Feasibility study of Air Traffic Control Towers around the globe

Research report

J. H. Hartmann

Delft University of Technolog

TU Delft Delft University of Technology

Challenge the future

Cover: This photo has been taken at Amsterdam Schiphol Airport. In the back (left) the main air traffic control tower with a height of 100 meter is shown and the secondary tower (right) is the old control tower and operates at this moment as air traffic controller training facility. The main tower is constructed by Bureau De Weger in cooperation with architect Netherlands Airports Consultants (NACO) in 1991. In front an Airbus A320-200 of Swiss International Air Lines is taxiing and ready for departure. [www.airchive.com]

Research report

“Feasibility study of air traffic control towers around the globe”

“International research regarding the local influences providing an
optimal structural design for air traffic control towers
around the globe in an economical perspective”

J.H. Hartmann

Department of Building Engineering
Faculty of Civil Engineering and Geosciences
Delft University of Technology
2628GN/2600GA Delft
The Netherlands
www.tudelft.nl

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For inquiries regarding this thesis research please contact the author via e-mail: joosthartmann@gmail.com

Colophon

Author:

Name: Hartmann, J.H. (Joost)
E-mail: Joosthartmann@gmail.com; Joost.Hartmann@rhdhv.com
Graduation date: August, 2014
Address: Piet Heinstraat 66A
2518 CK, The Hague
The Netherlands

Committee information

Chairman:	Professor ir. Nijsse, R. (Rob)	Delft University of Technology / ABT
Company mentor:	Ir. Font Freide, J.J.M. (Jan)	Royal HaskoningDHV
TU Delft mentor:	Dr. ir. Terwel, K.C. (Karel)	Delft University of Technology
TU Delft mentor:	Professor ir. van der Horst, A.Q.C. (Aad)	Delft University of Technology / Bam Infraconsult

University information

University: Delft University of Technology
Faculty: Civil Engineering and Geosciences
Master: Building Engineering – Structural design
Department: Design & Construction
Address: Stevinweg 1
2826 CN, Delft
The Netherlands
Website: www.be.citg.tudelft.nl

Company information

Company: Royal HaskoningDHV
Department: Business line buildings – Structural design
Address: George Hintzenweg 85
3068 AX, Rotterdam
The Netherlands
Website: www.royalhaskoningdhv.com

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Abstract

At this moment the global human wealth is getting to the next level, which means a growing amount of people is able to travel by plane and these growth figures are seen in the latest global annual passenger's flows. These latest developments demand building new airports and extending the existing airports heavily around the world in the nearby future (10 years), subsequently resulting in a higher demand of air traffic control towers (ATC towers).

Air traffic control towers are very unique buildings. Most countries possess only one or a few towers and the specific knowledge of the technical and functional design of these towers are owned by a few consultants around the world. One of these consultants is Royal HaskoningDHV. However these (Dutch) designers do not possess knowledge about the entire global construction market and geological conditions, making it very difficult to design an optimal ATC tower in a certain country.

From this specific design difficulty, the overall objective of this thesis research is to perform an international investigation regarding the main local influences in order to provide an economical optimal structural design methodology for ATC towers which can be used to design these towers anywhere around the globe. The main research question which follows from the research objective is:

"What are the local influences on the structural design of an air traffic control tower and how do they relate with an economical optimal structural design?"

First, an investigation has been performed in order to select a few representative countries that will cover the scope for this thesis research. Based on motivated reasons the chosen countries are: the Netherlands, Nigeria, Japan, China, Turkey and Indonesia.

On basis of a literature study the main structural characteristics for high and tall building design are investigated. The lateral forces caused by wind and earthquake action are the most vital forces for structural design and the structures must provide enough structural reliability. Next, the local building codes of the chosen countries are compared and it has been examined that all the codes contain the same factors and approaches as the Eurocode (European building standard), which is used along the research.

To be able to perform this complex international research, the elementary design process is chosen as a sequential guidance in order to obtain economical optimal structural concepts around the globe. By simulating these concepts (case studies) with designs and calculations, the behaviour can be qualified and relations can be made between the local influences and structural design.

This process starts with a comprehensive analysis of the fundamental design principles of ATC towers. It is concluded that ATC towers are the most important buildings on the airport domain regarding the guidance and safety of air traffic in the proximity of an airport, providing all the facilities and utilities air traffic controllers need to operate.

Even with advanced radar technical and camera technology this guidance is mainly done (and will be done in future) by visual observation and these towers give the air traffic controllers the best view over active pavement. The towers consist of three basic components; the control cab, tower shaft and base building, each having their own primary function.

Next, the fundamental requirements for ATC towers facilities are determined. They are drafted by the two major aviation authorities in the world, the FAA and ICAO. In addition to these requirements; desires, starting points and boundary conditions are determined for ATC tower design. The stated desires and starting points are applicable for every ATC design in a general manner, whereas the local boundary conditions have their own influence and importance on every individual ATC design. The following four local boundary conditions are found to be the most important to determine:

- Current and projected future air activity airport
- Wind climate
- Earthquake hazard
- Construction industry

For each of the six countries these boundary conditions are determined, by examining literature and conducting interviews with experts in the Netherlands and in foreign countries. It is found that for each country different results are obtained.

After the analysis, wherein all the necessary information in a diverging process was gathered in order to design an ATC tower, choices are made in order to achieve targeted optimal design solutions. This choice determination is done by applying a converge process with a self-developed methodology which is performed on basis of three main aspects; structural optimum solutions, labour optimum solutions and material optimum solutions. The input variables for this converge process are directly related with the specific boundary conditions found for each country, resulting in different possible optimal structural solutions as output of this converging process.

Next, these optimal structural solutions are simulated to understand and to quality how the local boundary conditions relate with the structural design characteristics. E.g. how does an earthquake load compare with a wind load in certain countries, or how does a steel variant compare with a concrete variant.

Unfortunately it is not possible to determine which structural design is the most economical solution, but this thesis research provides a design methodology which gives the designers a direction towards the most optimal solution when they take the specific cost aspects into account.

The report closes with two kinds of recommendation: themes for follow-up research based upon the issue are which are not elaborated in detail in this report and some advices for using the design methodology as described.

Preface

After ten months, I proudly present my graduation research results in this master thesis research report. This document contains an international research regarding the local influences providing an optimal structural design for air traffic control towers around the globe in an economical perspective.

Next to this document an extensive appendix report, literature study and interview report is written. These documents act as foundations of this research report. Due to its size and/or nature these documents are not added as an appendix to this research report but should be seen and used as separate documents.

This thesis report was written in support of candidature for the Master of Science title in Civil Engineering at Delft University of technology. The research was carried out in cooperation with Delft University of Technology, Faculty of Civil Engineering & Geosciences, Design and construction and Royal HaskoningDHV, department Business line Buildings – Structural design.

My personal motivation for choosing this subject is developed already a long time ago. During my bachelor and master studies it became clear to me that my interests were in the design and construction of utility buildings. I became attracted to these kinds of buildings, because of their major influence on an architect and structural engineer. In general these buildings are beautiful, iconic, well-known, unique, innovative and most of all challenging for the structural engineer. The importance of the architecture of the building can be found in all the specific details and the chosen façade, which makes every building special. Another major influence on the shape of the building is its purpose, the function during their lifetime, which enables new structural design methods.

