontal and vertical, plays an important role. Making decisions to achieve an optimal vertical transportation indicates an expert knowledge or research on existing buildings. For this demand, sometimes, elevator specialist are participating into the conceptual design stage. Otherwise, designers may have problems at further design steps if the determined core dimensions or the number of elevators are not satisfy the building needs.

The design of an elevator system is a multi-objective optimization problem that comprises the selection of the number, speed and capacity of the lifts, as well as, the selection of the most appropriate elevator configuration. Elevator system also aims to minimize traffic parameters like the average waiting time and the average travelling time of the passengers in addition to cost, energy efficiency and safety, structural and seismic considerations. As the building gets higher, the parameters getting more complicated. In other words, designers need to consider several factors affect the vertical transportation design to achieve an optimal elevator system solution.

Principally, the design of an elevator system is based on traffic analysis. Various methods and different commercial software have been developed for analyzing the elevator traffic of a building. Fundamentally, each method are using standard traffic calculations. While conventional methods are using analytical equations, advanced methods combines the analytical equations with complex computer models of simulations. With few exceptions, most of them are developed to analyze initially designed elevator systems to check the efficiency according to traffic requirements. Conventional traffic calculations are based on a principle that designer picks a relevant speed and car capacity of elevators will be used in the building. Then, round-trip time (RTT) is calculated according to designated speed and car capacity. Finally, the number of required elevators are calculated by dividing the RTT to the target interval. The determined number of elevators are then, analyzing to check if it satisfies the performance parameters or not. If not, designer increases or decreases the number of elevators and makes all calculations from the beginning. In this trial and error method, the most important problem is that how designer would act if some parameters were within the performance criteria and how he/she would decide that he/she had the optimal solution. Yet, making decisions to achieve an optimal elevator system indicates an expert knowledge or research on existing buildings.

In brief, the proposed model established in this research focuses on following problems:

- The design of an elevator system for tall buildings involves multidisciplinary considerations in terms of architectural, functional and technical requirements.
- Various methods and different commercial software developed for elevator traffic design, mostly, analyze initially designed elevator systems to check the efficiency of the system according to traffic requirements.
- Traffic calculations used for determining the required number of elevators in a building, based on a principle that designer picks a relevant speed and car capacity of elevators. Without any experience or expert knowledge, the decision of picking a rated speed for elevators is arbitrary.
- After determining the number of elevators using traffic calculations, designer cannot be sure if he/she has an optimum solution.

This research aims to establish a decision support model for elevator system design in tall buildings. The model is conceptualized for giving support to architects in the planning and conceptual design stage of a tall building that helps to find optimum number of passenger elevators, their speed and capacity without having any expert knowledge or experience. In addition, the model establish a method for splitting a building into zones to optimize the number of elevators and the core space needed.

The proposed model is considered as part of a comprehensive system, which determines the optimum vertical transportation for tall buildings including elevators, escalators and stairs. In this research, elevator system, which is the major element of a vertical transportation of a building, is examined. The model only comprise passenger elevators so, goods elevators and fire-fighter lifts are out of scope. In addition, the model is implemented for tall office buildings as the traffic analysis calculations are coded for up-peak traffic conditions which is the determinant traffic pattern of an office building elevator system. If complex analytical equations were added in the model for other types of traffic patterns, the model could also be implemented for different building uses. The model has a height limit of 40-storey, because tall building more than 40-storey need special solutions like sky lobby system. Since, the calculations of sky lobby system are more complex than other solutions, the model implemented for office buildings under 40-storey.

Implementation of the model comprises:

1) Office buildings under 40-storey,
2) Passenger elevators,
3) Up peak traffic calculations,
4) Conventional traffic control algorithm

Assumptions made in derivation of the model:

1) One type of elevator kinematics used for traffic calculations,
2) There is one main entrance to the building,
3) There is no special floors like restaurant, entertainment or technical floor,
4) Fire safety regulations are omitted,
5) There is no stair use between inter floors,
6) Cost used as a constraint only by reducing the number of elevators

As an output, the model produces number of elevators, their capacity and speed for a given project. If it is needed model also, propose a zoning policy besides, the elevators, their speed and capacity for each zone. Eventually, all results are transferring into a spreadsheet as a final documentation.

4.1 Method

The model named as a decision support model as it is conceptualized for giving support to architects in the planning and conceptual design stage of a tall building that helps to find optimum elevator system without having any expert knowledge or experience. Since therefore, designer can avoid having problems at further design steps that forces to change the all vertical transportation system decisions by trial and error method, if the determined core dimensions or the number of elevators are not satisfy the building needs.

Analytical traffic analysis method is used in the model and conventional up-peak traffic calculations are combined with Al Sharif's inverse calculation method. The inverse method is used to find the number of passengers will be in elevator car in any round trip journey of the elevator, and then this number is used in standard up-peak traffic calculations. The parameters affect the elevator system design are provided from previous field studies through literature survey and elevator kinematics are provided by lift companies.

The reason of using the Grasshopper for the implementation of the model is to supply a medium for geometric relations and queries for further developments. For instance, the distance from main entry to the elevator lobby, efficiency of elevator configuration, fire regulations could be added to the model.

4.2 Model Development

Model use inputs generated by recommended technical standards and general assumptions from literature surveys; and user defined parameters about the building's characteristics. The process starts with the calculation section. In this part, analytical equations of elevator traffic analysis are used to determine the number of elevators, their speed, capacity and total area for specified elevators. The result of the calculation part excludes any elevator grouping or zoning policy, they are all assumed as single deck cars in single shafts. The aim is to estimate an approximate number of elevators for a specified building. The second part is optimization. In this part, the model aims to increase the number of elevators by using elevator grouping and zoning policy. As a result of the optimization section, model suggest alternative solutions that fit with building characteristics and estimated building traffic. In the last part, alternative solutions testing by existing simulation software to find the best solution.

As shown in the **Figure 4.1**, there are three types of inputs used in the model; building data, traffic data and elevator data. Building data comprises user-defined parameters like building height, number of floors, net floor area and so forth. Traffic data is related with the traffic analysis parameters like, arrival rate, target interval etc. The values of the parameters are taken from the traffic surveys exist in the literature. The third type of data is elevator data, which consists parameters about the dynamics of elevator, would be used in the elevator system of the building. These data type is dependent on the elevator type, means elevator specific. In the implementation phase, the values of the parameters are specified by the elevator standards. All data types are used in all sections of the model.

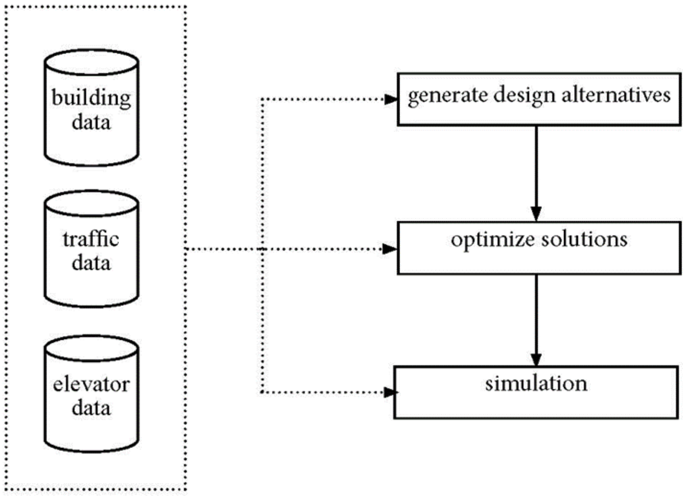


Figure 4.1 : Process flow of the model.

4.2.1 Flow chart

The first section of the model is generating design alternatives. The concept of this section is finding three alternatives that gives the best fitted solution for the number of elevators, their speeds and capacity, dimensions and the total shaft area needed. They are all specifying by using analytical equations of traffic analysis.

The process starts when the user enters building data (parameters are defined in Section 4.2.2) as shown in **Figure 4.2**. If the total building population is entered, process continues with calculating number of passenger will board in elevator in a single car. If not, building population is calculated first and then number of passengers in car. According to target travel time for an office building and its total height, the applicable three alternative elevator speed is calculated. By using elevator speed, number of passengers in a single journey and traffic data, traffic calculations are produced. Process continues calculating the round trip time. As, the round trip time obtained from calculations, model finds the number of elevators required in specified speed. Then, performance criterions handling capacity, average travel time, average waiting time is calculated according to specified number of elevators. Finally, for a specified speed and number of elevators the car capacity and the area of elevators occupy a place in the plan layout is calculated. The whole process is repeated for the second alternative speed. After, finishing the calculations, all results for three alternative are transferring to a spreadsheet via add-on that connects Grasshopper to MS Office Excel.

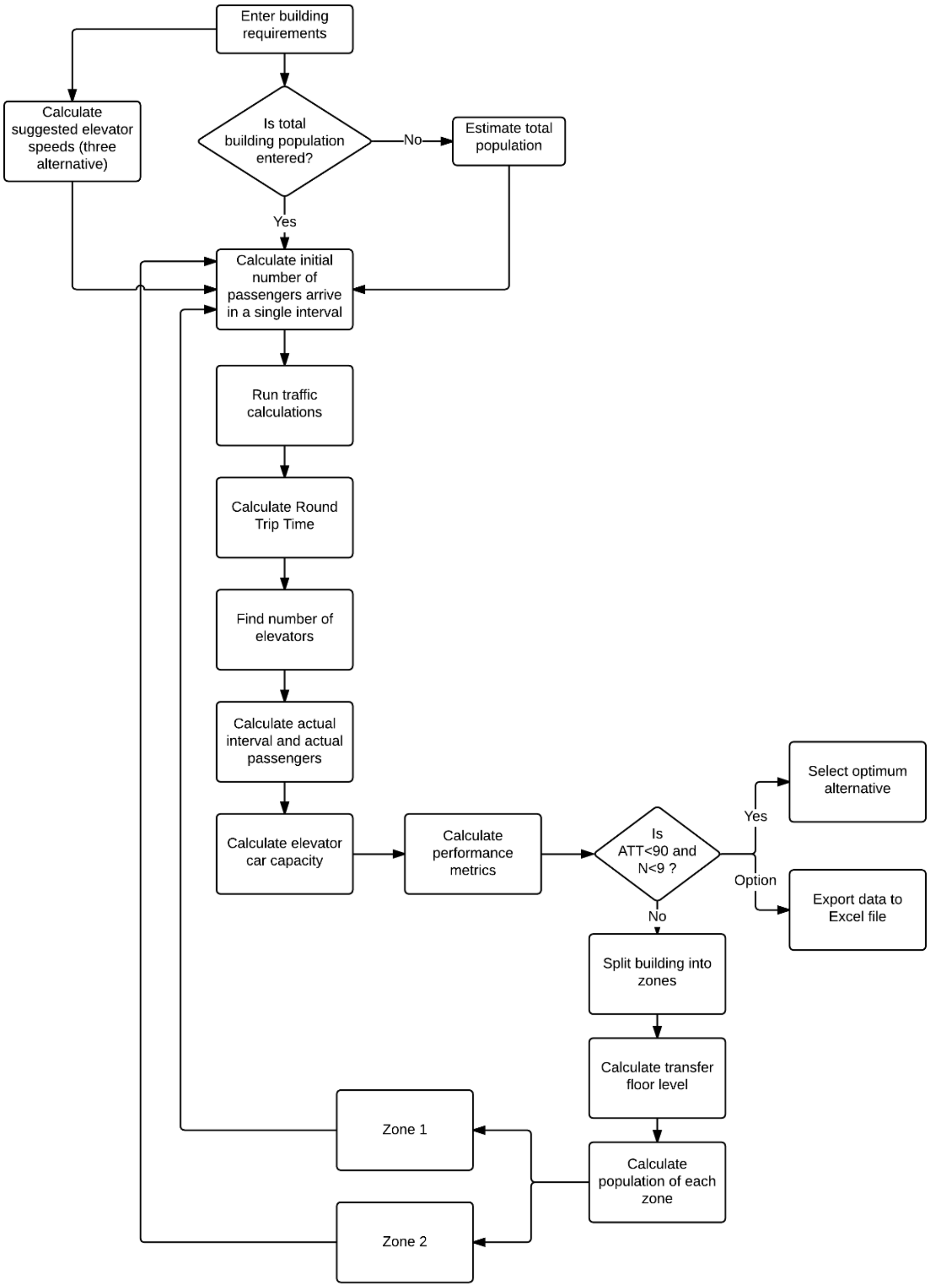


Figure 4.2 : Flow chart of the model.

According to results of three alternatives, if the performance results within the target values, then the alternative, which has the minimum number of elevators is selecting as a result. If all alternatives have the same number of elevators, the result is approved as the alternative, which has the minimum speed. Unless, all results satisfy the performance criterion then, the second part of the model starts.

The second section is optimizing solutions. To increase the number of elevators, a zoning policy is implemented. Zoning is the method to split the building into zones. If the average travel time is larger than 90 seconds or the number of elevators are more than 9 elevators, model splits the building into zones. For each zone model finds the number of elevators, speed and capacity by traffic calculations as in the first section. Zoning policy of the model uses general rule of thumb, which is splitting total number of building floor to 60% to 40%. As an output, the optimization section crates again three alternatives for each zone, separately. The important criterion in the zoning is selecting the same number of elevators for each zone. Like the design generation section, three alternatives are created for three different elevator speed. The number, capacity, dimensions and shaft area needed is defined as an output.

After all calculations are finished, the model proposes only one alternative as an optimum solution if there is no zoning result. Otherwise, the model proposes two alternatives; the solution without zoning and the optimum solution for zoning to give selection chance to user. All design alternatives and results are transferring into an Excel file to demonstrate.

4.2.2 Input parameters

Inputs used in the model can be categorized into three as building data, traffic data and elevator data. The first one is building data that can be also named as project data, as it consists of user defined building parameters (**Figure 4.3**).

The parameters of the building data are listed below:

Building function: is the use of building like office, residence, hotel etc. In the implemented model, the only option is office building.

Building character: For office buildings, the character of the building is categorized according to its tenant. The options are diversified; multiple tenants from different professions, diversified single-purpose; multiple tenants from the same profession; single purpose; one tenant building like headquarter.

Number of floor above main entrance: In the model development process, it is assumed that building has one main entrance so; the number of floor above main entrance corresponds to number of floors minus one.

Building population/floor populations (people): User enters the total number of building population or each floor population individually, if it is specified. If not, to calculate the building population user enters net floor area of the floor plate.

Average floor height/inter-floor distance (m): User enters average floor height or if it is specified, enters each floor height individually. If the floor height differs, it must be added to calculations to get accurate solutions.

Net floor area/gross floor area (m^2): If the total building population is not known, net floor area or gross floor area of the building plate is used to calculate the population.

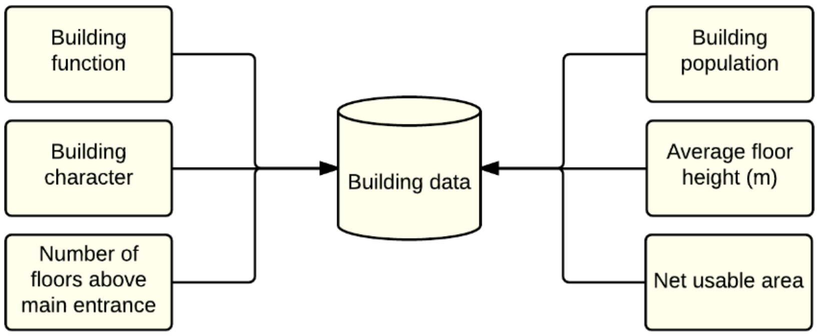


Figure 4.3 : Parameters of building data.

The second type of input is traffic data that consists values derived from past researches and used as target traffic values for building (**Figure 4.4**). Traffic data can be user defined in terms of target service level of the building, which is determined by project owner. In this model, target values are specified from previous studies. Ex; the target interval for office buildings are 25-30 seconds.

The parameters of traffic data are as followed:

Area per person (m^2/person): is used if the building population is not defined by user. Due to the use of building area per person differs.

Arrival rate (%): The number of passengers arriving at an elevator system for service during a five minute peak period depends on the use of building.

Target interval (s): The average time between successive car arrivals at the main terminal is assumed as quality of service parameter of the elevator system in some instances. As it is used traffic calculations, the target values are specified in literature according to use of building.

Target travel time (s): is used to analyze the performance of an elevator system. Thus, the target values also defined as a range for different building functions.

Target handling capacity (%): The total number of passengers that an elevator system can transport in a period of five minutes during the up peak traffic condition with a specified car loading has target values for different use of buildings. As a performance measure, the elevator system should satisfy the demand.

Passenger loading/unloading time: The average period of time required for a single passenger to enter and to leave an elevator car depend on door type of an elevator and elevator layout.