Looking at the range of utility buildings, my interests are predominantly focused on high-rise buildings and airports. High-rise buildings determine the iconic view of a certain city, the well-known skyline. The structures are often complex. The buildings are slender, the building pits small and the logistics difficult. My interest in airports started during my private holidays and study tours by travelling the last years often by plane and saw all different type of airports. From the busiest airport of the Netherlands “Schiphol”, to the newest ones in Shanghai, Beijing and Moscow. From the one of the biggest in the world “Atlanta” to one of the most dangerous in the world “Sint Maarten”. All these airports made me very enthusiastic due to the following aspects; Airports are one of the largest utility groups of buildings in the world with massive passenger’s flows. The latest terminals are built with an open and wide philosophy, thereby super-frames are designed in the roof-structure and a reduction of vertical load bearing structures is stimulated. The logistics in every aspect (passengers, luggage, security and airplane equipment) is challenging and I believe the design of the airport is mostly influenced by those aspects.

To combine my study interest with my “attraction” to airports, it turns out that the subject “Air Traffic Control towers” was a perfect match. I hope you will read this report with the same amount of curiosity as I enjoyed while conducting this research.

The Hague, August 2014

Joost Hartmann

Keywords: air traffic control tower, airport control, structural engineering, high rise structural design, international construction industry, The Netherlands, Japan, China, Turkey, Indonesia, Nigeria, wind engineering, earthquake engineering, international buildings codes, design methodology air traffic control towers

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First and foremost, I would like to thank Royal HaskoningDHV for providing me the opportunity to graduate within a first class international engineering company, in particular Jan Font Freide. Royal HaskoningDHV acted as an inspiring environment which gave me a clear insight in the Dutch and international construction industry.

Next, my gratitude goes to my graduation committee for providing me with all the information, guidance and support. Without their effort I would not be able to present the reader this report. Therefore I would to thank the following committee members:

Prof.ir. R. Nijsse	ABT / Delft University of Technology, chairman
Prof.ir. A.Q.C. van der Horst	Bam Infraconsult / Delft University of Technology
Ir. J.J.M. Font Freide	Royal HaskoningDHV
Dr. ir. K.C. Terwel	Delft University of Technology

I am grateful to all the experts for providing me with all the information gained during interviews, consults and their contribution filling in the questionnaires. Especially my colleagues from Royal HaskoningDHV, who assisted and inspired me by telling their personal experiences about the international building industry and global cultures.

Especially, I would like to thank my parents, Hugo and Anne-Marie who helped, supported and had faith in me through my entire high school and study period becoming a graduated engineer.

Finally, I would like to thank my friends for their support, encouragement and pleasant study period.

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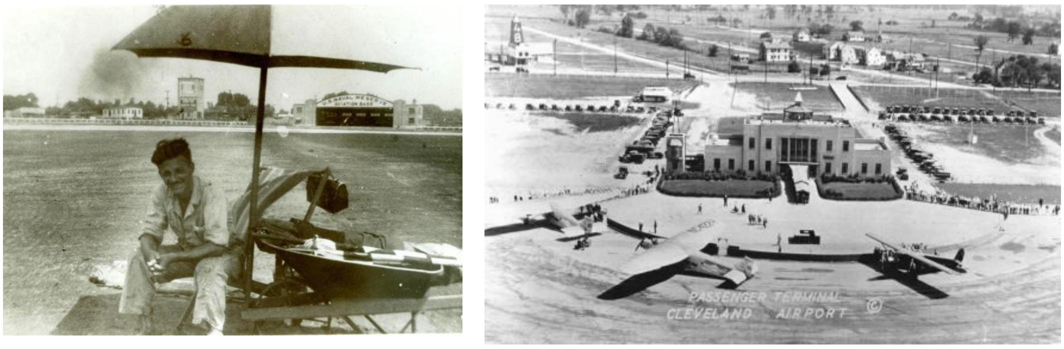
1. Introduction

1.1 History

The first powered flight was made by the Wright brothers on 17th December 1903 and from this historical moment the global aviation development started. During the World War I the development of aviation technology, aircraft manufacturing and pilot training accelerated furthermore resulting in increasing aircraft traffic and speeds. This led to safety concerns due to the lack of control capacity and the leaders of the aviation industry concluded federal action was needed to set safety standards.

In 1929 the first air traffic controller was hired. His name was Archie W. League and his “control tower” was a wheelbarrow, which functioned as carriage for his chair, umbrella and signal flags. League sat down along the runway directing the aircraft with the signals “Go” or “Hold”. However this technique was soon out-dated by the introduction of the radio technology that allowed air traffic control to expand beyond airport boundaries.



Figures 1.1 & 1.2: The first air traffic controller Archie W. League (left) and the first air traffic control tower (right) [wikipedia.org, 2013]

The first radio equipped control room was opened in 1930 at Cleveland’s Municipal Airport and can be seen as the first air traffic control tower in the world. In the following five years about twenty other air traffic control towers were built in the United States. Another milestone in the aviation development was the introduction of air traffic control centres in 1936. From that time airlines began tracking their flights between airports along their route, to ensure more safety.

During, and after, the World War II the need for passengers transport increased even more. The largest impact the World War II had on the aviation was the development of the radar. With this invention air traffic controllers were able to track airplanes very closely by a synchronized transmitter and receiver, which revolutionized air traffic control. The last major development in the aviation was the introduction of the jet engine in the late 50’s. Larger and faster planes were being built and travelling by plane became more and more accessible and ordinary for the world [NATCA, 2009].

1.2 Function

At large airports the first tall object that will attract the people's attention is the high slender tower, often located near the terminals or standing next to the runway. For safety considerations not an optimal combination to build a high building on an airport, where airplanes are departing and descending. So why are these buildings being designed in that way and with which purpose?

During the entire day several airplanes are located simultaneously on the ground and in close proximity of an airport. The primary method of controlling this air traffic is by visual observation from a tower; the well-known air traffic control tower, in other words the ATC tower. To give air traffic controllers a panoramic view, ATC towers are designed to give view of the entire airport and its surroundings. To achieve the best view, high structures are designed with a windowed structure on the top. This windowed structure, the control cab, is the work floor of the air traffic controller, whereby the controller's responsibility falls into three general operational disciplines; ground control, tower control and clearance. In the tower all these disciplines are working besides each other to ensure safe and efficient movement of all the airplanes and vehicles on the taxiways and runways of the airport, as well as for airplanes in the air in the proximity of the airport [Belgocontrol, 2008].

Figure 1.3: Air traffic control towers at Schiphol Airport [Hartmann, J., 2013]

1.3 Current situation

At this moment the global human wealth is getting to the next level, which means a growing amount of people is able to travel and these growth figures are seen in the latest annual passenger's flows [Tracy, J, 2011]. The third world countries are getting more developed and civilized and their accessibility by air will be increased during the coming decades.

In the future, aviation safety will be further increased by the introduction of the NextGEN [FAA, 2013]. The American Federal Aviation Administration (FAA) is developing satellite-based navigation. While at this moment radars require aircraft to fly over their physical locations on the ground, in the future satellite-technology will allow controllers to guide aircraft in more direct routes. Decreasing flight-time and increasing flight capacity.

These latest developments demand building new airports and extending the existing (hub) airports heavily around the world in the nearby future. This can also be seen in the development of the air traffic control towers presented in figure 1.4.