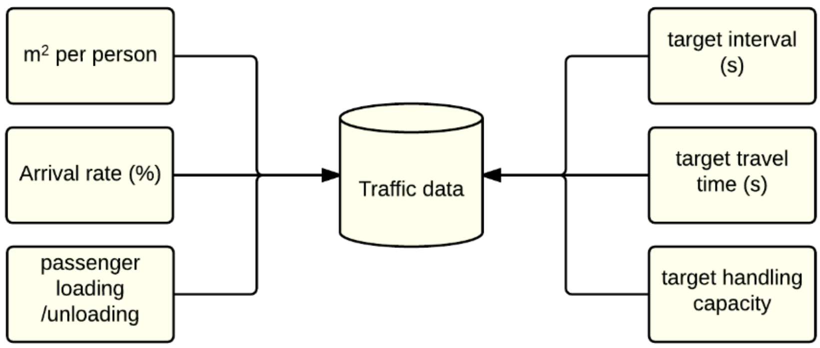


Figure 4.4 : Parameters of traffic data.

The third type of input is elevator data. Elevator data comprises parameters related with technical specifications of an elevator (**Figure 4.5**). Since the values changes according to type of the elevator, in the model selected type and its technical parameters are derived from a lift company. The parameters are listed as followed:

Elevator type: According to elevator type used in the building, different results are obtained from traffic calculations. As it is assumed in the model, one elevator type and its kinematics are used.

Car capacity (person): is the number of people that elevator can carry.

Car area (m²): According to car capacity, elevator has a car wide and car depth. Car is the inside area of the elevator cabin.

Acceleration (m/s^2): The time it takes for a lift to travel between two floors is limited by the rated speed, acceleration and jerk. Acceleration is related with jerk.

Jerk (m/s^3): Acceptable jerk values for lift performance are dependent on the lift speed. The jerk is rate of change of acceleration.

Door opening/closing times (s): Due to the door type of an elevator (central, one side etc.), the time of opening and closing differs and it effects the time calculations.

Advanced door opening time (s): The initiation of door opening whilst a car is slowing into a floor, under normal operating conditions, usually when the car is in a door zone of plus or minus 200 mm of floor level and such that the car is substantially level at the floor before passengers can attempt to exit.

Start delay time (s): is the time between elevator gets a call and responses when it starts.

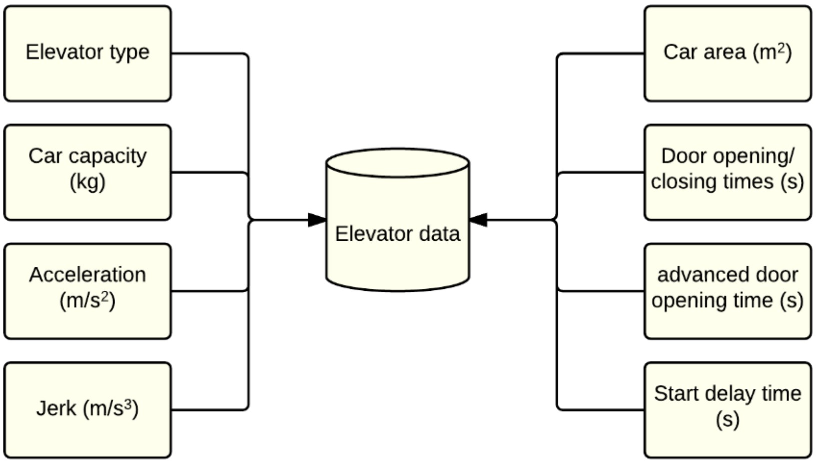


Figure 4.5 : Parameters of elevator data.

4.2.3 Calculations

As the model is implemented in Grasshopper tool, clusters are created for each calculation step. Each cluster consists different analytical equations inside. It has input(s), equation(s) and output(s). The clusters and calculations are discussed in this section.

The numerical values used in the equations taken from the standards and pervious works can be found in Appendix C.

Calculation of building population (U):

Estimation of building population is the basis of calculations. There are three options related with building population. User can define the amount of total building population or individual floor populations (**Table 4.1, Table 4.2**). If both of them is not stated, the estimation would be made using net floor area indicated by user and spatial standards constitutes the area per person for a specific building type. For each option, the calculation procedure varies.

Table 4.1 : Population estimation through net usable area.

Input	Formulae	Output
• Net Usable Area (m^2) • Area/person (m^2) • Number of floors above main terminal	$U = \left(\frac{NUA}{app}\right) N$	• Total building population
Cluster		

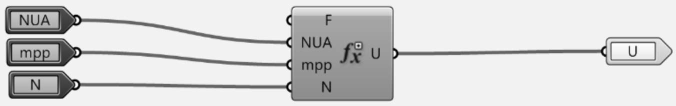
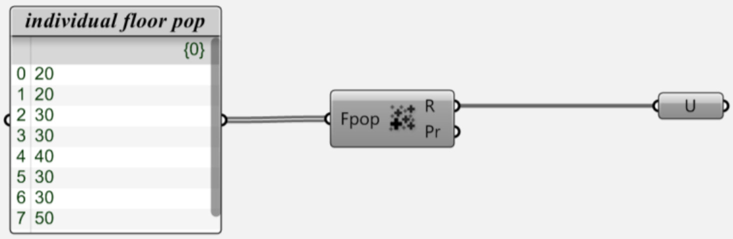


Table 4.2 : Population estimation through individual floor populations.

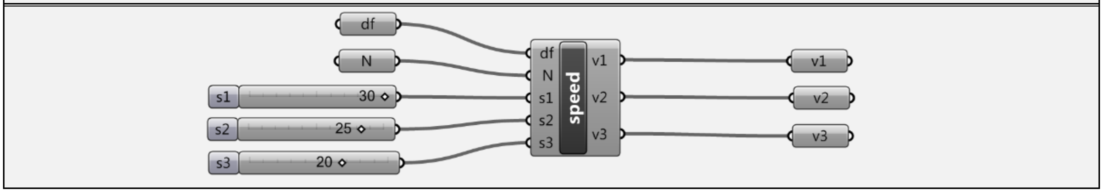
Input	Formulae	Output
• Individual floor population (U_i) • Number of floors above main terminal	$U = \sum_{i=1}^{N} U_i$	• Total building population
Cluster		



Calculation of suggested elevator speeds (v):

The model is conceptualized for creating three design alternatives for suggested elevator speeds (**Table 4.3**). The suggested speed is calculated due to the time that passengers could travel in the elevator. The maximum time is 30 seconds in practice. For three suggested speed, total travel height is divided by 30, 25 and 20 seconds. The total height is calculated by multiplying the floor-to-floor height with number of floors above main entrance.

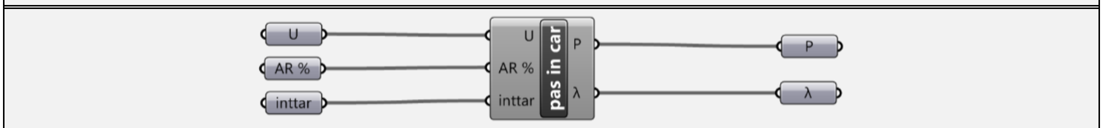
Table 4.3 : Calculation of suggested speed.

Input	Formulae	Output
• Floor height • Number of floors above main terminal • Suggested travel time 1 • Suggested travel time 2 • Suggested travel time 3	$v = \left(\frac{d_f\ N}{s}\right)$	• Suggested speed 1 • Suggested speed 2 • Suggested speed 3
Cluster		
		

Number of passengers in a car:

This is the number of passengers that will board the elevator from the main entrance (in the case of a single-entrance arrangement). This depends on three parameters that are all known at the start of the design process and are usually provided by the client, the developer or the architect (**Table 4.4**). These are the target interval, int_{tar}, the arrival rate, AR%, and the total building population, U. The calculation is different from the conventional method. In the model, the inverse calculation method proposed by Al-Sharif is used as mentioned in Chapter 3.5.

Table 4.4 : Calculation of passengers that will arrive in a single interval.

Input	Formulae	Output
• Total building population • Arrival rate • Target interval	$P = (int_{tar} \ . \ \lambda)$ $\lambda = \frac{AR\% \ \ U}{300}$	• Actual number of passengers that will arrive in a single interval • The arrival rate expressed in units of persons per second
Cluster		
		

Traffic Calculations (S, H, t_v, T, t_p, d_H):

Traffic calculations are the name of the cluster that calculates the parameters used in round trip time calculations. It comprises heights reversal floor, number of probable stops, average passenger transfer time, single floor transit time and floor-to-floor cycle time for equal floor population (**Table 4.5, Table 4.6**). In addition, for unequal floor population and floor height calculation differs. Travel distance to the highest reversal floor is calculating for unequal floor heights.

Table 4.5 : Traffic calculations for equal floor populations.

Input	Formulae	Output
• Number of floors above main terminal • Passengers in a single interval • Floor height • Speed • Acceleration • Jerk • Door opening time • Door closing time • Start delay time • Advanced door opening • Passenger loading time • Passenger unloading time	$S = N \cdot \left(1 - \left(1 - \frac{1}{N}\right)^{P}\right)$ $H = N - \sum_{i=0}^{N-1} \left(\frac{i}{N}\right)^{P}$ $\mathrm{t_V} = \frac{\mathrm{d_f}}{\mathrm{v}}$ $T = t_f(1) + t_{sd} + t_c + t_o - t_{ad}$ $t_p = \frac{t_1 + t_u}{2}$	• Number of probable stops • Highest reversal floor • Single floor transit time • Floor to floor cycle time • Average passenger transfer time

Cluster

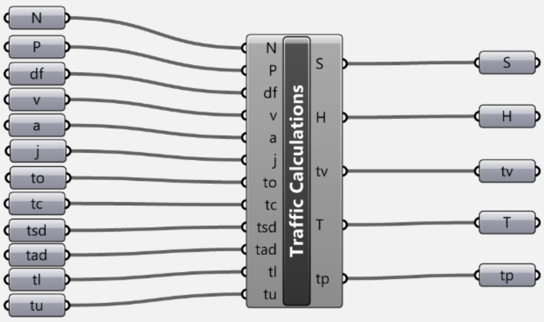
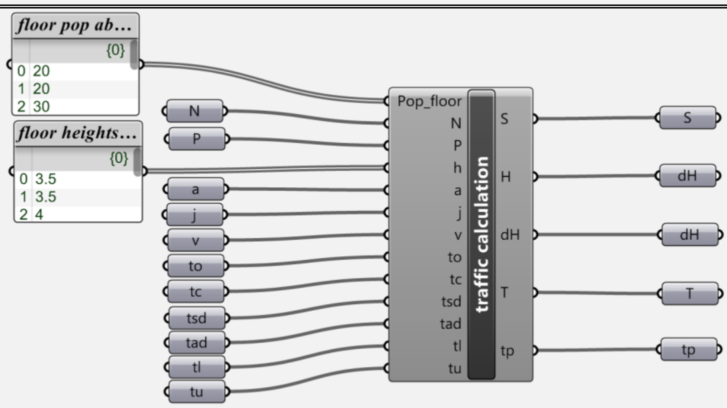


Table 4.6 : Traffic calculations for unequal floor population and floor height.

Input	Formulae	Output
• Individual floor populations • Number of floors above main terminal • Passengers in a single interval • Individual floor heights • Acceleration • Jerk • Speed • Door opening time • Door closing time • Start delay time • Advanced door opening • Passenger loading time • Passenger unloading time	$S = N - \sum_{i=1}^{N} \left(1 - \frac{U_i}{U}\right)^{P}$ $H = N - \sum_{j=1}^{N-1} \left(\sum_{i=1}^{j} \frac{U_i}{U}\right)^{P}$ $d_H = \left(\sum_{i=0}^{floor(H-1)} h_i\right) + \left(H - floor(H)\right)$ $T = t_f(d) + t_{sd} + t_c + t_o - t_{ad}$ $t_p = \frac{t_1 + t_u}{2}$	• Number of probable stops • Travel distance to highest reversal floor • Floor to floor cycle time • Average passenger transfer time

Cluster



Round trip time calculation (RTT):

Conventional traffic calculations are based on the calculation of round trip time. The model also proposes design solutions through the calculation of RTT. For unequal floor population and floor height, the calculations are more complex than the equal ones (**Table 4.7, Table 4.8**).. For complex equations, Visual Basic code was written.

Table 4.7 : Calculation of round trip time for equal floor population and floor height.

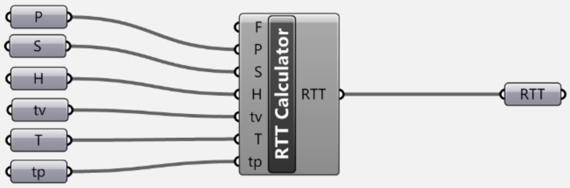
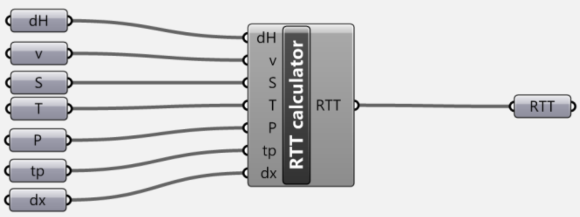
Input	Formulae	Output
• Passengers in a single interval • Number of probable stops • Highest reversal floor • Single floor transit time • Floor to floor cycle time • Average passenger transfer time	$RTT = 2\,H\,t_V + (S+1)(T - t_V) + 2\,P\,t_P$	• The round trip time
Cluster		
		

Table 4.8 : Calculation of round trip time for unequal floor population and floor height.

Input	Formulae	Output
• Travel distance to highest reversal floor Speed • Number of probable stops • Floor to floor cycle time • Passengers in a single interval • Average passenger transfer time	$RTT = \left(\frac{2d_H}{v} + (S+1)\left(T \quad - \frac{d_h}{vS}\right) + 2\,P\,t_p\right)$	• The round trip time
Cluster		
		

In express zone calculation, the time an elevator travels during the unserved floor is adding to the round trip time calculation to find the time an elevator spends to reach the upper floor zone. The calculation of round trip time for express zone is shown in **Table 4.9**.

Table 4.9 : Calculation of round trip time for express zone.

<table>
<tr><th>Input</th><th>Formulae</th><th>Output</th></tr>
<tr><td>

- Travel distance to highest reversal floor Speed
- Number of probable stops
- Floor to floor cycle time
- Passengers in a single interval
- Average passenger transfer time
- Total height for unserved floors in express zone

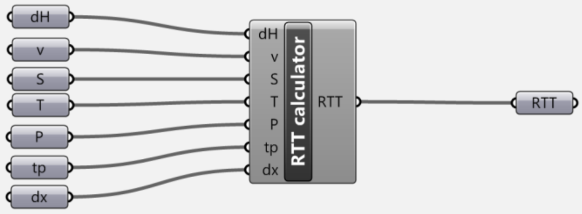
</td><td>

$\mathrm{RTT} = \left(\frac{2d_H}{v} + (S+1)\left(T^* - \frac{d_h}{vS}\right) + 2\,P\,t_p + \frac{2d_x}{v}\right)$

</td><td>

- The round trip time

</td></tr>
<tr><th colspan="3">Cluster</th></tr>
<tr><td colspan="3">



</td></tr>
</table>

Number of elevators (L):

The number of elevators are derived from the division of RTT by the target interval time. The target interval is dependent on the building function. For office buildings, the target interval is mostly between 25-30 seconds. The exact number is specified by the building character, which is classified as single tenant, multi- tenant and multi-tenant for single purpose office buildings (**Table 4.10**). As the value of round trip time is found as decimal number, it should be round to an integer.

Table 4.10 : Calculation of required number of elevators.

<table>
<tr><th>Input</th><th>Formulae</th><th>Output</th></tr>
<tr><td>

- Round trip time
- Target interval

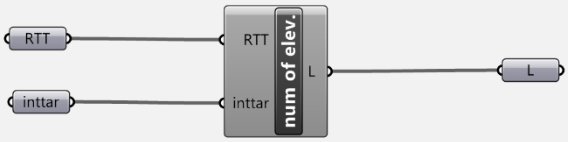
</td><td>

$L = \frac{\mathrm{RTT}}{\mathrm{int}_{tar}}$

</td><td>

- Number of elevators

</td></tr>
<tr><th colspan="3">Cluster</th></tr>
<tr><td colspan="3">



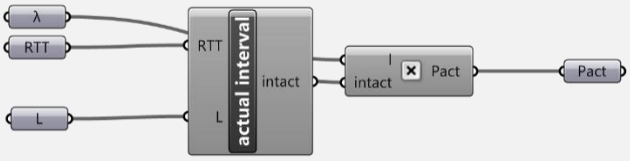
</td></tr>
</table>

Actual interval and number of passengers in a single interval:

While deciding the number of elevators, the model round down the decimal number to an integer. First, actual interval is derived from the division of round trip time by the arrival rate expressed in units of persons per second. Then, actual number of passengers specified due to the actual interval (**Table 4.11**). As the target interval is used in calculations, the model finds the actual number of passengers in a single interval of determined number of elevators.