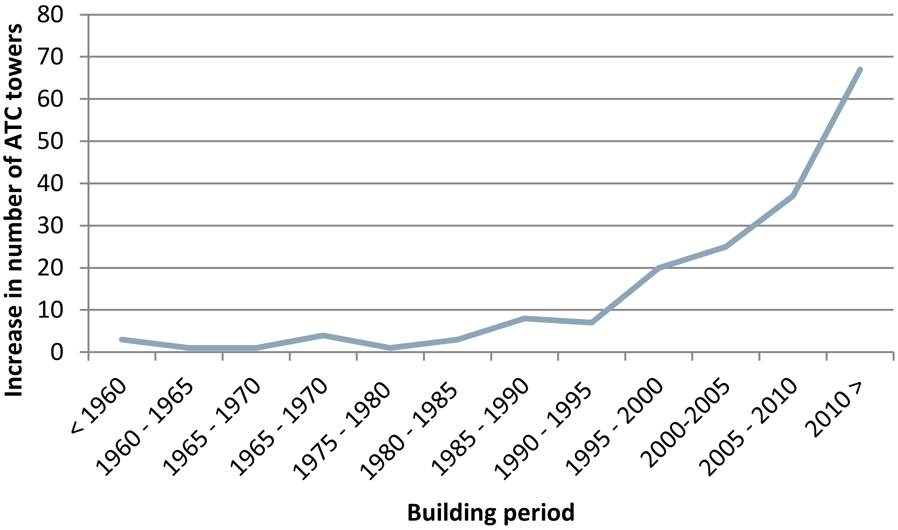


Figure 1.4: ATCT growth [Appendix II]

Also the latest control towers are getting higher and higher to satisfy the visibility of the controllers. In the past five years eleven new towers are built or under construction with an average height of 130 meters. The total development of the air traffic control towers, higher than 100 meters, is given in figure 1.5 below.

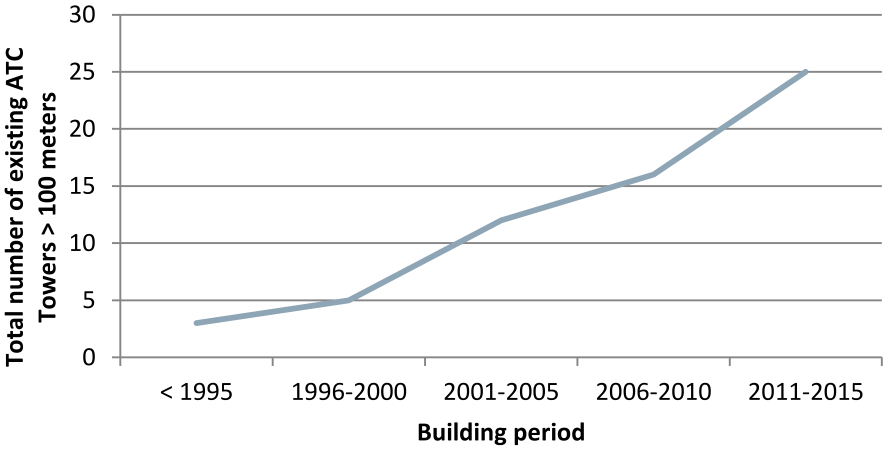


Figure 1.5: Development past 20 years [Appendix II]

1.4 Research purpose

Looking at the aviation development, expectations of each continent show that these towers will be (mainly) built in the less developed areas of the world [Tracy, J, 2011]. Like Latin America, Africa and Asia-Pacific. The building industries in these areas are less comprehensive than for example European countries and several questions arise.

What are the influences of these local building aspects on the preliminary structural design of these towers? Will they be built only with a certain material or system? Is it structurally possible to build a slender tower under local weather and geological conditions with the local systematics and is this the optimal way of doing it?

These design questions and problems arise because air traffic control towers are unique buildings. Most countries possess only one or a few towers and the specific knowledge of the technical and functional design of these towers are owned by a few consultants around the world. One of these consultants is NACO, Netherlands Airport Consults B.V, a subdivision of Royal HaskoningDHV (RHDHV).

RHDHV wants to extend their international market around the globe. By doing this master research more knowledge is gained about different building markets and their relationships regarding the design of air traffic control towers. Furthermore, at this moment, NACO and RHDHV is more involved in the design of airport terminals due to several reasons, e.g. designing terminals is more profitable. Their aim is to enlarge their knowledge and portfolio of air traffic control towers and therefore more structural and local investigation is desired.

1.5 Research objective and main question

The overall objective of this thesis research is to perform an international investigation regarding the main local influences in order to provide an economical optimal structural design methodology for air traffic control towers which can be used to design these towers anywhere around the globe.

This investigation addresses next to the design philosophy of these towers; the global air traffic control tower requirements, the most important local boundary conditions, influences and the global construction industries.

At the end more insight in the ATC tower industry is obtained and conclusions are given in order to stimulate proactive design. It provides the designer an all-embracing overview of the most important design considerations suitable for the first conceptual phases of the design process, stimulating more optimal design solutions in economically prospect for ATC towers located anywhere around the globe.

The main research question which follows from the research objective is:

"What are the local influences on the structural design of an air traffic control tower and how do they relate with an economical optimal structural design?"

In order to answer the main research question, this thesis is divided into three phases. Each of these three phases addresses its own field of research answering its own sub-question to obtain the main question. The following sub-questions are defined:

Phase 1 *What are the design characteristics of high and tall buildings in the chosen countries around the globe?*

Phase 2 *What are the characteristics of air traffic control towers?*

Which steps are taken in order to define and design an economical optimal structural solution?

Phase 3 *Which conclusions can be given in order to satisfy an optimal ATC tower design*

1.6 Research approach and key questions

In order to attain the desired outcome, this thesis process is divided into three phases.

- Phase I comprises all the relevant information needed to be able to make a proper design for a high and tall building around the globe. This research is elaborated in detail in the literature report and a short summary is given in chapter 2 of this booklet.

- Phase II comprises first a background research regarding air traffic control towers, next the chosen design methodology and local influences are determined from which subsequently variant designs are developed in an economical optimal prospect in order to qualify the influences of the local conditions on the structural design.

- On basis of the previous findings, conclusions for the structural design of an economical optimized air traffic control tower around the globe are given, answering the main question.

Phase I

The structural design aspects of high and tall buildings will be discussed in order to investigate the structural solutions and different load bearing systems. Furthermore wind and earthquake actions are discussed in more detail, because these are the most critical load actions.

Phase I will be completed by discussing the construction methodology. To develop a concept that meets all functional requirements and boundary conditions and at the same time is an economical solution, a methodology should be followed during the conceptual phase.

The sub-question of this phase *"What are the design characteristics of high and tall buildings in the chosen countries around the globe*" is divided in the following key-questions:

1.1 *What are the structural characteristics of high and tall buildings?*
1.2 *Which structural systems are available and suitable for high and tall building design?*
1.3 *What are the local building codes and how do these local building codes relate with the Eurocode?*
1.4 *What are the general characteristics for wind and earthquake loading?*
1.5 *Which criteria are essential for an optimal integrated structural design*?

Phase II

The first action of this phase is defining the purpose and function of air traffic control towers followed by an exploratory research of the current ATC towers around the globe, with the objective to gain more knowledge about these buildings.

After the ATC tower research the chosen design methodology is shortly defined followed by the fundamental requirements stated by the FAA and ICAO. These requirements will be complemented with starting points and desires. Special attention is placed on the local influences conditions of these six chosen countries, because they will form the main topic of this thesis research. The selection of these countries is explained in appendix I and is also defined shortly in section 1.8. The local influences are determined with help of literature, questionnaires and interviews with experts around the globe. Subsequently, per country, several concept designs are examined with the focus on an economical optimal structure. In this phase no detailed design specifications are produced in order to enlarge the design freedom.

The sub-question of this phase "*What are the characteristics of air traffic control towers*" is divided in the following key-questions:

2.1 *What is the purpose and function of an air traffic control tower?*
2.2 *What is the current appearance of these towers worldwide?*

The sub-question of this phase *"Which steps are taken in order to define and design an economical optimal structural solution"* is divided in the following key-questions:

2.3 *Which design methodology will be used in order to obtain the thesis research objective?*
2.4 *What are the fundamental design principles and criteria for ATC towers?*
2.5 *Which cost aspects influence an economically optimal structural design?*
2.6 *What are the local boundary conditions of the six chosen countries?*
2.7 *Which concept designs must be investigated in order to achieve satisfying results regarding optimal structural design versus local conditions?*
2.8 *How do these local boundary conditions relate with the structural design characteristics?*

Phase III

In the last phase all the findings from phase II are jointed together. Conclusions are given for the structural designer in order to design an economical optimal air traffic control tower anywhere on the globe. Always some aspects require further investigation and these are discussed by providing clearly defined recommendations.