Table 4.11 : Calculation of actual interval and number of passengers in a single interval.

Input	Formulae	Output
• Round trip time • Target interval	$\text{int}_{act} = \frac{RTT}{L}$ $P_{act} = \frac{\lambda}{\text{int}_{act}}$	• Number of elevators
Cluster		

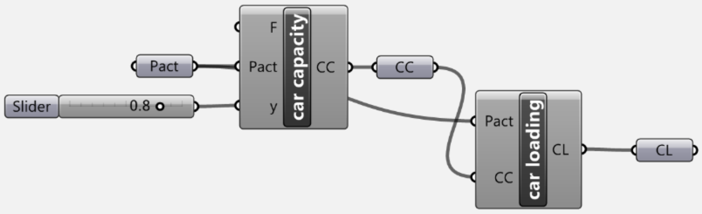


Elevator car capacity (CC):

As distinct from the conventional methods, the model determines the required elevator capacity by using the actual number of passengers that will arrive during the single interval. Elevator capacity is directly related with the rated load of passengers. In the model one passenger weight is assumed as 75 kg. The elevator car capacity calculation cluster is showed in **Table 4.12**.

Table 4.12 : Calculation of elevator car capacity.

Input	Formulae	Output
• Actual number of passengers in a single interval • Maximum car loading factor	$CC = \frac{P_{act}}{0.8}$ $CL = \frac{P_{act}}{CC}$	• Elevator car capacity • Car loading factor
Cluster		



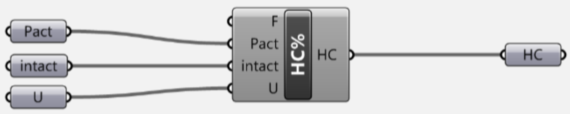
4.2.4 Performance metrics

In the model, as a performance criterion the handling capacity, average waiting time and average travel time is used. Each criterion is important for an elevator system design. In conventional methods, handling capacity is the determinant factor. But the model, first check the handling capacity of the desired system then, the average travelling time. Because, the average travelling time both effects the handling capacity and the average waiting time.

Handling capacity (HC):

Handling capacity is the total number of passengers that an elevator system can transport in a period of five minutes during the up peak traffic condition with a specified car loading, usually taken as 80% of rated capacity. The handling capacity calculation cluster is showed in **Table 4.13**.

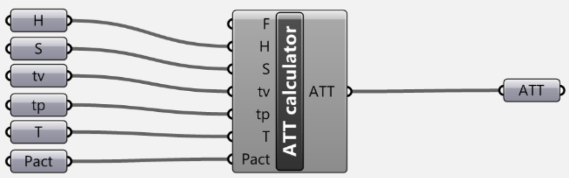
Table 4.13 : Calculation of handling capacity.

Input	Formulae	Output
• Actual number of passengers in a single interval • Actual interval • Total building population	$\mathrm{HC} = \frac{300\ \mathrm{P_{act}}}{\mathrm{U\ int_{tar}}}$	• Handling capacity
Cluster		
		

Average transit time (ATT):

Average travelling is the time from when a responding lift begins to open its doors at the boarding floor until the doors begin to open again at the destination floor. In AWT calculations, the outputs of traffic calculations are used.

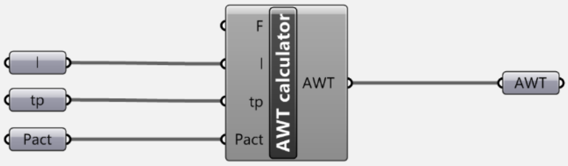
Table 4.14 : Calculation of average transit time.

Input	Formulae	Output
• Highest reversal floor • Number of probable stops • Single floor transit time • Average passenger transfer time • Floor to floor cycle time • Actual number of passengers in a single interval	$\mathrm{ATT} = 0.5\ \mathrm{H\ t_V} + 0.5\ \mathrm{S}\ (T - t_v) + 1.5\ \mathrm{P\ t_P}$	• Average trip time
Cluster		
		

Average waiting time (AWT):

Passenger average waiting time is the sum of all the individual passenger waiting times divided by the number of calls. Actually, the calculation of average waiting time is more complicated than a basic formula. The best way of estimating AWT is simulation. In the model, the general analytical calculation is used to find the average waiting time.

Table 4.15 : Calculation of average waiting time.

<table>
<tr><th>Input</th><th>Formulae</th><th>Output</th></tr>
<tr><td>• The arrival rate expressed in units of persons per second
• Actual number of passengers in a single interval
• Average passenger transfer time</td><td>$AWT = \lfloor 0.4 + (1.8 \times cc / 100 - 0.77)^2 \rfloor INT$</td><td>• Average waiting time</td></tr>
<tr><th colspan="3">Cluster</th></tr>
<tr><td colspan="3">
</td></tr>
</table>

4.3 User Interface

The user interface mainly consists of three parts. The first part comprises inputs filled up by user (**Figure 4.7**). In this part also, traffic data and elevator data are set (**Figure 4.8**). User enters project requirements manually into the panels. According to data entered by user, the calculations are made. The second part consists traffic calculations, which are piled into clusters. If user wants to change any parameter, it is easy to change from inside of the clusters. The third part is the final part, which specifies the optimum solutions, and implements data transfer to spreadsheet. The interface of the model can be seen in **Figure 4.6**.

The parameters defined by the user comprises number of floors above main entrance, building population, inter floor distance, Net floor area and building character. The population can be defined as total building population or individual floor populations.

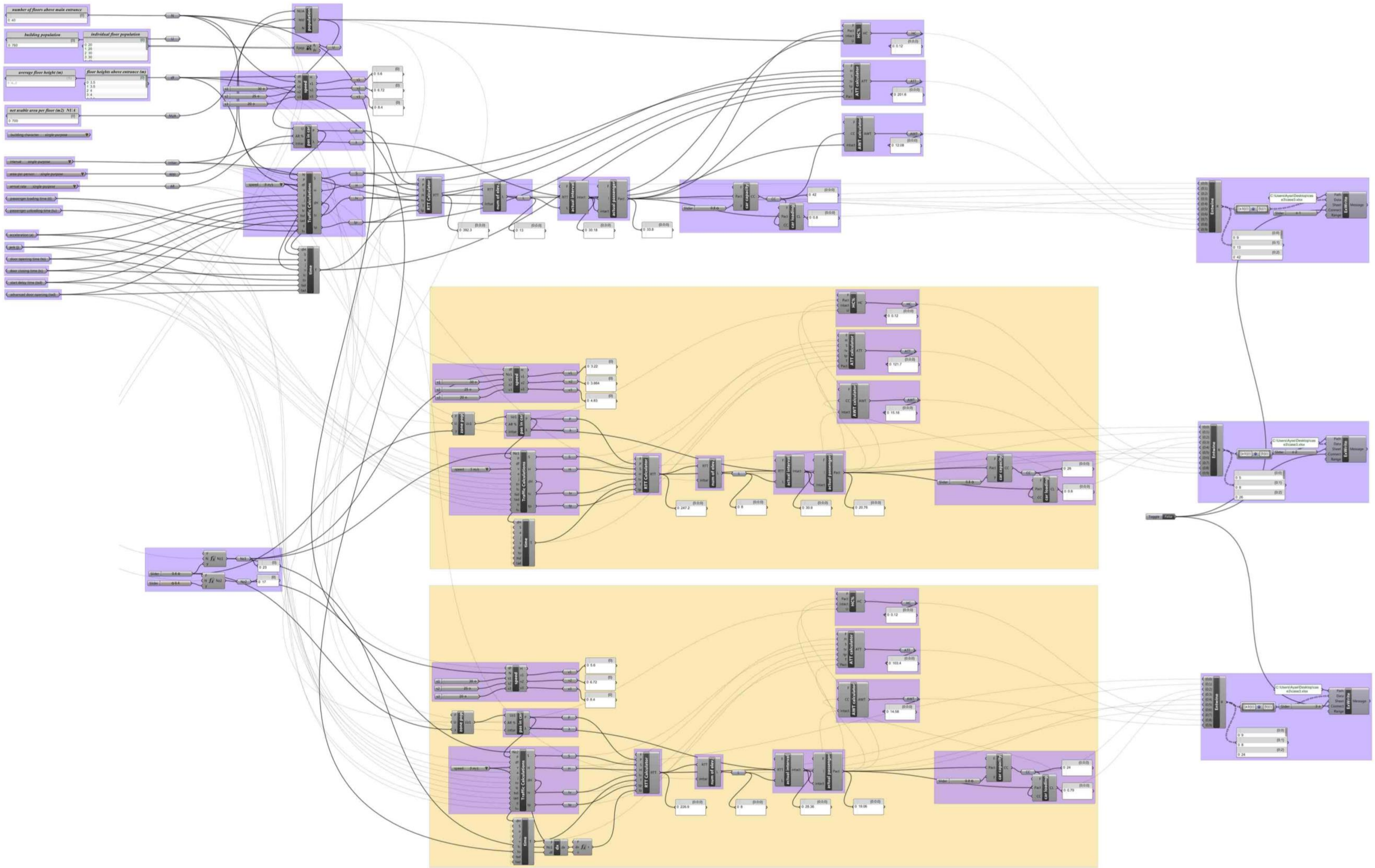


Figure 4.6 : Interface of the model in Rhinoceros-Grasshopper.

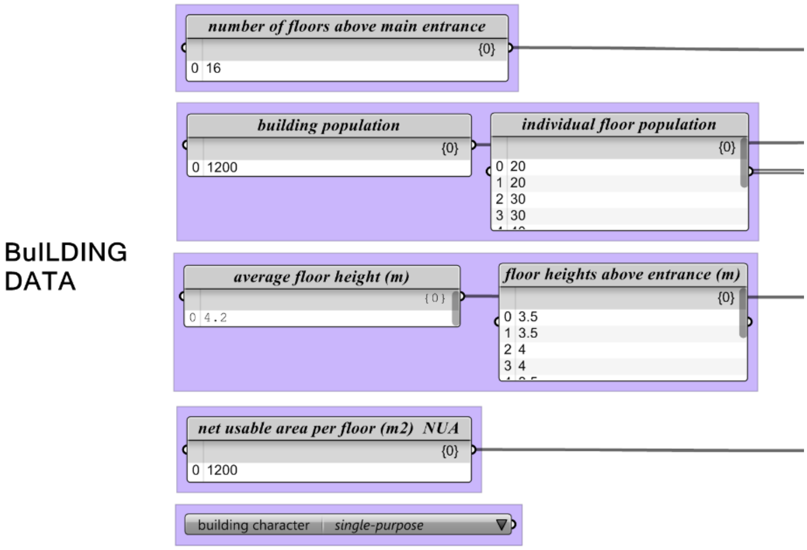


Figure 4.7 : Building data defined by the user in Rhinoceros-Grasshopper.

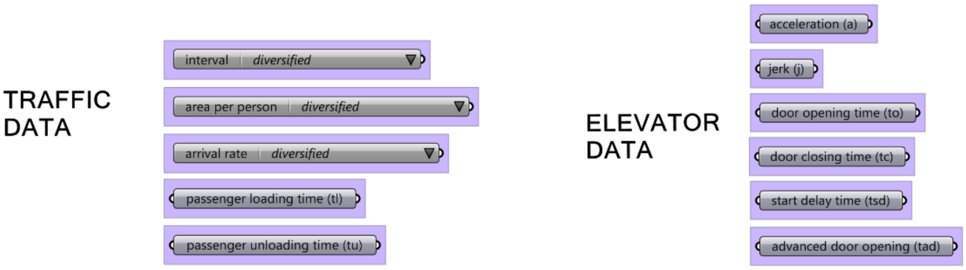


Figure 4.8 : Elevator and traffic data in Rhinoceros-Grasshopper.

After all calculations are finished, the results are exported to spreadsheet via Grasshopper-Excel connection add-on as shown in the **Figure 4.9**. The add-on works in the recording mode. When the toggle switched of true the data, transfer starts. The outputs are set as default. However, the user can add more data to be transferred just by connecting the output to the data list (**Figure 4.10**).

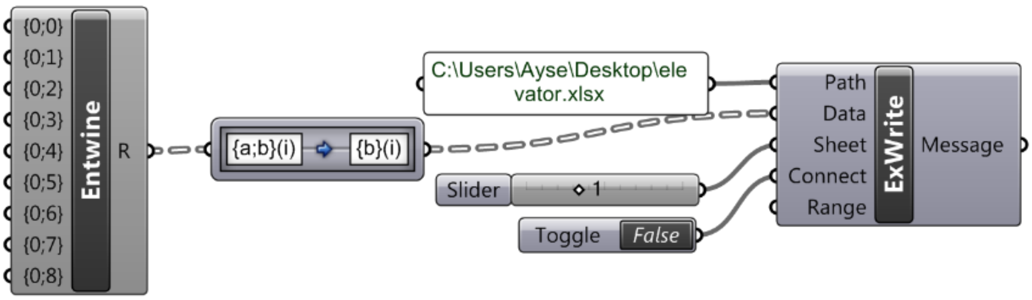
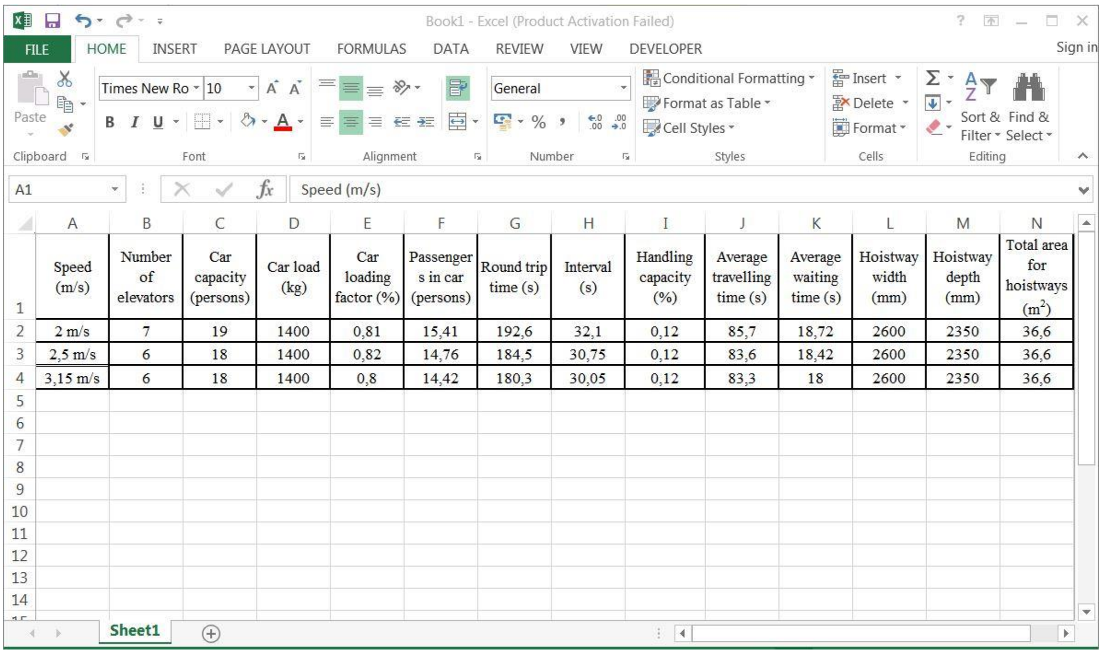


Figure 4.9 : Data transfer from Grasshopper to MS Excel.

Model provides following parameters as an output in the spreadsheet:

- Speed (m/s),
- Number of elevators,
- Car capacity (persons),
- Car load (kg),
- Car loading factor (%),
- Passengers in car (persons),
- Round trip time (s),
- Interval (s),
- Handling capacity (%),
- Average travelling time (s),
- Average waiting time (s),
- Hoist way width (mm),
- Hoist way depth (mm),
- Total area for hoist ways (m^2).



Speed (m/s)	Number of elevators	Car capacity (persons)	Car load (kg)	Car loading factor (%)	Passengers in car (persons)	Round trip time (s)	Interval (s)	Handling capacity (%)	Average travelling time (s)	Average waiting time (s)	Hoistway width (mm)	Hoistway depth (mm)	Total area for hoistways (m^2)
2 m/s	7	19	1400	0,81	15,41	192,6	32,1	0,12	85,7	18,72	2600	2350	36,6
2,5 m/s	6	18	1400	0,82	14,76	184,5	30,75	0,12	83,6	18,42	2600	2350	36,6
3,15 m/s	6	18	1400	0,8	14,42	180,3	30,05	0,12	83,3	18	2600	2350	36,6

Figure 4.10 : Output of the model in MS Office Excel.

4.4 Case Studies

The decision support model proposed within the scope of this thesis tested through three different case studies. The first case study is 16-storey high, single-tenant office building. The second one is 32-storey, multi-tenant office building. The last case is 40-storey, single-tenant office building. The first and second case have two different conditions, which consist different values for the same parameters in order to compare the results of the changing values. As an output, model generated spreadsheets for all case results in MS Office Excel. Then, due to the results generated by the model, more alternatives tested in the Elevate Simulation Software. Through the detailed simulation, the results are analyzed with regard to feasibility of the proposed model. Simulation results are demonstrated in Appendix E.

Case 1:

The first case is 16-storey, single tenant office building. Values within the building data are user defined, as they are project specific. However, the traffic data and elevator data values are set as default (**Table 4.16**). As the arrival rate, area per person and target interval values are related with the building character (i.e. single tenant), the values are constant but dependent on the data user entered. In Case 1A, the building has 1200 people total population specified by the user. In Case 1B, population is specified by individual floor populations, which corresponds to 800 people total population.

Case 1A:

Table 4.16 : Inputs of Case 1A

Data Type	Parameters	Values
Building data	Building type:	Office
	Building character:	Single-tenant
	Number of floors above main entrance (N):	16
	Average floor height (df)	4.2 meters
	Individual floor population :	-
	Total building population (U):	1200 people
	Individual floor population :	-
	Net usable area (NUA):	-
Traffic data	Area per person (app)	-
	Arrival rate AR)	12%
	Target interval (int_{tar})	30 s
	Target average travelling time (ATT)	90 s
	Target average waiting time (AWT)	20 s
	Passenger loading time (t_l)	2 s
	Passenger unloading time (t_u)	3 s
Elevator data	Acceleration (a)	1 s
	Jerk (j)	1 s
	Door opening time	2 s
	Door closing time	3 s
	Advanced door opening	1 s
	Start delay time	0.5

For three different speed, the model evaluated all results and suggested the optimum solution as alternative 1 for Case 1A (**Table 4.17**). The building needs 6 elevators at 2, 5 m/s rated speed with 1400 kg capacity. Although, all alternatives have the same number of elevators, model choses the alternative, which has the minimum speed. If numbers of elevators were different, then the model would choose the alternative, which has the minimum number of elevators. The aim of generating three alternatives and exporting all results to a spreadsheet is to offer an option to user. Thus, the user could select other alternatives to be used in his/her elevator system design.

Table 4.17 : Output of the model for Case 1A.

Outputs	**Design alternative 1**	**Design alternative 2**	**Design alternative 3**
Speed (m/s)	2 m/s	2,5 m/s	3,15 m/s
Number of elevators	7	6	6
Car capacity (persons)	19	18	18
Car load (kg)	1400	1400	1400
Car loading factor (%)	0,81	0,82	0,8
Passengers in car (persons)	15,41	14,76	14,42
Round trip time (s)	192,6	184,5	180,3
Interval (s)	32,1	30,75	30,05
Handling capacity (%)	0,12	0,12	0,12
Average travelling time (s)	85,7	83,6	83,3
Average waiting time (s)	18,72	18,42	18
Hoist way width (mm)	2600	2600	2600,0
Hoist way depth (mm)	2350	2350	2350,0
Total area for hoist ways (m^2)	36,6	36,6	36,6

The results are then, evaluated with the elevator traffic simulator program to compare the results of the model with the results of elevator traffic simulator (**Figure 4.11**). For a detailed analysis three different speed, number and capacity of elevators simulated in Elevate. Due to the results of the model, the number of elevators are selected as five, six and seven; speed is selected as 2 m/s, 2.5 m/s and 3.15 m/s; capacity is selected as 1200 kg, 1400 kg and 1600 kg. Elevate generated a list of outputs like average waiting time, average transit (travelling) time, average time to destination and so forth. The results within the performance metrics listed in **Table 4.18**.

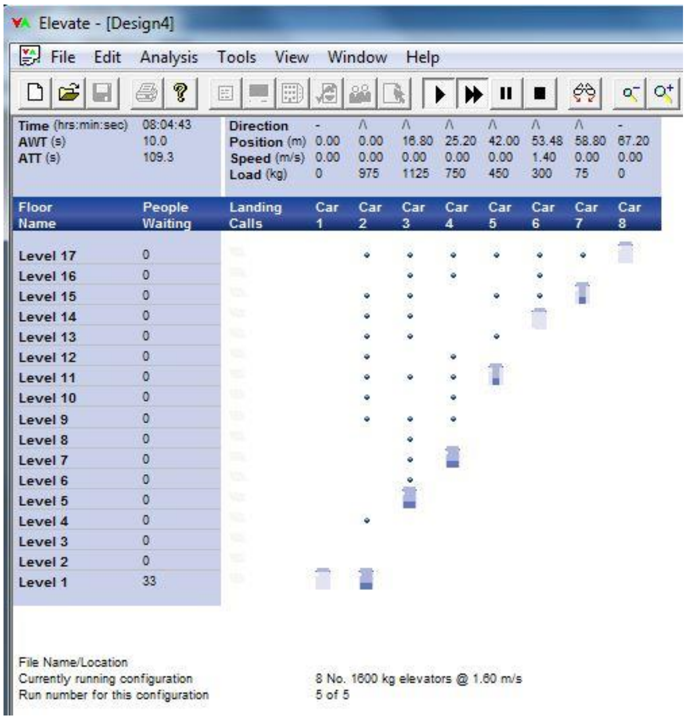


Figure 4.11 : Simulation process with Elevate software for Case 1A.

Compared to the results of the model, Elevate software generated higher results for average waiting time. Although, average waiting time is used as performance criteria in the model, the results under the 30 seconds are acceptable in practice. Average trip time results coincides. In simulation results, the optimum solution suggested by the model has 1 second longer ATT but as the difference is so small, the alternative, which has the minimum speed, could also be acceptable according to simulation results.

Table 4.18 : Output of Elevate software within the performance metrics for Case 1A.

No. of Elevator	Speed (m/s)	Elevator Capacity (kg)	Average Waiting Time (s)	Average Transit Time (s)	Average Time to Dest (s)
6	2.00	1400	25.11	85.22	114.76
6	2.50	1400	22.85	84.50	111.38
6	3.15	1400	21.10	84.24	109.06
7	2.00	1400	20.09	85.22	108.84
7	2.50	1400	18.68	84.50	106.48
7	3.15	1400	17.59	84.24	104.93

Case 1B:

Compared to Case 1A, individual floor populations are specified by user (**Figure 4.12**). The total building population corresponds to 800 people. For the number of individual floor populations, the model suggested alternatives as shown in **Table 4.19**. All alternatives have the same number of elevators and alternative 1 has the minimum rated speed which makes it optimum solution for Case 1B. The average trip time is quite smaller than the target time. As a result, the optimum solution is 5 elevators at 2 m/s rated speed with 1000 kg capacity (**Table 4.20**).

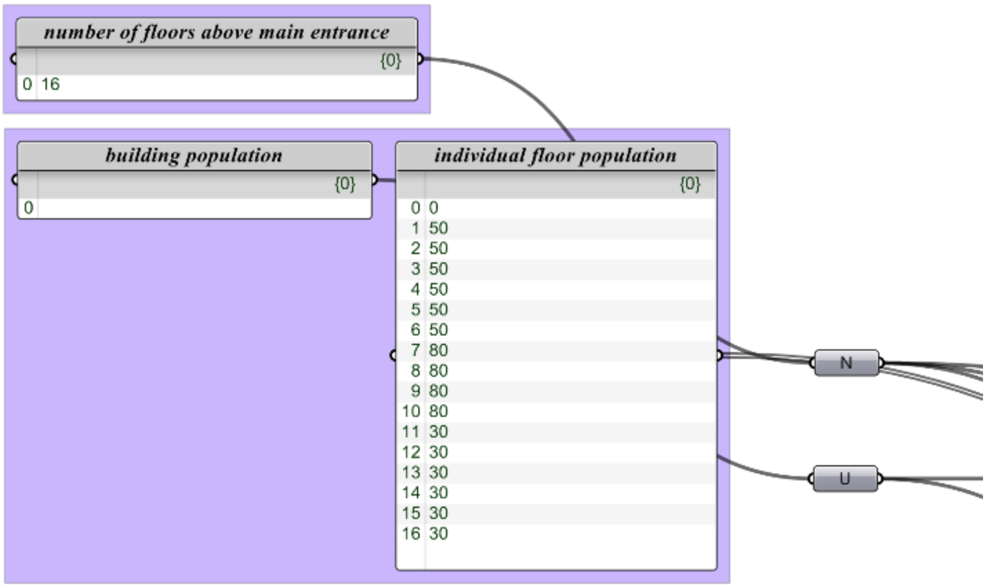


Figure 4.12 : Individual floor population input for Case 1B.

Table 4.19 : Output of the model for Case 1B for three alternatives.

Outputs	**Design alternative 1**	**Design alternative 2**	**Design alternative 3**
Speed (m/s)	2 m/s	2,5 m/s	3,15 m/s
Number of elevators	5	5	5
Car capacity (persons)	13	12	11
Car capacity (persons)	1000	900	900
Car loading factor (%)	0,77	0,79	0,84
Car load (kg)	1000	900	900
Passengers in car (persons)	10,05	9,52	9,2
Round trip time (s)	157,1	148,7	143,8
Interval (s)	31,42	29,74	28,76
Handling capacity (%)	0,12	0,12	0,12
Average travelling time (s)	65,2	62,9	62,2
Average waiting time (s)	21,59	21,02	20,91
Hoistway width (mm)	2500	2300	2750,0
Hoistway depth (mm)	2350	2200	2250,0
Total area for hoistways (m^2)	29,5	28	28

Table 4.20 : Output of Elevate software for design alternatives of Case 1B.

No. of Elevator	**Speed (m/s)**	**Elevator Capacity (kg)**	**Average Waiting Time (s)**	**Average Transit Time (s)**	**Average Time to Dest (s)**
5	2.00	1000	24.15	101.22	67.54
5	2.50	900	22.96	79.73	67.16
5	3.15	900	18.48	67.62	66.83

In case 1B, the population reduced compared to Case 1A. The results show that the number of elevators, their speed and capacity reduced as well, when the number of building population increased. **Table 4.21** shows the results of Case 1A and Case 1B.

Table 4.21 : Comparison of optimum design alternatives for Case 1A and Case 1B.

	Population (people)	No. of Elevators	Speed (m/s)	Capacity (kg)
Case 1A	1200	6	2.5	1400
Case 1B	800	5	2	1000

Case 2:

The second case is 32-storey, multi-tenant office building. In Case 2A, the building has 3.5 meters inter-floor distance with equal floor height and 112 meters travel distance. In Case 2B, the building has unequal floor heights that is defined by user (**Table 4.22**). The total travel distance is 134, 4 meters for the same number of floors.

Case 2A:

Table 4.22 : Inputs of case 2A.

Data Type	Parameters	Values
Building data	Building type:	Office
	Building character:	Multi-tenant
	Number of floors above main entrance (N):	32
	Average floor height (df)	3.5 meters
	Individual floor population :	-
	Total building population (U):	760 people
	Individual floor population :	-
	Net usable area (NUA):	-
Traffic data	Area per person (app)	-
	Arrival rate AR)	12%
	Target interval (int_{tar})	30 s
	Target average travelling time (ATT)	120 s
	Target average waiting time (AWT)	20 s
	Passenger loading time (t_l)	2 s
	Passenger unloading time (t_u)	3 s
Elevator data	Acceleration (a)	1 s
	Jerk (j)	1 s
	Door opening time	2 s
	Door closing time	3 s
	Advanced door opening	1 s
	Start delay time	0.5

For Case 2A, two design solutions are produced. The first one is not stacking the building into zones. As the building has more than 25 floors, there may be a need of zoning policy. Therefore, in this case, the model generated an alternative with the zoning besides the without zoning solution. According to the first result, the building needs 6 elevators at 4 m/s rated speed with 900 kg capacity. As the building height is more and the population is smaller, the optimum solution has high speed but small car capacity. In practice, this is not a reliable solution for elevator system design. The result of first are shown in **Table 4.23**.

Table 4.23 : Output of three alternatives for Case 2A, without zoning.

Outputs	**Design alternative 1**	**Design alternative 2**	**Design alternative 3**
Speed (m/s)	3,15 m/s	4 m/s	5 m/s
Number of elevators	7	6	6
Car capacity (persons)	11	12	12
Car load (kg)	900	900	900
Car loading factor (%)	0,81	0,81	0,77
Passengers in car (persons)	8,92	9,76	9,29
Round trip time (s)	205,3	192,7	183,4
Interval (s)	29,33	32,12	30,57
Handling capacity (%)	0,12	0,12	0,12
Average travelling time (s)	84,2	82,9	80,1
Average waiting time (s)	21,33	22,71	21,61
Hoist way width (mm)	2300	2300	2300
Hoist way depth (mm)	2220	2200	2200
Total area for hoist ways (m^2)	39,2	33,6	33,6

The second result has lower and upper zone solutions with three alternatives of each (**Table 4.24, Table 2.25**). Model generated optimum solution for lower zone, which, has 18 floors above main entrance, and the upper zone with 14 floors. The lower zone needs four elevators at 2.5 m/s with 630 kg capacity and four elevators with 4 m/s rated speed with 630 kg capacity.

Table 4.24 : Output of three alternatives for Case 2A, lower zone of the building.

Outputs	**Design alternative 1**	**Design alternative 2**	**Design alternative 3**
Speed (m/s)	2 m/s	2,5 m/s	3,15 m/s
Number of elevators	5	4	4
Car capacity (persons)	7	7	7
Car load (kg)	630	630	630
Car loading factor (%)	0,77	0,76	0,8
Passengers in car (persons)	5,38	6,08	5,63
Round trip time (s)	147,4	133,4	123,5
Interval (s)	29,48	33,35	30,88
Handling capacity (%)	0,12	0,12	0,12
Average travelling time (s)	55,3	52,7	49,5
Average waiting time (s)	24,02	25,16	26,41
Hoist way width (mm)	2150	2600	2600
Hoist way depth (mm)	2050	2350	2350
Total area for hoist ways (m^2)	22	17,6	17,6

Table 4.25 : Output of three alternatives for Case 2A, upper zone of the building.

Outputs	Design alternative 1	Design alternative 2	Design alternative 3
Speed (m/s)	3,15 m/s	4 m/s	5 m/s
Number of elevators	5	4	4
Car capacity (persons)	7	8	7
Car load (kg)	630	630	630
Car loading factor (%)	0,77	0,76	0,81
Passengers in car (persons)	5,39	6,12	5,67
Round trip time (s)	147,8	134,3	124,3
Interval (s)	29,56	33,58	31,08
Handling capacity (%)	0,12	0,12	0,12
Average travelling time (s)	44,1	44,3	42,7
Average waiting time (s)	24,08	25,32	26,59
Hoist way width (mm)	2150	2600	2600
Hoist way depth (mm)	2050	2350	2350
Total area for hoist ways (m^2)	22	17,6	17,6

Table 4.26 : Output of Elevate software for design alternatives of Case 2A.

	No. of Elevator	Speed (m/s)	Elevator Capacity (kg)	Average Waiting Time (s)	Average Transit Time (s)	Average Time to Dist. (s)
Without zoning	7	3.15	900	25.50	92.90	85.77
	6	4.00	900	25.78	116.90	85.03
Upper Zone	5	3.15	630	28.80	47.25	61.87
	4	4.00	630	24.82	47.96	72.78
	4	5.00	630	25.30	46.70	62.00

Case 2B:

In Case 2B, compared to Case 2A, individual floor heights are specified by user. The total travel distance is 134, 4 meters for the same number of floors and corresponds to 4.2 meters average floor height. As in Case 2A, the results are produced by the model. The first one is not stacking a building into zones (**Table 4.27**). For this solution, the building needs 6 elevators at 6 m/s rated speed with 900 kg capacity. For this height, the speed of required elevators are too much for implementation. However, as the speed is mostly related with the budget and environmental considerations, the feasibility of the solution depends on the user.

The second solution has upper and lower zone with three alternatives of each (**Table 4.28, Table 2.29**). The optimum solution for lower zone of the building is the alternative has four elevators at 4 m/s rated speed with 630 kg capacity; for the upper zone 4 elevators with 6 m/s rated speed with 630 kg capacity. The number of elevators are smaller than the other alternatives but the speed is the highest one.

Table 4.27 : Output of three alternatives for Case 2B, without zoning the building.