The sub-question of this phase: *"Which conclusions can be given in order to satisfy an optimal ATC tower design*" is divided in the following key-questions:

3.1 What are the overall conclusions to answer the main research question?
3.2 Which recommendations can be given that lead to improvements?

1.7 Schematization research methodology

On the next page the research methodology is visualized and represents also the outline of this research report. The square boxes represent the chapters and form the mainline of the report, the circular boxes represents important sections within the chapters. The chapters left of the line are globally applicable and the chapters on the right of the line are locally applicable.

Chapter 1 discusses the research objective, research approach and research questions. Also the scope for this research is determined by choosing 6 countries.

Phase I comprise the literature study and is described in chapter 2, whereby also the local codes of the 6 chosen countries are discussed.

Phase II is divided into 2 sections; the first two chapters, 3 "ATCT research" and 4 "design methodology", are globally applicable and present the general principles of designing an air traffic control tower. These design principles are applied on concept designs and elaborated in the chapter 5, 6 and 7. Chapter 5 presents the local boundary conditions. In chapter 6, concepts designs are generated and worked out in detail in chapter 7 to obtain specified results.

Phase III comprises the overall conclusions of this thesis research in order to answer the main research questions. Next recommendations are discussed to motivate further research.

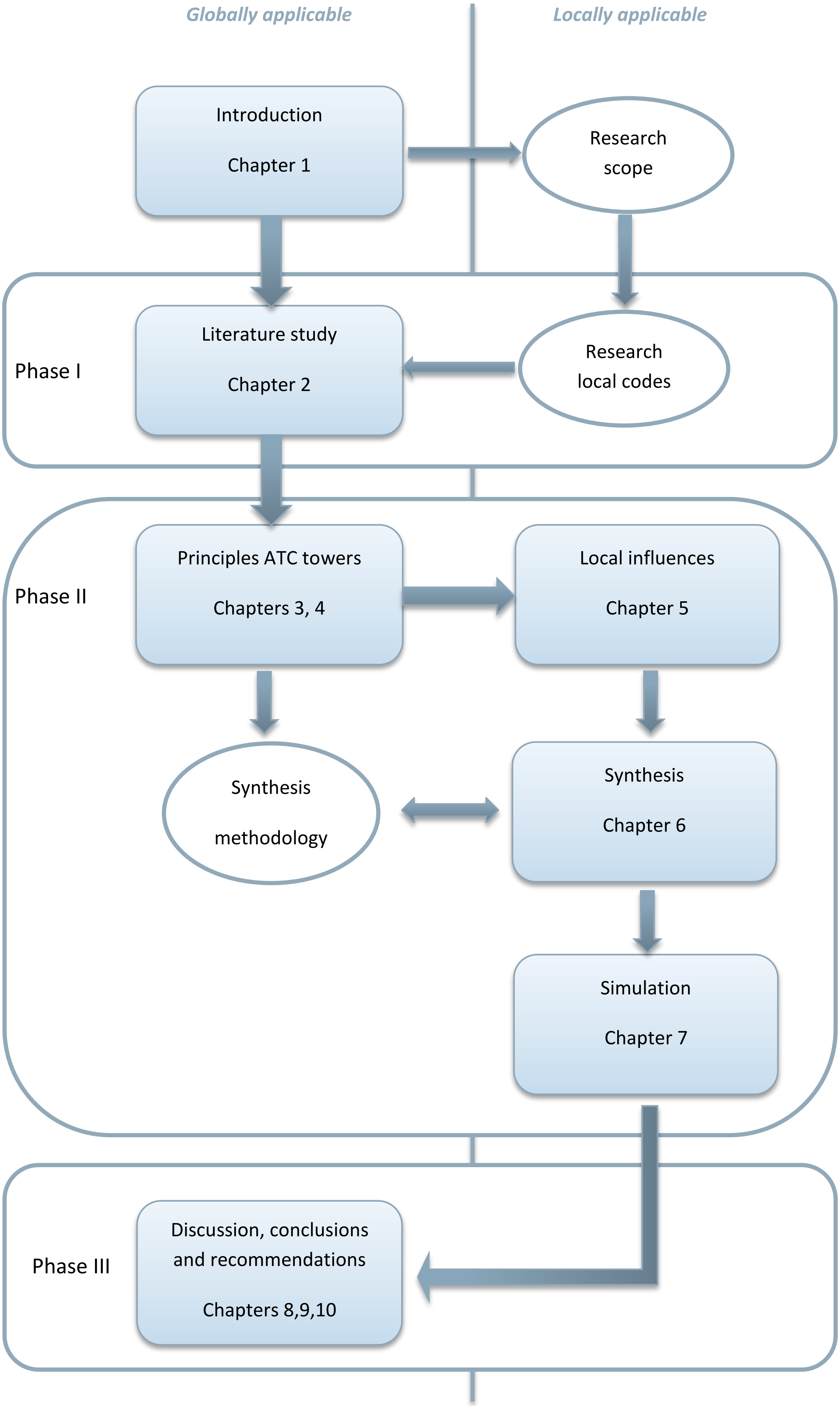


Figure 1.6: Research schematisation

1.8 Defining the research scope

This thesis research is focussing on the local influences around the globe, e.g. geographical, weather, social and building conditions. Around the globe 195 different countries exist. In order to get reliable and sufficient information as input for this research and on the other hand reduce research time, first an investigation has been performed in order to select a few representative countries that will cover the research scope.

The chosen countries for this thesis research are presented in table 1.1 with their special property. In appendix I “country determination”, this research is written in more detail.

Table 1.1: Chosen countries [Literature report]

Country	Special property	Wind	Earthquake	Wealth
China	Wind and earthquakes	Yes	Yes	Intermediate
Indonesia	Poor and earthquakes	Yes	Yes	Poor
Japan	Rich and earthquakes	Yes	Yes	Rich
Netherlands	Rich	No	No	Rich
Nigeria	Poor	No	No	Poor
Turkey	Earthquake	No	Yes	Intermediate