Outputs	**Design alternative 1**	**Design alternative 2**	**Design alternative 3**
Speed (m/s)	4 m/s	5 m/s	6 m/s
Number of elevators	7	7	6
Car capacity (persons)	11	11	12
Car load (kg)	900	900	900
Car loading factor (%)	0,83	0,79	0,81
Passengers in car (persons)	9,15	8,65	9,71
Round trip time (s)	210,8	199,2	191,6
Interval (s)	30,11	28,46	31,93
Handling capacity (%)	0,12	0,12	0,12
Average travelling time (s)	87,4	84	84,2
Average waiting time (s)	21,9	20,7	22,57
Hoist way width (mm)	2300	2300	2300
Hoist way depth (mm)	2220	2200	2200
Total area for hoist ways (m^2)	39,2	39,2	39,2

Table 4.28 : Output of three alternatives for Case 2B, lower zone of the building.

Outputs	**Design alternative 1**	**Design alternative 2**	**Design alternative 3**
Speed (m/s)	2,5 m/s	3,15 m/s	4 m/s
Number of elevators	5	5	4
Car capacity (persons)	7	6	7
Car load (kg)	630	630	630
Car loading factor (%)	0,78	0,82	0,83
Passengers in car (persons)	5,44	4,95	5,79
Round trip time (s)	149,2	135,8	126,9
Interval (s)	29,84	27,16	31,72
Handling capacity (%)	0,12	0,12	0,12
Average travelling time (s)	56,2	51,8	51,3
Average waiting time (s)	24,31	22,77	25,84
Hoist way width (mm)	2150	2150	2150
Hoist way depth (mm)	2050	2050	2050
Total area for hoist ways (m^2)	22	22	17,6

Results show that if user choose the solution without zoning, the building would have six elevators travelling at all floors with 6 m/s rated speed. When the building is splitting into zones, at fist 18 floor there would be 8 elevators in plan layout but just four of them would serve at each floor (**Table 4.30**). At the upper floors, there would be just four elevators in plan layout serving at these floors.

Table 4.29 : Output of three alternatives for Case 2B, upper zone of the building.

Outputs	Design alternative 1	Design alternative 2	Design alternative 3
Speed (m/s)	4 m/s	5 m/s	6 m/s
Number of elevators	5	5	4
Car capacity (persons)	7	6	7
Car load (kg)	630	630	630
Car loading factor (%)	0,78	0,84	0,84
Passengers in car (persons)	5,46	5,01	5,89
Round trip time (s)	149,7	137,4	129,2
Interval (s)	29,94	27,48	32,3
Handling capacity (%)	0,12	0,12	0,12
Average travelling time (s)	45,6	43,8	44,7
Average waiting time (s)	24,39	23,03	26,32
Hoist way width (mm)	2150	2600	2600
Hoist way depth (mm)	2050	2350	2350
Total area for hoist ways (m^2)	22	22	17,6

Table 4.30 : Output of Elevate software for design alternatives of Case 2B.

	No. of Elevator	Speed (m/s)	Elevator Capacity (kg)	Average Waiting Time (s)	Average Transit Time (s)	Average Time to Dist. (s)
Without zoning	7	4.00	900	16.34	91.47	107.80
	7	5.00	900	24.85	90.67	105.47
	6	6.00	900	24.85	90.67	105.47
Lower zone	5	2.50	630	30.70	48.42	79.12
	5	3.15	630	20.70	47.62	68.32
	4	4.00	630	25.80	53.13	78.93
Upper Zone	5	3.15	630	28.80	47.25	61.87
	4	4.00	630	24.82	47.96	72.78
	4	5.00	630	25.30	46.70	62.00

Table 4.31 : Comparison of optimum design alternatives for Case 2A and Case 2B.

		No. of Floors	Travel Distance (m)	Population (people)	No. of Elevators	Speed (m/s)	Capacity (kg)
Case 2A	Without zoning	32	112	760	6	4	900
	Lower zone	18	63	456	4	2.5	630
	Upper zone	14	49	304	4	4	630
Case 2B	Without zoning	32	134,4	760	6	6	900
	Lower zone	18	81	456	4	4	630
	Upper zone	14	53,4	304	4	6	630

Case 3:

The last case is 40-storey, single tenant office building. In this case, the total building population is not specified by user, calculated through the net floor area of the floor plate (**Table 4.32**). As in the Case 2, the model produced alternatives for lower and upper zones (**Table 4.33, Table 4.34**). The results show that building needs to be split at the 24th floor. The lower zone has 24 floors and the upper zone has 16 floors. The optimum result for the lower zone has 8 elevators at 4 m/s rated speed with 2000 kg capacity; for the upper zone, 8 elevators at rated speed 7 m/s with 1800 capacity. It means, the building needs 16 elevators at plan layout of first 24 floors and then 8 elevators continue to serve at last 16 floors.

Table 4.32 : Inputs of Case 3.

Data Type	Parameters	Values
Building data	Building type:	Office
	Building character:	Single-tenant
	Number of floors above main entrance (N):	40
	Average floor height (df)	4.2 meters
	Individual floor population :	-
	Total building population (U):	-
	Individual floor population :	-
	Net usable area (NUA):	750 m^2
Traffic data	Area per person (app)	-
	Arrival rate AR)	12%
	Target interval (int_{tar})	30 s
	Target average travelling time (ATT)	120 s
	Target average waiting time (AWT)	20 s
	Passenger loading time (t_l)	2 s
	Passenger unloading time (t_u)	3 s
Elevator data	Acceleration (a)	1 s
	Jerk (j)	1 s
	Door opening time	2 s
	Door closing time	3 s
	Advanced door opening	1 s
	Start delay time	0.5

Table 4.33 : Output of three alternatives for Case 3, lower zone of the building.

Outputs	**Design alternative 1**	**Design alternative 2**	**Design alternative 3**
Speed (m/s)	3,15 m/s	4 m/s	5 m/s
Number of elevators	9	8	8
Car capacity (persons)	25	27	26
Car load (kg)	1800	2000	2000
Car loading factor (%)	0,78	0,79	0,8
Passengers in car (persons)	19,62	21,32	20,76
Round trip time (s)	262,7	253,8	247,2
Interval (s)	29,19	31,72	30,9
Handling capacity (%)	0,12	0,12	0,12
Average travelling time (s)	121,9	123,6	121,7
Average waiting time (s)	14,67	15,25	15,18
Hoist way width (mm)	2750	2950	2950
Hoist way depth (mm)	2600	2500	2500
Total area for hoist ways (m^2)	63,9	59,2	59,2

Table 4.34 : Output of three alternatives for Case 3, upper zone of the building.

Outputs	Design alternative 1	Design alternative 2	Design alternative 3
Speed (m/s)	6 m/s	7 m/s	9 m/s
Number of elevators	8	8	8
Car capacity (persons)	25	25	24
Car load (kg)	1800	1800	1800
Car loading factor (%)	0,82	0,79	0,79
Passengers in car (persons)	20,38	19,82	19,06
Round trip time (s)	242,6	235,9	226,9
Interval (s)	30,32	29,49	28,36
Handling capacity (%)	0,12	0,12	0,12
Average travelling time (s)	106,4	105,1	103,4
Average waiting time (s)	15,23	14,82	14,58
Hoist way width (mm)	2750	2750	2750
Hoist way depth (mm)	2600	2600	2600
Total area for hoist ways (m^2)	56,8	56,8	56,8

Table 4.35 : Output of Elevate software for design alternatives of Case 3.

	No. of Elevator	Speed (m/s)	Elevator Capacity (kg)	Average Waiting Time (s)	Average Transit Time (s)	Average Time to Dist. (s)
Lower zone	9	3.15	1800	17.60	113.31	119.61
	8	4.00	2000	18.00	125.19	143.19
	8	5.00	2000	17.70	125.19	142.89
Upper Zone	8	6.00	1800	13.70	106.78	120.48
	8	7.00	1800	10.40	98.72	109.12
	8	9.00	1800	12.63	97.24	106.24

5. CONCLUSION

In tall building design process generally, architects are the main decision maker for the building conception. Especially in the conceptual design phase, decisions on building circulation, both horizontal and vertical, plays an important role, as it is the lifeblood of a tall building. Making decisions to achieve an optimal vertical transportation indicates an expert knowledge or research on existing buildings' elevator systems for a new building design. For this demand, sometimes, elevator specialist are participating into the conceptual design stage. Otherwise, designers may have problems at further design steps if the determined core dimensions or the number of elevators are not satisfy the building needs. Then, designer may need to fix the complete vertical transportation system by trial and error method.

In the scope of this research, elevator system design parameters and design process are analyzed. In addition, elevator traffic analysis methods used in the design process examined in detail to understand the relation between analysis and design process. In this research, the model called a decision support model for elevator system design in tall buildings is proposed. The proposed model is considered as part of a comprehensive system but implemented for office buildings under 40-storey are tested, as the calculations are coded for up-peak (incoming) traffic conditions. As the model bases on analytical traffic calculations, only the up peak traffic calculations are held.

Through the case studies, the model is tested due to its feasibility. As an output, the model produces three design alternatives and select the optimum solution among them. The buildings under 25-storey, generally has one local elevator group serving to all floor. For the buildings above 25-storey, model produces two options. The first option has three alternatives without any zoning policy, if the target transit time is within the performance criteria. If it is not, there is only one option that has the zoning policy. If the model produces lower and upper zones, the most important criteria is having the same number of elevators in each zone. In case 2, the user has two options of elevator system without zoning and with zoning. The model suggests the optimum solution for each condition, but the last decision maker is the user. As the elevator system directly related with cost and requirements specified by project developer, the model select any results from alternatives. The most important advantage of the model is, exporting all alternatives to a spreadsheet.

Compared to simulation results of case studies, average waiting time is generally smaller than simulation results. The reason is AWT calculations in the model is dependent on the interval time. However, the waiting time could be analyzed by simulations. The average transit time is mostly coincide with simulation results. Due to the evaluation of all results, the model does not work properly for high speed elevators. To correct the results, more complex equations should be add to the calculation process. As a general opinion, the model is a useful tool for the conceptual design phase of tall buildings.

For future development, the model is planned to be a comprehensive system that consists of all circulation devices and elements in addition to, have an interactive interface that user adds geometric specifications, such as elevator configurations or building entrances. By adding different types of building traffic patterns, different types of devices and their relations as well as the more complex control algorithms, the model could be used as an open source software.

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APPENDICES

APPENDIX A: Glossary.
APPENDIX B: Round trip time calculations for unequal floor height and population.
APPENDIX C: Data tables.
APPENDIX D: List of clusters used in the model.
APPENDIX E: Simulation results of case studies.

APPENDIX A

Definitions are taken from the CIBSE Guide D- transportation Systems in Buildings.

Advance door opening: The initiation of door opening whilst a car is slowing into a floor, under normal operating conditions, usually when the car is in a door zone of plus or minus 200 mm of floor level and such that the car is substantially level at the floor before passengers can attempt to exit.

Arrival rate: The number of passengers arriving at an elevator system for service during a five minute peak period within a specific traffic period.

Bottom terminal. Lowest floor in a building zone from which elevator cars can load and unload passengers.

Call: A demand for service by a passenger, which is entered into an elevator supervisory control system, by the passenger pressing either a landing or car call pushbutton.

Call allocation: The action of an elevator supervisory control system, when allocating a landing call to a specific car for service car. The load-carrying unit comprising enclosure (cab), car frame, platform and door(s).

Circulation: The process by which persons in a building move around the building in both horizontal and vertical modes highest reversal. The highest landing that an elevator visits during a trip in the upward direction before reversing its direction of travel.

Double deck(er) elevator: An elevator having two compartments located one above the other.

Down peak traffic: A down peak traffic condition exists, when the dominant or only traffic flow is in the downward direction, with all or the majority of the passengers leaving the building at the main terminal floor of the building.

Door closing time: The period of time measured from the instant that the elevator door close push button is pressed (or the first visible door movement) until the door interlocks are made up.

Door opening time: The period of time measured from the instant of the elevator car being level at a floor and when the doors are open 800 mm.

Elevator [syn: lift]: A permanent lifting equipment, serving two or more landing levels, provided with a car or platform for the transportation of passengers and/or freight, running at least partially in rigid guides either vertical or inclined to the vertical by less than 15 degrees.

Elevator: firefighting: An elevator, which ma be supplied with additional fire resistant protection, installed in a fire protected zone and designated to have controls that enable it to be used under the direct control of the firefighting services for emergency purposes.

Elevator: freight: An elevator primarily used to transport freight and goods, where only the operator and persons necessary to load and unload the freight are permitted to travel.

Elevator: passenger. An elevator primarily used to carry passengers other than the operator (if any).

Express run: The distance an elevator travels without stopping during a movement between terminal floors or when crossing an unserved building zone.

Express zone: A building zone situated in the middle or top of the building.

Floor: express zone terminal: The lowest floor of a high-rise zone in a building, which is served by an elevator car after it leaves the main terminal floor.

Floor: highest reversal: The floor at which a car reverses direction, when travelling in an upward direction having completed its last car call, in preparation to serve registered down landing calls.

Floor: lowest reversal. The floor at which a car reverses direction, when travelling in a downward direction having completed its last car call, in preparation to serve registered up landing calls, particularly during an inter-floor traffic condition.

Handling capacity: The total number of passengers that an elevator system can transport in a period of five minutes during the up peak traffic condition with a specified car loading, usually taken as 80% of rated capacity.

Hoist way: A vertical opening through a building or structure in which elevators, material lifts, dumbwaiters etc. travel extending from the pit at the bottom to the underside of the roof or machinery space above.

Inter-floor distance: The vertical distance between two adjacent landing floors.

Interval. The average time between successive car arrivals at the main terminal (or other defined) floor with no specified level of car loading or traffic condition.

Landing. A portion of floor or corridor adjacent to elevator car entrances or escalator terminal end, where passengers may board or exit.

Load: The weight of passengers inside an elevator car.

Load: average: The weight of passengers carried in an elevator car averaged over the number of trips made in a five-minute period.

Lobby: sky. A terminal floor at the highest floor served by a low zone group of elevators, where passengers may wait for service by a high-rise group of elevators.

Local zone: A building zone adjacent to and including the main floor.

Passenger journey time: The period of time that a passenger spends travelling to a destination floor measured from the instant that the passenger registers a landing call at the departure floor until the instant the passenger alights at the destination floor.

Passenger loading time: The average period of time required for a single passenger to enter an elevator car.

Passenger unloading time: The average period of time required for a single passenger to leave an elevator car.

Passenger waiting time: The period of time that a passenger spends waiting for an elevator car measured from the instant that the passenger registers a landing call until the instant the passenger enters the car.

Passenger transfer time: The average period of time required for a single passenger to enter or leave an elevator car.

Probable stops: The average number of stops an elevator car makes, during a round trip under up peak traffic conditions, calculated using statistical methods.

Quality of service: The passenger's perception of the efficiency of an elevator installation measured in terms of passenger waiting time.

Quantity of service: The handling capacity of an elevator installation.

Rated capacity: The maximum legal load, which an elevator car is permitted to carry, measured in a number of passengers or a specific weight in kg.

Rated load: The weight of passengers, which the elevator car is certified to carry.

Rated speed: The linear car speed in the hoist way, which the elevator manufacturer contracts to supply.

Round trip time: The average period of time for a single elevator car trip around a building, usually during up peak traffic conditions, measured from the time the car doors open at the main terminal, until the car doors reopen at the main terminal, when the car returns to the main terminal, after its trip around the building.

Single floor flight time: The period of time measured from the instant when the door interlocks are made up at the departure floor until the instant that the elevator car is level at the next adjacent landing.

Traffic analysis: Determination of the statistical characteristics of passenger movements (average passenger waiting and journey times, percentiles, etc.) in an elevator and escalator systems.

Two-way traffic: A two-way traffic condition exists when the dominant traffic flow is to and from one specific floor, which is not the main floor.

Up peak traffic: An up peak traffic condition exists when the dominant or only traffic flow is in the upward direction with all or the majority of the passengers entering the lift system at the main floor of the building.

Vertical transportation: Where the movement of people and materials is in the vertical plane.

Zone. A number of floors, usually adjacent, in a building served by a group or groups of cars.

APPENDIX B

Notations:

a	acceleration/deceleration, m/s^2
CC	contract (rated) capacity, persons
d_f	average inter-floor height
H	expected highest reversal floor
d_f	the distance the lift express traveled before the reaching the zone served
L	number of lifts
N	number of floors in the zone above main terminal
P	expected number of passengers
RTT	average round trip time
S	expected number of stops
t_c	door closing time (between 2s and 4s depending on types of doors, but slower than door opening time)
t_o	door opening time (between 0.5s and 3s usually, faster if advance opening is used)
t_l	passenger loading time (usually taken as 1.2s)
t_u	passenger unloading time (usually taken as 1.2s)
UPPHC	average up-peak handling capacity (persons served in the 5-minute up-peak interval)
UPPINT	average up-peak interval
v	Contract (rated) speed, m/s
% POP	percentage of population served in the 5-minute up-peak interval

Formulas:

Formulas are taken from the CIBSE Guide D- transportation Systems in Buildings. .