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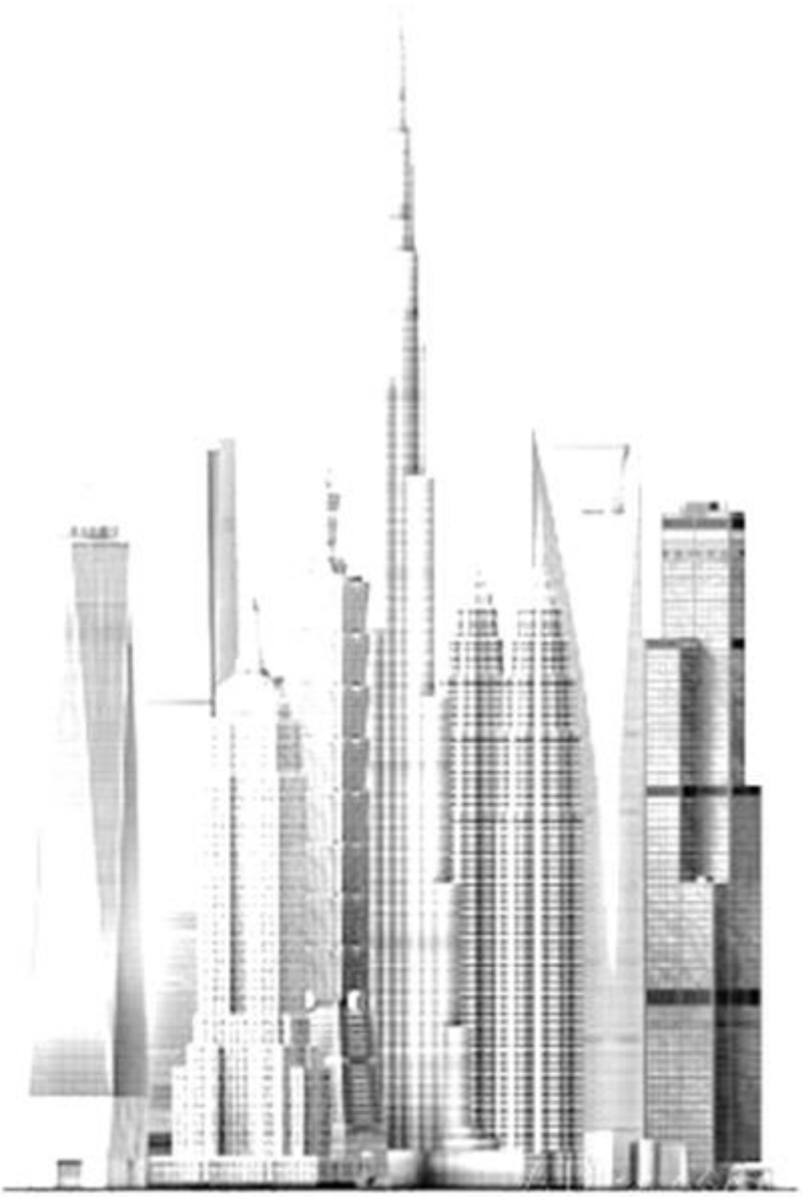
Phase I

"Research of the design characteristics of high and tall buildings around the globe"



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2. Literature review

2.1 Introduction

The first phase of this thesis research comprises all the relevant information needed to be able to make a proper structural design following the sub research question and thought; *What are the design characteristics of high and tall buildings in the chosen countries around the globe?* This chapter summarizes all findings of the literature report and are divided into four main topics; tower design, wind engineering, earthquake and construction methodology.

2.2 General tower design

Taking the height range and the slenderness of air traffic control towers; these towers can be defined as tall buildings as well as high-rise buildings. However, the main essence of both expressions is the effect of lateral forces that will play an important role in the structural design. The most common and important lateral forces are generated by wind and earthquake actions.

To provide enough structural reliability, the design has to fulfil structural requirements regarding stability, strength and stiffness. The influence of the vertical dimension of the building on its structural behaviour is an important aspect. Doubling the height has the following consequences with respect to stability, strength and stiffness, assuming a constant lateral load and stiffness along the height.

- The uniform stress due to vertical loads at ground level, increases with a factor $2^1 = 2$
- The shear load at base level increases to the power one, increases with $2^1 = 2$
- The bending moment increases to the power two, increases with $2^2 = 4$
- The drift index at the top increases to the power three, increases with $2^3 = 8$
- The deflection at the top increases to the power four, increases with $2^4 = 16$

The aim of a structural designer is to make the most optimal structural solution which results in different load bearing systems. In figures 2.1 and 2.2 the optimal height (expressed in the number of stories) versus structural system are presented for concrete and steel structures.

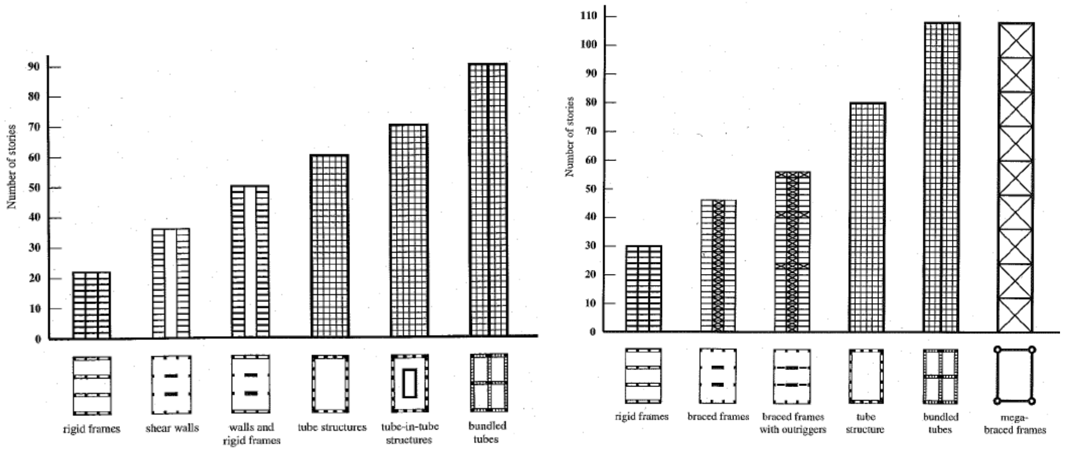

Figure 2.1 and 2.2: Reinforced concrete (left) and steel (right) loading bearing structures [Hoenderkamp, J.C.D, 2007]

As a result rigid frames, shears walls, braced frames, core structures and tube-structures are the most suitable load bearing structures for the structural design of air traffic control towers. Larger structures like outriggers, tube-in-tube structures, bundled tubes and mega braced frames are disregarded.

Air traffic control towers are vital buildings in case of emergence, due to war or disasters by nature, and form the link with the outer world. Therefore they are scaled in one of the highest consequence classes and progressive collapse of the structure is unacceptable, often caused by events such as explosions, fires and earthquakes.

Two different strategies are taken in the design phase to limit these events resulting progressive collapse. The first strategy is the identification of accidental actions and measures should be taken to mitigate the risk of accidental actions. The second strategy is limiting the extent of localised failure. When only one single load-bearing path is provided, the Eurocode state that the structural elements must be designed as key elements, capable to sustain a distributed load A_d of 34 kN/m^2.

The load bearing structures transfer the horizontal and vertical loads to the foundation. The foundation transfers the load subsequently to the surrounding soil. The success of a foundation project is a thorough understanding of the ground conditions, therefore geological ground investigations are a prerequisite. In the building industry two foundation types are used; shallow and deep foundations.

2.3 Wind engineering

Wind is a constantly appearing phenomenon along the earth surface. This process is constantly changing from direction and magnitude and plays an important role in the structural design of large towers. The mean wind force acting on a structure is based on two different components;

The mean wind speed

The mean wind speed is a static component and represents the wind velocity at a certain height above the ground. The magnitude of the mean wind speed depends on its geographical location and represents the characteristic wind speed value with a certain annual probability of exceedance.

Fluctuation wind force

The fluctuating wind force is a dynamic component. It takes into account wind turbulent fluctuations and wind gusts. The effect of fluctuating wind force on a building depends not only on the characteristics of fluctuating wind force but also on the size and vibration characteristics of the building.

For most buildings the effect of fluctuating wind force generated by wind turbulence is predominant. In this case, horizontal wind loading on the structural frame in the along-wind direction is important and often applied in the calculations.

However, for relatively flexible buildings, horizontal wind loads on structural frames in the across-wind and torsional directions should not be ignored. Next to these loads, the buildings will also aerodynamically respond on wind action. The building can vibrate due to vortex shedding or galloping and these motions need to be considered during the design as well.

To make an efficient global wind research, first the Eurocode is analysed in detail. The calculating method, wind parameters and other important wind are investigated. On the basis of the Eurocode the other "local" building codes have been analysed in short.