Rated capacity (CC):

$$CC = floor\left(\frac{RL}{m}\right) \quad \textbf{(B 1.1)}$$

Where floor is a function-meaning round down to the nearest whole number.

Number of passengers (P) in the lift:

$$P = \left(\frac{\%CF}{100}\right)CC \qquad \textbf{(B 1.2)}$$

Effective building population (*U*):

$$U = \sum_{i=1}^{N} U_i \qquad \textbf{(B 1.3)}$$

Highest reversal floor *(H)*:

$$H = N - \sum_{j=1}^{N-1}\left(\sum_{i=1}^{j}\frac{U_i}{U}\right)^P \qquad \textbf{(B 1.3)}$$

Probable number of stops (S):

$$S = N - \sum_{i=1}^{N}\left(1 - \frac{U_i}{U}\right)^P \qquad \textbf{(B 1.4)}$$

Average passenger transfer time$(\boldsymbol{t_p})$:

$$t_p = \frac{t_1 + t_u}{2} \qquad \textbf{(B 1.5)}$$

Travel distance to highest reversal floor $(\boldsymbol{d_H})$

$$d_H = \left(\sum_{i=0}^{floor(H-1)} h_i\right) + \big(H - floor(H)\big) \qquad \textbf{(B 1.6)}$$

Transit time function:

If: $d \geq \frac{a^2v + v^2j}{j\,a}$ then: $t_f(d) = \frac{d}{v} + \frac{a}{j} + \frac{v}{a}$ **(B 1.7)**

If: $\frac{2a^3}{j^2} \leq d < \frac{a^2v + v^2j}{j\,a}$ then: $t_f(d) = \frac{a}{j} + \sqrt{\frac{4d}{a} + \left(\frac{a}{j}\right)^2}$ **(B 1.8)**

If: $d < \frac{2a^3}{j^2}$ then: $t_f(d) = \left(\frac{32d}{j}\right)^{\frac{1}{3}}$ **(B 1.9)**

Round trip time (RTT):

$$\mathrm{RTT} = \left(\frac{2\mathrm{d_H}}{\mathrm{v}} + (\mathrm{S}+1)\left(\mathrm{T}^* - \frac{\mathrm{d_H}}{\mathrm{vS}}\right) + 2\,\mathrm{P}\,\mathrm{t_p} + \frac{2\mathrm{d_x}}{\mathrm{v}}\right)\left(1 + \frac{\%\mathrm{LOSS}}{100}\right) \qquad \textbf{(B 1.10)}$$

$$\text{where } \mathrm{T}^* = \mathrm{t_f(d)} + \mathrm{t_c} + \mathrm{t_o} + \mathrm{t_{sd}} - \mathrm{t_{ad}} \qquad \textbf{(B 1.11)}$$

Up-peak interval ($UPPINT$):

$$\mathrm{UPPINT} = \frac{\mathrm{RTT}}{\mathrm{L}} \qquad \textbf{(B 1.12)}$$

Up-peak handling capacity**:**

$$\mathrm{UPPHC} = \frac{300\ \mathrm{P}}{\mathrm{UPPIT}} \qquad \textbf{(B 1.13)}$$

Handling capacity expressed as percentage of building population (%POP):

$$\%\mathrm{POP} = \frac{\mathrm{UPPHC}}{\mathrm{U}} \times 100 \qquad \textbf{(B 1.14)}$$

APPENDIX C

Tables are taken from the Elevator Traffic Handbook.

Table C.1 : Approximate net usable area, various height buildings.

Building Height	Net Usable Area as Percentage of Gross Area
0-10 floors	Approximately 80%
0-20 floors	Floors 1-10 approximately 75%
	11-20 approximately 80%
0-30 floors	Floors 1-10 approximately 70%
	11-20 approximately 75%
	21-30 approximately 80%
0-40 floors	Floors 1-10 approximately 70%
	11-20 approximately 75%
	21-30 approximately 80%
	31-40 approximately 85%

Table C.2 : Suggested building population factors related to building height – based on net usable area.

Building Type	Estimated Population	Arrival Rate (%)	Interval (s)
Hotel	1.5-1.9 persons/room	10-15	30-50
Flats	1.5-1.9 persons/bedroom	5-7	40-90
Hospital	3.0 persons/bed space	8-10	30-50
School	0.8-1.2 m2 net area/pupil	15-25	30-50
Office (Mixed, Multiple Tenancy):			
Standard	11-14 m2 NUA/person	11-14	25-30
Prestige	12-17 m2 NUA/person	12-15	20-25
Office (Sector, Multiple Tenancy):			
Standard	10-13 m2 NUA/person	12-14	25-30
Prestige	11-16 m2 NUA/person	13-16	20-25
Office (Single Tenancy):			
Standard	8-10 m2 NUA/person	12-15	25-30
Prestige	10-14 m2 NUA/person	13-17	20-25

Table C.3 : Suggested intervals.

Office Buildings	Up-Peak	Up-Peak with 10% Down Traffic	Two-Way
Diversified	25 to 30 sec	30 to 35 sec	35 to 45 sec
Diversified single-purpose	23 to 28 sec	28 to 33 sec	33 to 43 sec
Single-purpose	20 to 25 sec	25 to 30 sec	30 to 40 sec
Professional buildings			30 to 50 sec
Self-parking garages	40 to 50 sec		40 to 60 sec
Stores			30 to 50 sec
Industrial buildings	25 to 30 sec		30 to 40 sec

Table C.4 : Expected peak traffic periods – various commercial buildings.

	Percentage of Population in a 5-min Period		
	Peak Arrivals	**Up-Peak with 10% Down Traffic**	**Noontime or Two-way**
Office Buildings			
Diversified offices	10 to 11%	11 to 12%	10 to 12%
Diversified single-purpose	11 to 13%	12 to 15%	12 to 15%
Single-purpose	12 to 18%	13 to 20%	13 to 17%
Other Building Types			
Characteristic Peak Traffic: Professional buildings	Peak traffic	Two-way, based on 1 to 2 visitors per doctor, each 15 min coming and going	
Garages —self-parking	Peak traffic commuter garage	10% to 15%, one-way traffic	
	Peak traffic, store, transportation terminal garage	10% to 15%, one-way traffic	
Stores	Population to be turned over, i.e., up and down (two-way) in 1 hour		
Industrial buildings	Population to be turned Peak traffic, 15 to 20% (up-peak or two-way)		

Table C.5 : Suggested elevator capacity (kg) – commercial buildings.

Type of Building	Class of Building		
	Small	**Average**	**Large or Prestige**
Offices, suburban	1200	1400	1600
Service elevator	1800	1800	1800
Offices, downtown	1400	1600	1800
Service elevator	1800	2000	3000
Professional offices			
Passenger	1200	1600	1800
Service	1800	1800	2300
Stores			
Passenger	1600	1600	1800
Serviced	1800	1800 to 2700	2700 to 3600
Garages	1200	1400	1600
Industrial	1800	1800	1800

Table C.6 : Suggested elevator speeds.

	Class of Building			
	Small	**Average**	**Large or Prestige**	**Service**
Office				
Up to 5 floors	1 m/s	1.5 – 2 m/s	2 m/s	1 m/s
5 to 10 floors	1.5 m/s	2 m/s	2.5 m/s	1.5 m/s
10 to 15 floors	2 m/s	2.5 m/s	2.5 m/s	2 m/s
15 to 25 floors	2.5 m/s	3.5 m/s	3.5 m/s	2.5 m/s
25 to 35 floors	-	5 m/s	5 m/s	2.5 m/s
35 to 45 floors	-	5-6 m/s	6 m/s	3.5 m/s
45 to 60 floors over	-	6-7 m/s	7-8 m/s	4 m/s
60 floors	-	-	9 m/s	4 m/s
Stores				
2 to 5 floors	1 m/s	1 m/s	1.5 m/s	1 m/s
5 to 10 floors	2 m/s	2 m/s	2.5 m/s	2 m/s
10 to 15 floors	2.5 m/s	2.5 m/s	2.5-3.5	2 m/s
Garages				
2 to 5 floors	1 m/s	1 m/s	1 m/s	
5 to 10 floors	1 m/s	1.5 m/s	2 m/s	
10 to 15 floors	1.5 m/s	2 m/s	2.5 m/s	

Table C.7 : Area versus capacity – suggested standards.

Capacity (kg)	Car Inside			Hoist way			Observed Loading (people)	Maximum Loading (people)
	Wide (mm)	Deep (mm)	Area (m^2)	Wide (mm)	Deep (mm)	Area (m^2)		
1200	2100	1300	2,7	2750,0	2100,0	5,8	10	19 (16)
1400	2100	1450	3,1	2750,0	2250,0	6,2	12	22 (18)
1600	2100	1650	3,5	2750,0	2450,0	6,7	16	26 (21)
1800	2350	1650	3,8	3000,0	2450,0	7,2	18 to 19	28 (24)
2000	2350	1800	4,2	3000,0	2600,0	7,8	20	32 (27)
2250	2350	1950	4,6	3000,0	2750,0	8,3	22	34 (30)
2700	2350	2150	5,1	3000,0	2950,0	8,9	25	39 (36)

Table C.8 : Typical lift dynamics.

Lift travel (m)	Rated speed (m/s)	Acceleration (mist)	Jerk (m/s3)	Single floor flight time (s)
<20	<1.00	0,4	0.6	8.0
20	1.00	0.4-0.7	0,75	7.0
32	1.60	0.7-0.8	0.9	6.0
50	2.50	0.8-0.9	1.0	5.5
63	3.00	1.0	1,25	5.0
100	5.00	1.2	1.5	4.7
120	6.00	1.2	1.8	4.5

Table C.9 : Typical door closing and opening times.

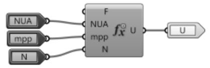
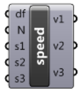
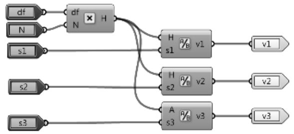
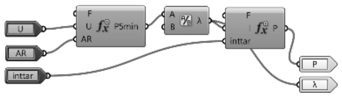
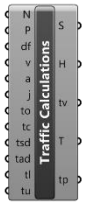
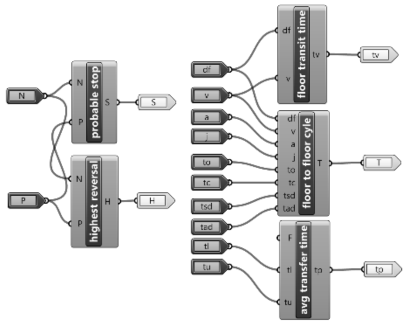
Door Type	Closing and Opening Times (s) For Given Door Width					
	Closing		Closing (no advanced opening)		Opening (with advanced opening)	
	800 mm	1100 mm	800 mm	1100mm	800 mm	1100 mm
Side	3.0	4.0	2.5	3.0	2.0	1.5
Centre	2.0	3.0	2.0	2.5	1.0	1.5

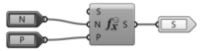
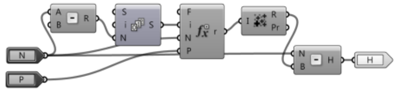
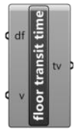
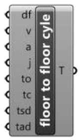
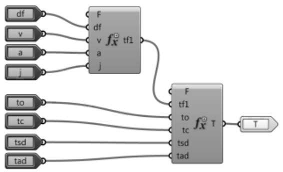
Table C.10 : Probable quality of service in office buildings.

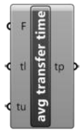
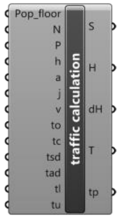
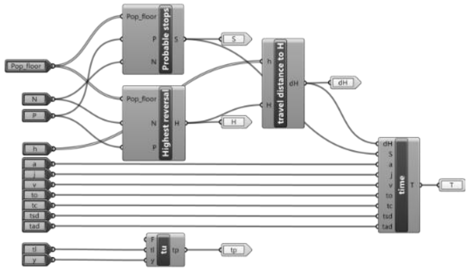
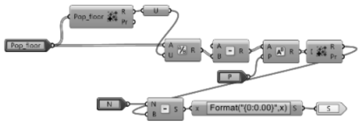
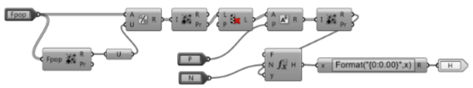
Interval (s)	Quality of service
<20	Excellent system
25	Very good system
30	Good system
40	Poor system
>50	Unsatisfactory system

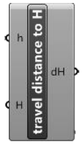
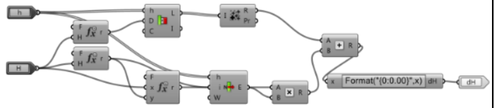
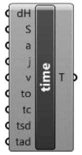
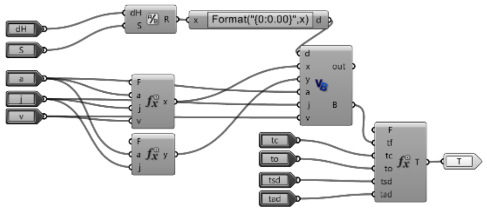
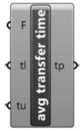
APPENDIX D

Table D. 1: List of clusters used in the model.

Cluster	Input	Output	Inside of the cluster	Formula
	• Net Usable Area • Area/person • Number of floors above main entrance	• Total building population		$U = \left(\frac{NUA}{app}\right) N$
	• Floor height • Number of floors above main terminal • Suggested travel time 1 • Suggested travel time 2 • Suggested travel time 3	• Suggested speed 1 • Suggested speed 2 • Suggested speed 3		$v = \left(\frac{d_f\, N}{s}\right)$
	• Total building population • Arrival rate • Target interval	• Actual number of passengers that will arrive in a single interval • The arrival rate expressed in units of persons per second		$P = (int_{tar} \,.\, \lambda)$ $\lambda = \frac{AR\%\ U}{300}$
	• Number of floors above main terminal • Passengers in a single interval • Floor height • Speed • Acceleration • Jerk • Door opening time • Door closing time • Start delay time • Advanced door opening • Passenger loading time • Passenger unloading time	• Number of probable stops • Highest reversal floor • Single floor transit time • Floor to floor cycle time • Average passenger transfer time		$S = N\,.\left(1 - \left(1 - \frac{1}{N}\right)^{P}\right)$ $H = N - \sum_{i=0}^{N-1} \left(\frac{i}{N}\right)^{P}$ $t_V = \frac{d_f}{v}$ $T = t_f(1) + t_{sd} + t_c + t_o - t_{ad}$ $t_p = \frac{t_1 + t_u}{2}$

Cluster	Input	Output	Inside of the cluster	Formula
	• Number of floors above main terminal • Passengers in a single interval	• Number of probable stops		$S = N\,.\left(1 - \left(1 - \frac{1}{N}\right)^{P}\right)$
	• Number of floors above main terminal • Passengers in a single interval	• Highest reversal floor		$H = N - \sum_{i=0}^{N-1} \left(\frac{i}{N}\right)^{P}$
	• Floor height • Speed	• Single floor transit time		$\mathrm{t_V} = \frac{\mathrm{d_f}}{\mathrm{v}}$
	• Floor height • Speed • Acceleration • Jerk • Door opening time • Door closing time • Start delay time • Advanced door opening	• Floor to floor cycle time		$T = t_f(1) + t_{sd} + t_c + t_o - t_{ad}$

Cluster	Input	Output	Inside of the cluster	Formula
	• Passenger loading time • Passenger unloading time	• Average passenger transfer time		$t_p = \frac{t_1 + t_u}{2}$
	• Individual floor populations • Number of floors above main terminal • Passengers in a single interval • Individual floor heights • Acceleration • Jerk • Speed • Door opening time • Door closing time • Start delay time • Advanced door opening • Passenger loading time • Passenger unloading time	• Number of probable stops • Highest reversal floor • Travel distance to highest reversal floor • Floor to floor cycle time • Average passenger transfer time		$S = N - \sum_{i=1}^{N} \left(1 - \frac{U_i}{U}\right)^P$ $H = N - \sum_{j=1}^{N-1} \left(\sum_{i=1}^{j} \frac{U_i}{U}\right)^P$ $d_H = \left(\sum_{i=0}^{floor(H-1)} h_i\right) + \left(H - floor(H)\right)$ $T = t_f(d) + t_{sd} + t_c + t_o - t_{ad}$ $t_p = \frac{t_1 + t_u}{2}$
	• Individual floor populations • Passengers in a single interval • Number of floors above main terminal	• Number of probable stops		$S = N - \sum_{i=1}^{N} \left(1 - \frac{U_i}{U}\right)^P$
	• Individual floor populations • Number of floors above main terminal • Passengers in a single interval	• Highest reversal floor		$H = N - \sum_{j=1}^{N-1} \left(\sum_{i=1}^{j} \frac{U_i}{U}\right)^P$

Cluster	Input	Output	Inside of the cluster	Formula
	• Individual floor heights • Highest reversal floor	• Travel distance to highest reversal floor		$d_H = \left(\sum_{i=0}^{floor(H-1)} h_i\right) + (H - floor(H))$
	• Travel distance to highest reversal floor • Number of probable stops • Acceleration • Jerk • Speed • Door opening time • Door closing time • Start delay time • Advanced door opening	• Floor to floor cycle time		$T = t_f(d) + t_{sd} + t_c + t_o - t_{ad}$
	• Passenger loading time • Passenger unloading time	• Average passenger transfer time		$t_p = \frac{t_1 + t_u}{2}$

APPENDIX E

Table E. 1: Simulation results for Case 1A.