In table 2.1 all the (input) parameters of the Eurocode are presented which influence the characteristic wind load. These parameters can be subdivided into 3 different aspects; building, structural and geographical. The geographical parameters are depending on the actual location of the tower and are fixed parameters and cannot be changed. The other parameters; building and structural aren't fixed parameters. The building parameters include the shape and building dimensions, while the structural parameters include the structural materials, vibration modes and damping of each building. Basic design principles can be used to design safer, efficient and more economical structures.

Table 2.1: Wind parameters Eurocode [Literature study]

Building parameters	Structural parameters	Geographical parameters
Depth	Damping devices	Air density
Diameter	Decay constants	Average time for reference wind velocity
Height	Natural frequency	Fundamental wind value
Mass	Structural damping	Kinematic viscosity
Radius	Surface roughness	Orography factor
Shape	Vibration shapes	Reference height
Width		Reference scale length
		Reference value
		Roughness length
		Season factor
		Turbulence factor
		Wind direction factor

Summary global wind codes

A general description of wind loading can be produced by the "wind loading chain" given by the equation 2.1 made by Davenport [Yaojun, G., Xinyang, J., Shuyang, C., 2010].

$$W = q \times C_e \times C_p \times C_g \tag{2.1}$$

Whereby:

W	*Wind laod*
q	*Reference wind pressure*
C_e	*Exposure factor*
C_p	*Structural shape factor*
C_g	*Gust response factor*

The reference wind pressure q is determined by three factors:

- Reference height
- Average time
- Return period

The along wind load is determined with 3 parameters:

- Design wind speed (geographical dependent)
- Aerodynamic factor (shape building dependent)
- Gust response factor (dynamic behaviour dependent)

The maximum wind velocity for China, Japan and Indonesia is much higher than the Netherlands and Nigeria. Therefore these countries represent wind loading in hurricane zones.

Every code takes into account along wind loading. Only Japan takes in addition also cross and torsional wind loading into account.

Every code, except for Indonesia, takes into account vortex-shedding. In the Indonesian codes this is unknown.

2.4 Earthquake engineering

Next to wind also earthquake action causes horizontal loading on a structure and the magnitude of the force can be very simplified with the Newton's second law of motion given in equation 2.2 [Charleson, A., 2008]

$$F = m \times a \qquad (2.2)$$

Whereby

F	*Force*
m	*Mass*
α	*Acceleration*

The magnitude of the force is the mass multiplied with acceleration. Luckily earthquakes do not occur often, but the total magnitude of the applied forces during this relative short event is much higher. This often results in a major disaster. To construct safer, efficient and more economical structures some basic principles for seismic design of buildings can be adopted, such as reducing the building weight and applying (structural) damping.

To make an efficient global earthquake research, first the Eurocode is analysed in detail. The calculation method, earthquake parameters and other important issues are investigated. On basis of the Eurocode the other "local" building codes has been analysed in short.

The main goal of the Eurocode is to provide safe structures in seismic regions. Therefore two important performance requirements are established for structures.

- For earthquake with a high magnitude, the no-collapse requirement is normative and this requirement is based on a probability of exceedance of 10 % per 50 years.

- For earthquakes with a lower magnitude, damage limitation is normative and this requirement is based on a probability of exceedance of 10 % per 10 years.

The structural acceleration reaction on earthquake action is modelled with the so-called response spectrums. These response spectrums are established with calibration of the total structure response by Fourier transformation, taking n-order of vibration modes. These response spectrums include the ground acceleration, ground conditions, fundamental natural period of a structure and its damping.

The analyses of a structure can be done with several methods. The choice of method depends on the shape, mass, stiffness, but also on the preferred exactness of the structural analysis. Linear analyses are the most common methods and can be generated with the basic finite elements programs.

A non-lineair method takes, besides the strength, also the post-elastic behaviour of the structural elements into account. Only complex finite element programs can perform these analyses.

To satisfy the preliminary design regarding earthquake response, linear analyses will be sufficient and will be the applied calculation method in this master research.

The Eurocode prescribes an analytical method to obtain the lateral force by using a linear-elastic analysis method. With this method the characteristic earthquake load “base shear force” is calculated and is given by equation 2.3 [NEN-EN 1998-1:2005].

$$Fb = S_d(T_1) \times m \times \lambda \tag{2.3}$$

Whereby:

F_b	*Seismic base shear force*
$S_d(T_1)$	*Ordinate of the design spectrum at period* T_1
T_1	*Fundamental period of vibration of the structure*
m	*Mass*
λ	*Correct factor*

All the different kinds of spectrums and base shear force Fb are determined with the parameters presented in table 2.2.

Table 2.2: Earthquake parameters Eurocode [Literature study]

Building parameters	Structural parameters	Geographical parameters
Height	Behaviour factor	Ground type
Importance classes	Damping correction factor	Seismic hazard
Mass	Material	Soil factor
	Period limits	
	Response spectrum	
	Structure type	
	Vibration period structure	
	Viscous damping ratio	

Summary global earthquake codes

In all the investigated codes the structures are designed with the same probability of 10% per 50 years as well as with the same return period of 475 or 500 years.

Except for the Japanese code, the buildings are classified in several importance classes. This has consequences on the required safety level which results in higher levels for higher consequences, such as an air traffic control tower. For Japan, this factor is integrated within the codes.

Each building code has got his particular response centrum. Although they are built up with different parameter, all response spectrums are translating the ground acceleration into a building acceleration.

The maximum earthquake hazard for Turkey, Indonesia, China and Japan is much higher than the Netherlands and Nigeria. Therefore the first three countries are representative for earthquake loading.

2.5 Construction methodology

To develop a concept that meets all requirements, boundary conditions and at the same time is an economical solution a design methodology should be followed during the conceptual phase. Below the most important design criteria are given which are essential for an optimal integrated structural design. [Horst, A.Q.C van der, 2013]

- Cost
- Reliability and risk management
- Quality
- Constructability
- Redundancy aspects
- Future extension capability
- Maintenance cost
- Durability aspects
- Sustainability aspects

It will take too much time to take all these nine design criteria into account during phase II. Therefore to limit the research scope the following five design criteria are chosen, given below. The four remaining aspects (redundancy aspects, maintenance costs, sustainability aspects and durability aspects) are represented indirectly by the other five aspects. The five criteria are considered as most important and are expected to give the most interesting results regarding the international, structural and economical focus.

Cost

Cost is one of the most import design criteria. The largest percentages of cost of a project are made during the execution and they consist out of labour, use of equipment and materials. Changes in the preliminary design phase can have a large impact on the costs during execution. Costs can be subdivided in the followings aspects;

- Cost of materials
- Labour
- Equipment
- Construction time

Reliability

The structural concept should ensure enough reliability during its lifetime. The structure must provide enough structural safety and meet the serviceability requirements.

Constructability

The structural concept must be checked on constructability aspects. Each country has a different construction industry with a certain level of construction knowledge. Therefore different techniques, available materials and equipment can be expected which will influence the design concept. Also construction time is an important figure whereby the focus is to limit the nuisance.

Quality

Quality in this respect is meant as aesthetics, appearance, reputation and maintenance demand. Basic requirements related to safety, reliability and serviceability shall always be met.

Future extensions capability

The designer should consider future extension possibilities. It is desirable to provide maximum flexibility for future changes.

2.6 Conclusions

The sub-question elaborated in chapter 2 states "*What are the design characteristics of high and tall buildings in the chosen countries around the globe*" and is answered with the following conclusions.

The most important structural characteristic for high and tall building design is the vital role of the lateral forces, wind and earthquake. To provide enough structural reliability, the design has to fulfil the structural requirements regarding stability, strength and stiffness prescribed in the Eurocode.