Page: 1 of 2
Job: case 1a
Job No:
Calculation Title:
Made By:
Check By:
File/Date:

ELEVATE
Elevate Version (Build 1814)

SIMULATION RESULTS

Based on avreage of all runs and passengers arriving between 08.00 to 08.05

No. of Elevators	Speed (m/s)	Acceln (m/s2)	Jerk (m/s')	Elevator Capacity (kg)	Door Type	Door Times Pre-Open,Open, Close (s)	Average Waiting Time (s)	Longest Waiting Time (s)	Average Transit Time (s)	Longest Transit Time (s)	Average Time to Dest (s)	Longest Time to Dest (s)
5	2.00	1.00	1.00	1400		0.00, 2.00, 3.00	31.24	115.57	85.22	159.58	121.97	275.15
5	2.00	1.00	1.00	1600		0.00, 2.00, 3.00	26.54	103.60	91.91	171.41	123.13	275.01
5	2.00	1.00	1.00	1800		0.00, 2.00, 3.00	20.47	89.57	99.26	187.40	123.34	276.96
5	2.50	1.00	1.00	1400		0.00, 2.00, 3.00	28.24	103.29	84.50	158.54	117.72	261.82
5	2.50	1.00	1.00	1600		0.00, 2.00, 3.00	24.57	94.54	91.26	170.63	120.17	265.16
5	2.50	1.00	1.00	1800		0.00, 2.00, 3.00	19.04	82.53	98.74	186.88	121.14	269.41
5	3.15	1.00	1.00	1400		0.00, 2.00, 3.00	26.42	95.97	84.24	158.02	115.32	253.99
5	3.15	1.00	1.00	1600		0.00, 2.00, 3.00	23.18	87.78	91.07	170.63	118.33	258.41
5	3.15	1.00	1.00	1800		0.00, 2.00, 3.00	18.00	77.39	98.61	186.88	119.78	264.26
6	2.00	1.00	1.00	1400		0.00, 2.00, 3.00	25.11	102.55	85.22	159.58	114.76	262.13
6	2.00	1.00	1.00	1600		0.00, 2.00, 3.00	19.67	86.73	91.91	171.41	115.05	258.14
6	2.00	1.00	1.00	1800		0.00, 2.00, 3.00	15.41	76.41	99.26	187.40	117.39	263.80
6	2.50	1.00	1.00	1400		0.00, 2.00, 3.00	22.85	91.70	84.50	158.54	111.38	250.24
6	2.50	1.00	1.00	1600		0.00, 2.00, 3.00	18.06	78.09	91.26	170.63	112.51	248.71
6	2.50	1.00	1.00	1800		0.00, 2.00, 3.00	14.31	69.79	98.74	186.88	115.57	256.67
6	3.15	1.00	1.00	1400		0.00, 2.00, 3.00	21.10	83.23	84.24	158.02	109.06	241.25
6	3.15	1.00	1.00	1600		0.00, 2.00, 3.00	16.84	71.82	91.07	170.63	110.88	242.45
6	3.15	1.00	1.00	1800		0.00, 2.00, 3.00	13.48	64.65	98.61	186.88	114.46	251.52
7	2.00	1.00	1.00	1400		0.00, 2.00, 3.00	20.09	89.53	85.22	159.58	108.84	249.11
7	2.00	1.00	1.00	1600		0.00, 2.00, 3.00	15.41	76.02	91.91	171.41	110.04	247.43
7	2.00	1.00	1.00	1800		0.00, 2.00, 3.00	11.82	63.39	99.26	187.40	113.15	250.78
7	2.50	1.00	1.00	1400		0.00, 2.00, 3.00	18.68	80.89	84.50	158.54	106.48	239.42
7	2.50	1.00	1.00	1600		0.00, 2.00, 3.00	14.49	67.83	91.26	170.63	108.31	238.46
7	2.50	1.00	1.00	1800		0.00, 2.00, 3.00	11.34	58.98	98.74	186.88	112.07	245.85
7	3.15	1.00	1.00	1400		0.00, 2.00, 3.00	17.59	74.13	84.24	158.02	104.93	232.15
7	3.15	1.00	1.00	1600		0.00, 2.00, 3.00	13.80	62.69	91.07	170.63	107.31	233.31
7	3.15	1.00	1.00	1800		0.00, 2.00, 3.00	10.95	55.55	98.61	186.88	111.49	242.42

Table E. 2: Simulation results for Case 1B.

Page: 1 of 2
Job: case 1b
Job No:
Calculation Title:
Made By:
Check By:
File/Date:

Elevate Version (Build 1814)

SIMULATION RESULTS

Based on avreage of all runs and passengers arriving between 08.00 to 08.05

No. of Elevators	Speed (m/s)	Acceln (m/s2)	Jerk (m/s')	Elevator Capacity (kg)	Door Type	Door Times Pre-Open,Open, Close (s)	Average Waiting Time (s)	Longest Waiting Time (s)	Average Transit Time (s)	Longest Transit Time (s)	Average Time to Dest (s)	Longest Time to Dest (s)
5	2.00	1.00	1.00	900		0.00, 2.00, 3.00	28.56	95.20	67.87	126.94	96.43	222.14
5	2.00	1.00	1.00	1000		0.00, 2.00, 3.00	24.15	101.22	67.54	132.66	91.69	233.88
5	2.00	1.00	1.00	1200		0.00, 2.00, 3.00	9.45	60.90	75.74	147.62	85.19	208.52
5	2.50	1.00	1.00	900		0.00, 2.00, 3.00	22.96	79.73	67.16	126.06	90.12	205.79
5	2.50	1.00	1.00	1000		0.00, 2.00, 3.00	19.11	85.75	66.66	131.78	85.77	217.53
5	2.50	1.00	1.00	1200		0.00, 2.00, 3.00	7.49	49.49	74.97	146.96	82.46	196.45
5	3.15	1.00	1.00	900		0.00, 2.00, 3.00	18.48	67.62	66.83	126.06	85.31	193.68
5	3.15	1.00	1.00	1000		0.00, 2.00, 3.00	15.26	73.64	66.17	131.78	81.43	205.42
5	3.15	1.00	1.00	1200		0.00, 2.00, 3.00	6.02	40.60	74.47	146.96	80.49	187.56
6	2.00	1.00	1.00	900		0.00, 2.00, 3.00	16.80	72.59	66.83	126.94	83.63	199.53
6	2.00	1.00	1.00	1000		0.00, 2.00, 3.00	13.23	78.61	66.00	132.66	79.23	211.27
6	2.00	1.00	1.00	1200		0.00, 2.00, 3.00	3.36	38.78	74.20	147.62	77.56	186.40
6	2.50	1.00	1.00	900		0.00, 2.00, 3.00	13.65	61.53	66.06	126.06	79.71	187.59
6	2.50	1.00	1.00	1000		0.00, 2.00, 3.00	10.71	67.55	65.12	131.78	75.83	199.33
6	2.50	1.00	1.00	1200		0.00, 2.00, 3.00	2.66	31.78	73.65	146.96	76.31	178.74
6	3.15	1.00	1.00	900		0.00, 2.00, 3.00	11.20	52.85	65.78	126.06	76.98	178.91
6	3.15	1.00	1.00	1000		0.00, 2.00, 3.00	8.68	58.87	64.68	131.78	73.36	190.65
6	3.15	1.00	1.00	1200		0.00, 2.00, 3.00	2.17	26.32	73.37	146.96	75.54	173.28
7	2.00	1.00	1.00	900		0.00, 2.00, 3.00	7.98	49.56	66.28	126.94	74.26	176.50
7	2.00	1.00	1.00	1000		0.00, 2.00, 3.00	5.74	56.49	65.23	132.66	70.97	189.15
7	2.00	1.00	1.00	1200		0.00, 2.00, 3.00	1.26	17.29	70.68	147.62	71.94	164.91
7	2.50	1.00	1.00	900		0.00, 2.00, 3.00	6.58	42.91	65.56	126.06	72.14	168.97
7	2.50	1.00	1.00	1000		0.00, 2.00, 3.00	4.69	49.84	64.52	131.78	69.21	181.62
7	2.50	1.00	1.00	1200		0.00, 2.00, 3.00	1.05	14.70	70.13	146.96	71.18	161.66
7	3.15	1.00	1.00	900		0.00, 2.00, 3.00	5.53	37.66	65.23	126.06	70.76	163.72
7	3.15	1.00	1.00	1000		0.00, 2.00, 3.00	3.92	44.59	64.13	131.78	68.05	176.37
7	3.15	1.00	1.00	1200		0.00, 2.00, 3.00	0.91	12.67	69.91	146.96	70.82	159.63

Table E. 3: Simulation results for Case 2A, without zoning.

Page: 1 of 2
Job: case 2a withoutzoning
Job No:
Calculation Title:
Made By:
Check By:
File/Date:

ELEVATE
Elevate Version (Build 1814)

SIMULATION RESULTS

Based on avreage of all runs and passengers arriving between 08.00 to 08.05

No. of Elevators	Speed (m/s)	Acceln (m/s2)	Jerk (m/s')	Elevator Capacity (kg)	Door Type	Door Times Pre-Open,Open, Close (s)	Average Waiting Time (s)	Longest Waiting Time (s)	Average Transit Time (s)	Longest Transit Time (s)	Average Time to Dest (s)	Longest Time to Dest (s)
5	2.50	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	79.10	243.60	87.58	162.93	166.68	406.53
5	2.50	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	53.60	150.10	100.20	193.68	153.80	343.78
5	2.50	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	31.90	138.80	114.64	238.37	146.54	377.17
5	3.15	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	68.70	218.80	85.85	160.23	154.55	379.03
5	3.15	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	47.40	137.30	98.56	191.22	145.96	328.52
5	3.15	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	26.70	126.80	113.32	236.49	140.02	363.29
5	4.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	62.60	202.00	85.03	159.41	147.63	361.41
5	4.00	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	43.90	128.60	97.91	189.83	141.81	318.43
5	4.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	23.50	118.50	112.67	235.67	136.17	354.17
6	2.50	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	47.00	139.30	87.49	162.93	134.49	302.23
6	2.50	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	29.60	109.20	99.96	193.68	129.56	302.88
6	2.50	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	9.80	78.20	114.06	238.37	123.86	316.57
6	3.15	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	41.40	126.10	85.77	160.23	127.17	286.33
6	3.15	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	25.60	97.10	98.40	191.22	124.00	288.32
6	3.15	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	8.40	66.80	112.75	236.49	121.15	303.29
6	4.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	25.78	116.90	85.03	159.41	122.73	276.31
6	4.00	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	23.10	89.50	97.83	189.83	120.93	279.33
6	4.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	7.60	59.80	112.26	235.67	119.86	295.47
7	2.50	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	30.00	106.00	87.49	162.93	117.49	268.93
7	2.50	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	14.70	74.90	99.96	193.68	114.66	268.58
7	2.50	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	5.20	35.70	113.82	238.37	119.02	274.07
7	3.15	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	25.50	92.90	85.77	160.23	111.27	253.13
7	3.15	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	12.00	62.80	98.40	191.22	110.40	254.02
7	3.15	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	5.10	35.10	112.50	236.49	117.60	271.59
7	4.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	22.60	84.30	85.03	159.41	107.63	243.71
7	4.00	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	10.40	55.20	97.83	189.83	108.23	245.03
7	4.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	5.10	35.10	112.09	235.67	117.19	270.77

Table E. 4: Simulation results for Case 2A, upper zone.

Page: 1 of 2
Job: case 2a upperzone
Job No:
Calculation Title:
Made By:
Check By:
File/Date:

ELEVATE
Elevate Version (Build 1814)

SIMULATION RESULTS

Based on avreage of all runs and passengers arriving between 08.00 to 08.05

No. of Elevators	Speed (m/s)	Acceln (m/s2)	Jerk (m/s')	Elevator Capacity (kg)	Door Type	Door Times Pre-Open,Open, Close (s)	Average Waiting Time (s)	Longest Waiting Time (s)	Average Transit Time (s)	Longest Transit Time (s)	Average Time to Dest (s)	Longest Time to Dest (s)
3	3.15	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	117.98	372.98	56.10	97.41	174.08	470.39
3	3.15	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	79.56	298.52	61.82	106.26	141.38	404.78
3	3.15	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	76.50	298.52	62.04	111.49	138.54	410.01
3	4.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	109.82	495.72	53.41	93.67	163.23	589.39
3	4.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	79.90	429.76	55.94	114.40	135.84	544.16
3	4.00	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	43.86	202.98	65.12	135.41	108.98	338.39
3	5.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	83.98	431.12	51.98	92.51	135.96	523.63
3	5.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	58.14	387.94	53.85	113.25	111.99	501.19
3	5.00	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	48.96	332.86	56.76	134.26	105.72	467.12
4	3.15	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	27.54	174.76	50.44	97.41	77.98	272.17
4	3.15	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	21.42	125.12	53.63	108.90	75.05	234.02
4	3.15	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	12.24	115.26	57.09	120.78	69.33	236.04
4	4.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	24.82	184.28	47.96	93.67	72.78	277.95
4	4.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	15.64	89.08	50.60	114.40	66.24	203.48
4	4.00	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	10.54	89.08	55.39	135.41	65.93	224.49
4	5.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	15.30	143.48	46.70	92.51	62.00	235.99
4	5.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	6.80	70.04	49.28	113.47	56.08	183.51
4	5.00	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	5.44	70.04	53.96	134.48	59.40	204.52
5	3.15	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	28.80	161.84	47.25	97.41	61.87	259.25
5	3.15	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	11.22	125.12	47.85	106.26	59.07	231.38
5	3.15	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	11.22	125.12	47.85	106.26	59.07	231.38
5	4.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	8.50	114.58	44.17	95.54	52.67	210.12
5	4.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	6.12	90.10	44.77	104.39	50.89	194.49
5	4.00	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	6.12	90.10	44.77	104.39	50.89	194.49
5	5.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	0.34	42583	42.24	90.86	42.58	99.02
5	5.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	0.34	42583	42.24	90.86	42.58	99.02
5	5.00	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	0.34	42583	42.24	90.86	42.58	99.02

Table E. 5: Simulation results for Case 2B, without zoning.

Page: 1 of 2
Job: case 2b withoutzoning
Job No:
Calculation Title:
Made By:
Check By:
File/Date:

Elevate Version (Build 1814)

SIMULATION RESULTS

Based on avreage of all runs and passengers arriving between 08.00 to 08.05

No. of Elevators	Speed (m/s)	Acceln (m/s2)	Jerk (m/s')	Elevator Capacity (kg)	Door Type	Door Times Pre-Open,Open, Close (s)	Average Waiting Time (s)	Longest Waiting Time (s)	Average Transit Time (s)	Longest Transit Time (s)	Average Time to Dest (s)	Longest Time to Dest (s)
6	4.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	37.50	87.90	79.72	147.68	117.22	235.58
6	4.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	28.73	67.01	93.66	176.08	122.38	243.08
6	4.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	22.55	65.33	108.11	216.81	130.66	282.14
6	5.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	34.41	81.54	78.69	146.37	113.10	227.91
6	5.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	26.31	61.95	92.86	174.91	119.17	236.86
6	5.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	20.69	62.52	107.46	216.08	128.14	278.60
6	6.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	32.45	77.49	78.26	145.85	110.70	223.34
6	6.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	24.78	58.70	92.49	174.40	117.27	233.09
6	6.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	19.52	60.78	107.02	215.86	126.53	276.64
7	4.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	20.52	49.31	79.64	147.68	100.16	196.98
7	4.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	16.34	50.28	91.47	175.71	107.80	225.99
7	4.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	11.51	33.17	105.49	216.66	116.99	249.83
7	5.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	18.69	46.55	78.62	146.37	97.31	192.91
7	5.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	24.85	47.21	90.67	174.03	105.47	221.24
7	5.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	10.08	29.42	104.83	215.64	114.91	245.06
7	6.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	17.49	44.57	78.18	145.85	95.67	190.42
7	6.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	13.86	45.32	90.30	173.08	104.16	218.40
7	6.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	9.16	26.90	104.46	215.13	113.63	242.03
8	4.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	11.97	36.93	79.21	147.68	91.18	184.61
8	4.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	8.14	22.80	90.74	175.71	98.88	198.51
8	4.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	4.84	21.32	103.88	216.66	108.72	237.98
8	5.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	10.59	33.71	78.18	146.37	88.77	180.07
8	5.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	7.36	21.14	89.72	174.03	97.08	195.17
8	5.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	4.17	19.76	103.15	215.64	107.32	235.40
8	6.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	9.84	31.74	77.67	145.85	87.51	177.59
8	6.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	6.96	20.07	89.35	173.08	96.31	193.15
8	6.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	3.78	18.74	102.71	215.13	106.49	233.87

Table E. 6: Simulation results for Case 2B, lower zone.