Suitable structural systems to construct high and tall buildings with a maximum height of 150 meters are rigid frames, shears walls, braced frames, core structures, tube-structures. These structural solutions are obtained by expressing the optimal height versus optimal structural systems for both concrete and steel structures. Next, deep foundations are the most common foundation systems for high and tall structures.

In order to limit progressive collapse, the identification of accidental actions and taking measures will be important aspects in the design phase. Due to the limited amount of time, this identification will be disregarded in this thesis research.

The local building codes of the chosen countries are very similar compared with the Eurocode. The wind and earthquake codes contain the same factors and approaches and therefore in the following thesis research the Eurocode will be used as normative building code.

The wind force is determined with three parameters. Whereby, the design wind speed and the aerodynamic factor are the most important parameters regarding the structural design. The gust response factor does not have a vital role and this parameter will be disregarded.

The magnitude of the earthquake force is equal to the mass of the building multiplied with the ground acceleration. In general, this load action is (very) decisive (in comparison with wind) and stricter requirements are taken as prescribed in the Eurocode.

The criteria which will be taken into account for optimal integrated structural design are; cost, reliability, quality, constructability and future extensions capability. These criteria are considered as most important and are expected to give the most interesting results regarding the international, structural and economical focus.

Phase II

"Air traffic control towers and their global structural design characteristics"

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3. Air traffic control towers

3.1 Introduction

This chapter discusses the background information of air traffic control towers and will form the input for the ATC towers design methodology. First the function of the towers is given which clarifies the purpose and the basic components. Next an exploratory research of 100 existing towers is performed in order to get more insight in the most important design aspects of these towers. This chapter is closed by a short summary of seven reference projects, discussed in more detail in appendix III.

3.2 Function

3.2.1 Purpose

As already mentioned in section 1.2 the primary method of controlling air traffic in the close proximity of an airport is done by visual observation from a tower, the air traffic control tower. These towers are designed to give the air traffic controllers the best panoramic view over the airports domain. This is achieved by a 360° windowed structure, the crown or in other words controls cab, on top of the tower which accommodates the work floor for the air traffic controllers. To enable direct communication, on this work floor all operational disciplines are working besides each other to ensure safe and efficient movement of all the airplanes and vehicles on the taxiways and runways of the airport, as well as for airplanes in the air in the proximity of the airport.

ATC experts claim that air traffic control will not be replaced by new high tech developments, e.g. camera observation and predict the need for new ATC towers will only increase in the nearby future. [Marey, R., Ringersma, P., Nooitgedagt, S., interview report]

3.2.2 Basic components

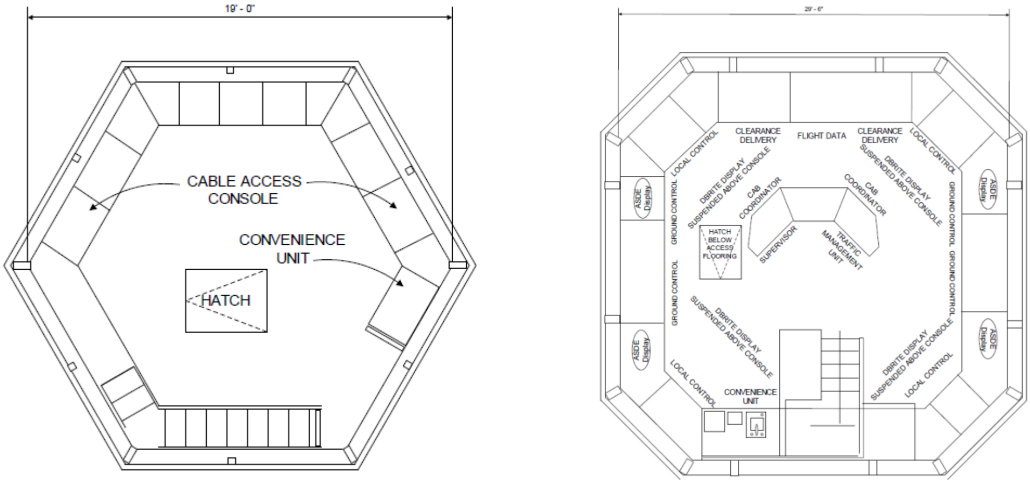
In general air traffic control tower facilities have three basic components. The main function of each component is described below. A typical ATC tower configuration is presented and numbered in figure 3.1.

Figure 3.1: Basic configuration ATC tower Manchester airport [images-google, 2013]

1. Control cab
2. Tower shaft
3. Base building

The control cab

The control cab is the most vital component of an ATC tower. The cab is the primary operating space where the controllers are working together and must provide the best unobstructed view on the active pavement. Active pavements are those surfaces where all the aircrafts activity takes place like runways, taxiways and gate platforms. The design considerations of the cab are based on magnitude of activity, configuration and airport size. In figures 3.2 and 3.3 two different configurations are given, based on capacity. Note that these figures are not scaled.



Figures 3.2 and 3.3: Standard low activity (left) and standard major activity (right) control cab layout [FAA, 2004]

Tower shaft

The primary function of the tower shaft is to support the control cab at a desired height. The shaft forms the link between the base building and the control cab and is provided with elevators and/or stairways. The secondary function of the tower shaft is to provide accommodations for personnel and equipment. The tower shafts can be structurally independent or an integral part of another related structure, such as a terminal building or base building. In general the tower shaft can be divided into three sections, which are described below.

Junction level

The floor level below the cab is commonly called the junction level. The junction level can accommodate spaces for mechanical equipment, elevator equipment, lavatories and other related spaces.

Sub-junction level

The floor level below the junction level is called the sub-junction level. Additional levels below the sub-junction level are possible. The level can accommodate spaces for electronic equipment, HVAC equipment, elevator lobbies, lavatories, cook and relax facilities.

Intermediate levels

Intermediate levels are commonly referred as the levels between the base level and the sub-junction level. The main purpose of these floor levels is to add height to the tower. Additionally, these levels provide access to the utility and elevator shafts at the various elevations of the tower.

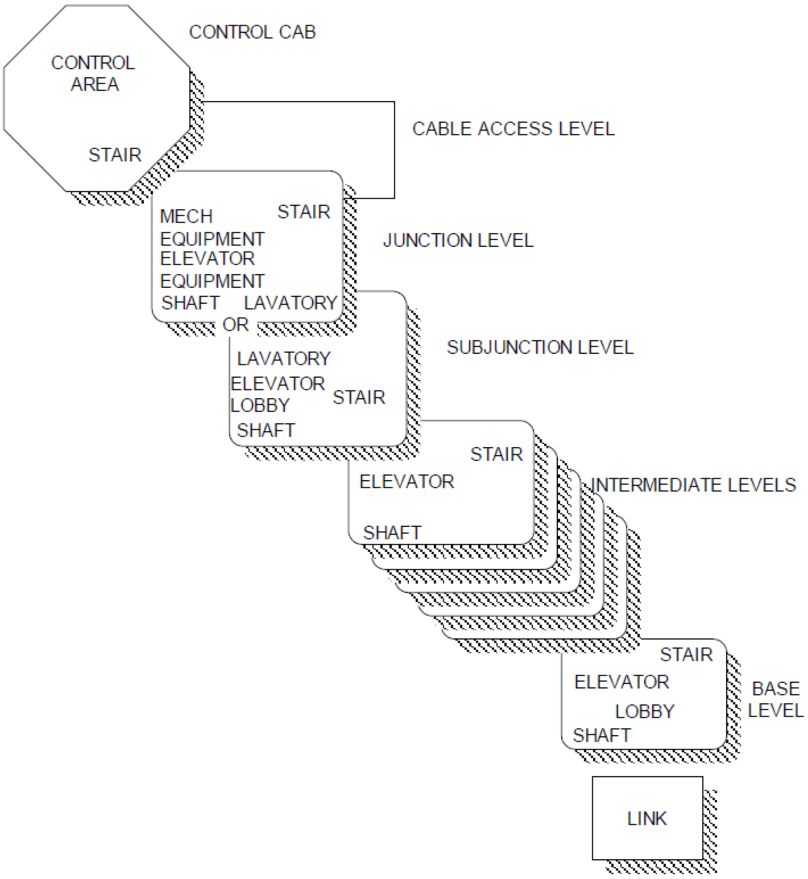


Figure 3.4: Common space relationship diagram non-functional shaft [FAA,2004]

Base building

The primary function of the base building is to provide additional functional space. The base building can accommodate additional equipment to support the operational need of the air traffic controllers and houses spaces for offices and training facilities. Some of the most common functions located within in a base building are indicated below. In this thesis research the emphasis will not be placed on the design of the base building.