Page: 1 of 2
Job: case 2b lowerzone
Job No:
Calculation Title:
Made By:
Check By:
File/Date:

ELEVATE
Elevate Version (Build 1814)

SIMULATION RESULTS

Based on avreage of all runs and passengers arriving between 08.00 to 08.05

No. of Elevators	Speed (m/s)	Acceln (m/s2)	Jerk (m/s')	Elevator Capacity (kg)	Door Type	Door Times Pre-Open,Open, Close (s)	Average Waiting Time (s)	Longest Waiting Time (s)	Average Transit Time (s)	Longest Transit Time (s)	Average Time to Dest (s)	Longest Time to Dest (s)
4	2.50	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	45.00	142.70	55.99	107.32	100.99	250.02
4	2.50	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	19.30	75.50	58.16	123.94	77.46	199.44
4	2.50	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	18.10	75.50	59.64	140.55	77.74	216.05
4	3.15	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	26.90	121.30	53.07	105.34	79.97	226.64
4	3.15	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	17.50	71.50	57.85	123.81	75.35	195.31
4	3.15	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	16.40	71.50	59.33	140.43	75.73	211.93
4	4.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	25.80	117.60	53.13	105.34	78.93	222.94
4	4.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	16.50	68.90	57.72	123.81	74.22	192.71
4	4.00	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	15.40	68.90	59.21	140.43	74.61	209.33
5	2.50	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	30.70	27.80	48.42	105.34	79.12	133.14
5	2.50	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	30.10	33.60	55.30	122.14	85.40	155.74
5	2.50	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	30.10	33.60	55.30	122.14	85.40	155.74
5	3.15	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	20.70	22.40	47.62	105.34	68.32	127.74
5	3.15	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	20.70	29.60	55.12	122.14	75.82	151.74
5	3.15	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	20.70	29.60	55.12	122.14	75.82	151.74
5	4.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	21.00	47.55	47.55	105.34	68.55	124.44
5	4.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	24.00	27.00	51.89	122.14	75.89	149.14
5	4.00	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	24.00	27.00	51.89	122.14	75.89	149.14
6	2.50	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	18.26	21.50	44.45	105.34	46.25	126.84
6	2.50	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	10.01	0.20	49.91	122.14	59.92	122.34
6	2.50	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	10.02	0.20	49.91	122.14	59.93	122.34
6	3.15	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	16.25	18.80	44.08	105.34	60.33	124.14
6	3.15	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	10.24	0.20	49.54	122.14	59.78	122.34
6	3.15	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	10.23	0.20	49.54	122.14	59.77	122.34
6	4.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	15.33	17.20	43.96	105.34	59.29	122.54
6	4.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	10.32	0.20	49.41	122.14	59.73	122.34
6	4.00	1.00	1.00	1000	CO 1100mm	0.00, 1.80, 2.90	10.46	0.20	49.41	122.14	59.87	122.34

Table E. 7: Simulation results for Case 2B, upper zone.

Page: 1 of 2
Job: case 2b upperzone
Job No:
Calculation Title:
Made By:
Check By:
File/Date:

ELEVATE
Elevate Version (Build 1814)

SIMULATION RESULTS

Based on avreage of all runs and passengers arriving between 08.00 to 08.05

No. of Elevators	Speed (m/s)	Acceln (m/s2)	Jerk (m/s')	Elevator Capacity (kg)	Door Type	Door Times Pre-Open,Open, Close (s)	Average Waiting Time (s)	Longest Waiting Time (s)	Average Transit Time (s)	Longest Transit Time (s)	Average Time to Dest (s)	Longest Time to Dest (s)
4	4.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	48.20	129.00	47.70	85.64	95.90	214.64
4	4.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	41.80	124.00	51.98	92.75	93.78	216.75
4	4.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	37.90	108.90	52.07	94.50	89.97	203.40
4	5.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	34.30	111.80	46.44	81.18	80.74	192.98
4	5.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	22.70	86.30	51.21	88.56	73.91	174.86
4	5.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	21.70	86.30	51.39	92.61	73.09	178.91
4	6.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	32.40	139.20	44.78	78.39	77.18	217.59
4	6.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	22.90	133.90	47.03	95.63	69.93	229.53
4	6.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	9.70	49.40	54.54	113.09	64.24	162.49
5	4.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	19.40	76.90	45.59	82.94	64.99	159.84
5	4.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	18.50	76.90	46.49	92.52	64.99	169.42
5	4.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	17.00	76.90	50.18	109.13	67.18	186.03
5	5.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	23.06	52.30	41.76	81.18	64.82	133.48
5	5.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	16.94	36.80	44.33	90.63	61.27	127.43
5	5.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	9.72	33.30	47.21	100.49	56.93	133.79
5	6.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	27.22	88.40	40.41	78.39	67.63	166.79
5	6.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	26.67	89.10	41.81	95.63	68.47	184.73
5	6.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	17.50	50.10	44.28	113.09	61.78	163.19
6	4.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	8.96	34.00	43.07	80.28	52.03	114.28
6	4.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	7.78	34.00	43.07	80.28	50.84	114.28
6	4.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	9.62	34.00	43.07	80.28	52.69	114.28
6	5.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	11.94	45.80	39.06	81.18	51.00	126.98
6	5.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	11..23	36.80	39.51	88.56	50.74	125.36
6	5.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	12.24	36.80	39.51	88.56	51.75	125.36
6	6.00	1.00	1.00	630	CO 1100mm	0.00, 1.80, 2.90	8.89	26.60	40.14	78.39	49.03	104.99
6	6.00	1.00	1.00	900	CO 1100mm	0.00, 1.80, 2.90	8.33	26.60	45.63	95.63	53.96	122.23
6	6.00	1.00	1.00	1200	CO 1100mm	0.00, 1.80, 2.90	6..67	26.60	47.16	113.09	53.83	139.69

Table E. 8: Simulation results for Case 3, without zoning.

Page: 1 of 2
Job: case3 withoutzoning
Job No:
Calculation Title:
Made By:
Check By:
File/Date:

Elevate Version (Build 1814)

SIMULATION RESULTS

Based on avreage of all runs and passengers arriving between 08.00 to 08.05

No. of Elevators	Speed (m/s)	Acceln (m/s2)	Jerk (m/s')	Elevator Capacity (kg)	Door Type	Door Times Pre-Open,Open, Close (s)	Average Waiting Time (s)	Longest Waiting Time (s)	Average Transit Time (s)	Longest Transit Time (s)	Average Time to Dest (s)	Longest Time to Dest (s)
12	6.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	23.33	52.10	157.41	290.52	180.74	342.62
12	6.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	18.80	45.92	191.04	356.01	209.84	401.93
12	6.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	16.85	36.76	212.28	387.87	229.14	424.63
12	7.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	22.81	50.87	156.94	290.52	179.75	341.38
12	7.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	18.43	44.95	190.81	356.01	209.24	400.95
12	7.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	16.57	36.19	212.16	387.87	228.74	424.06
12	9.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	22.50	50.11	156.82	290.52	179.32	340.63
12	9.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	18.20	44.35	190.81	356.01	209.01	400.36
12	9.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	16.39	35.82	212.16	387.87	228.56	423.69
13	6.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	17.18	39.41	157.41	290.52	174.60	329.93
13	6.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	13.10	30.70	191.04	356.01	204.15	386.71
13	6.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	11.93	30.73	212.28	387.87	224.21	418.59
13	7.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	16.82	38.56	156.94	290.52	173.76	329.07
13	7.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	12.84	30.09	190.81	356.01	203.65	386.10
13	7.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	11.72	30.13	212.16	387.87	223.88	417.99
13	9.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	16.60	38.03	156.82	290.52	173.42	328.54
13	9.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	12.67	29.71	190.81	356.01	203.48	385.71
13	9.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	11.58	29.74	212.16	387.87	223.74	417.61
14	6.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	13.00	27.74	157.41	290.52	170.41	318.25
14	6.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	9.89	25.74	191.04	356.01	200.94	381.75
14	6.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	8.68	20.20	212.28	387.87	220.96	408.07
14	7.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	12.73	27.17	156.94	290.52	169.67	317.68
14	7.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	9.70	25.13	190.81	356.01	200.50	381.13
14	7.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	8.54	19.90	212.16	387.87	220.70	407.77
14	9.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	12.55	26.81	156.82	290.52	169.37	317.32
14	9.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	9.58	24.74	190.81	356.01	200.38	380.75
14	9.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	8.45	19.71	212.16	387.87	220.61	407.58

Table E. 9: Simulation results for Case 3, lower zone.

Page: 1 of 2
Job: case 3lowerzone
Job No:
Calculation Title:
Made By:
Check By:
File/Date:

ELEVATE
Elevate Version (Build 1814)

SIMULATION RESULTS

Based on avreage of all runs and passengers arriving between 08.00 to 08.05

No. of Elevators	Speed (m/s)	Acceln (m/s2)	Jerk (m/s')	Elevator Capacity (kg)	Door Type	Door Times Pre-Open,Open, Close (s)	Average Waiting Time (s)	Longest Waiting Time (s)	Average Transit Time (s)	Longest Transit Time (s)	Average Time to Dest (s)	Longest Time to Dest (s)
7	3.15	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	82.20	236.10	96.84	185.13	179.04	421.23
7	3.15	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	46.80	146.00	114.66	231.21	161.46	377.21
7	3.15	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	39.60	133.60	123.84	254.07	163.44	387.67
7	4.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	80.80	232.60	96.66	185.13	177.46	417.73
7	4.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	45.30	141.70	114.39	231.21	159.69	372.91
7	4.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	44.80	144.60	125.82	254.07	170.62	398.67
7	5.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	79.90	230.60	96.66	185.13	176.56	415.73
7	5.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	44.50	140.40	114.39	231.21	158.89	371.61
7	5.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	44.40	143.30	125.82	254.07	170.22	397.37
8	3.15	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	42.20	106.40	96.57	185.13	138.77	291.53
8	3.15	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	18.00	88.40	113.49	231.21	131.49	319.61
8	3.15	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	12.40	70.90	122.22	254.07	134.62	324.97
8	4.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	41.20	104.30	96.48	185.13	137.68	289.43
8	4.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	17.60	86.40	113.49	231.21	131.09	317.61
8	4.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	18.00	98.60	125.19	254.07	143.19	352.67
8	5.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	40.70	103.10	96.48	185.13	137.18	288.23
8	5.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	17.30	85.20	113.49	231.21	130.79	316.41
8	5.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	17.70	97.30	125.19	254.07	142.89	351.37
9	3.15	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	23.20	74.10	96.57	185.13	119.77	259.23
9	3.15	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	17.60	47.20	113.31	231.21	119.61	278.41
9	3.15	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	3.70	25.50	121.77	254.07	125.47	279.57
9	4.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	22.50	72.00	96.48	185.13	118.98	257.13
9	4.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	6.10	45.20	113.31	231.21	119.41	276.41
9	4.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	5.10	46.70	124.83	254.07	129.93	300.77
9	5.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	22.00	70.80	96.48	185.13	118.48	255.93
9	5.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	6.00	44.00	113.31	231.21	119.31	275.21
9	5.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	5.00	45.40	124.83	254.07	129.83	299.47

Table E. 10: Simulation results for Case 3, upper zone.

Page: 1 of 2
Job: case 3 upperzone
Job No:
Calculation Title:
Made By:
Check By:
File/Date:

ELEVATE
Elevate Version (Build 1814)

SIMULATION RESULTS

Based on avreage of all runs and passengers arriving between 08.00 to 08.05

No. of Elevators	Speed (m/s)	Acceln (m/s2)	Jerk (m/s')	Elevator Capacity (kg)	Door Type	Door Times Pre-Open,Open, Close (s)	Average Waiting Time (s)	Longest Waiting Time (s)	Average Transit Time (s)	Longest Transit Time (s)	Average Time to Dest (s)	Longest Time to Dest (s)
7	6.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	61.70	199.60	91.69	170.05	153.39	369.65
7	6.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	36.00	100.80	107.37	189.51	143.37	290.31
7	6.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	25.30	104.10	110.63	207.79	135.93	311.89
7	7.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	55.40	183.80	89.91	168.35	145.31	352.15
7	7.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	31.50	93.60	105.45	187.81	136.95	281.41
7	7.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	21.10	96.90	108.48	206.09	129.58	302.99
7	9.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	51.60	173.80	88.73	167.24	140.33	341.04
7	9.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	28.60	88.90	104.04	186.70	132.64	275.60
7	9.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	18.30	92.20	107.00	204.98	125.30	297.18
8	6.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	30.80	110.20	91.39	170.05	122.19	280.25
8	6.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	13.70	57.40	106.78	189.51	120.48	246.91
8	6.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	8.00	38.80	109.82	207.79	117.82	246.59
8	7.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	27.70	94.70	89.69	168.35	117.39	263.05
8	7.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	10.40	56.40	98.72	194.47	109.12	250.87
8	7.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	4.70	36.20	102.71	194.99	107.41	231.19
8	9.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	22.90	84.90	87.02	167.24	109.92	252.14
8	9.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	12.63	51.70	97.24	193.36	106.24	245.06
8	9.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	3.70	31.50	100.94	193.88	104.64	225.38
9	6.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	8.30	57.50	88.50	170.05	96.80	227.55
9	6.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	1.40	17.00	102.93	189.00	104.33	206.00
9	6.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	0.90	16.60	104.86	204.91	105.76	221.51
9	7.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	7.80	51.30	86.21	168.35	94.01	219.65
9	7.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	1.00	17.40	93.02	194.47	94.02	211.87
9	7.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	0.10	4.20	93.54	194.99	93.64	199.19
9	9.00	1.00	1.00	1600	CO 1100mm	0.00, 1.80, 2.90	6.90	46.60	85.40	167.24	92.30	213.84
9	9.00	1.00	1.00	1800	CO 1100mm	0.00, 1.80, 2.90	0.70	17.00	91.91	193.36	92.61	210.36
9	9.00	1.00	1.00	2000	CO 1100mm	0.00, 1.80, 2.90	0.10	4.20	92.43	193.88	92.53	198.08

CURRICULUM VITAE

Name Surname: Ayşe Çolakoğlu

Place and Date of Birth: 04.07.1989

E-Mail: ayse.colakogluu@gmail.com

Education:

M.Sc.:

2012-2015 Graduate School of Science Engineering and Technology, Department of Informatics, Architectural Design Computing Program, İstanbul Technical University, Turkey.

2013-2014 Architecture and Urban Planning Department, Architectural Sciences Master Program, Vienna University of Technology, Austria (Exchange Student).

B.Sc.:

2011 Faculty of Architecture, Izmir Institute of Technology, Turkey.

Professional Practice:

2011-2012 Duran – Iltir Architecture

2010 Duran – Iltir Architecture (Intern)

2009 İzmir Metropolitan Municipality (Site Intern)

Honors and Awards:

2011 Uşak Bus Terminal, Architectural Design Competition (3. Mention Prize)

2010 Düzce Chamber of Industry and Trade Building, Architectural Design Competition (1. Mention and 4. Mention Prize)

Izmir Instıtute of Technology Academic Honor List (2007, 2008, 2009, 2010)

Publications:

Çolakoğlu, A., Küçükpehlivan, G. (2014). Kullanıcı odaklı bisiklet yolu güzergahı belirlenmesi için karar destek modeli önerisi. *VIII. Mimarlıkta Sayısal Tasarım Ulusal Sempozyumu*, İzmir, İYTE.