- Training and conference rooms
- Locker rooms
- Terminal radar approach control room (TRACON)
- Simulator room
- Communication equipment room
- Radar and electronic equipment room
- Storage
- Recorder playback room
- Telecommunication room
- Engine generator
- Uninterruptible power system (UPS) equipment room

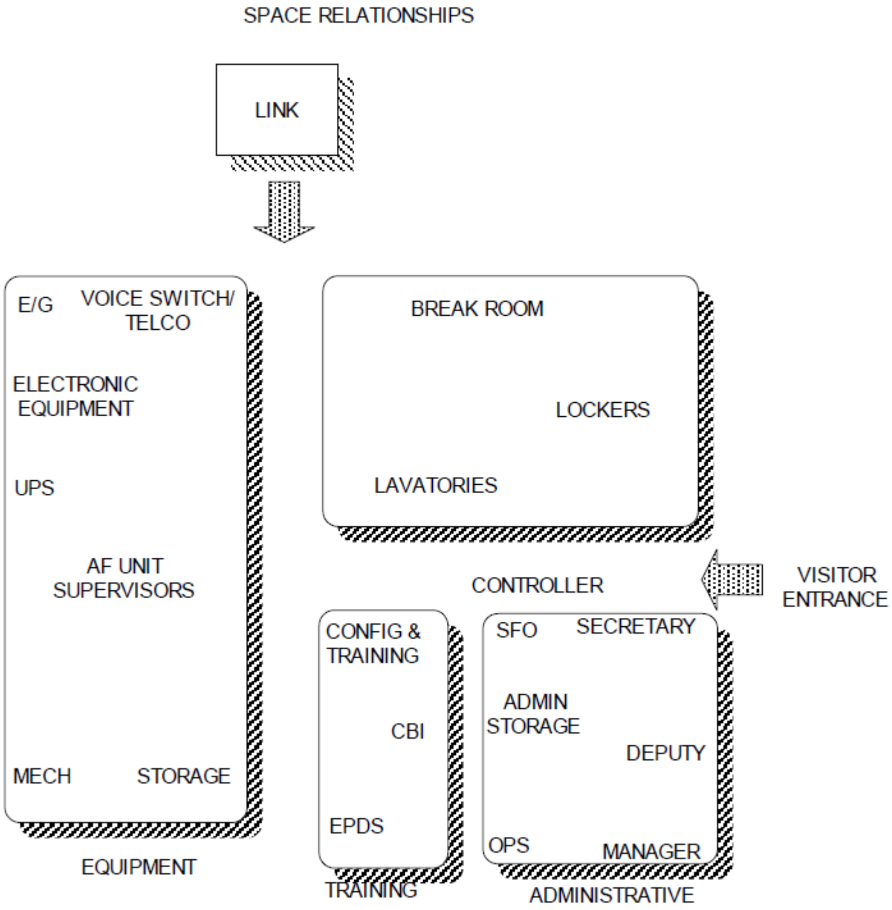


Figure 3.5: Common space relationship diagram administrative base building [FAA, 2004]

3.3 Exploratory research

To get more insight in the most important design aspects of these towers, first an exploratory research will be performed. An exploratory approach is chosen, because with relative less information interesting results can be obtained without deviating in small details. Also on basis of this research the first conclusions can be made, these conclusions are written in *italic.* Background information is presented in appendix II.

The research in this section is based on an already existing investigation made by Mr Brown [2014]. He made a thorough research regarding construction period and tower heights of the world's tallest civilian air traffic control towers around the globe.

An important variable in design and construction technology is time. Along the time a lot of aspects change such as; demand, functional and structural requirements, aesthetics and construction principles. These aspects are discussed in the upcoming sections.

3.3.1 Timeline

<u>Number of towers</u>

The timeline of constructing these towers in exact numbers is presented in figure 3.6., expressed in numbers of towers build in a 5 years period. One of the outcomes of Browns investigation is; at this moment, spring 2014, around 270 air traffic control towers higher than 100 ft. are being built around the globe. [Brown, R., 2014]

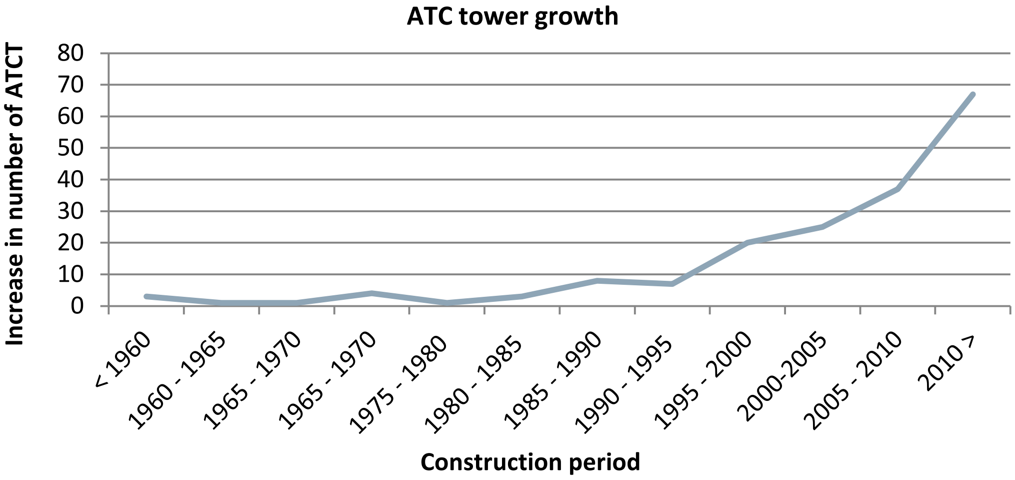


Figure 3.6: Air traffic control tower growth [Appendix II]

It can be concluded that ATC towers are relatively new buildings, only 21 of the 270 existing towers were built before 1990. From the 1990's the amount of towers exponentially increased, with a peak of 67 towers built in the last 4 years, from 2010 until today.

The main reason for the exponentially growth of ATC towers is explained by the global increase of air traffic activity since the 70's. Several forecast studies with respect to air traffic activity predict even more growth for the upcoming decades. Therefore it can be concluded that in the nearby future the demand of air traffic control tower will increase [IATA, 2012] and [Tracy,J.,2011].

Height of the towers

The height of the tower plays an important role in order to obtain the best unobstructed view. Innovative structural systems and building techniques along the time stimulate to build higher towers. The ATC tower of Jeddah King Abdul Aziz Airport, Saudi Arabia, with a height of 136 meter will become the highest ATC tower of the world. At this moment the tower is under construction and will be completed in 2014.

In figure 3.7 the highest towers of each construction period are presented.

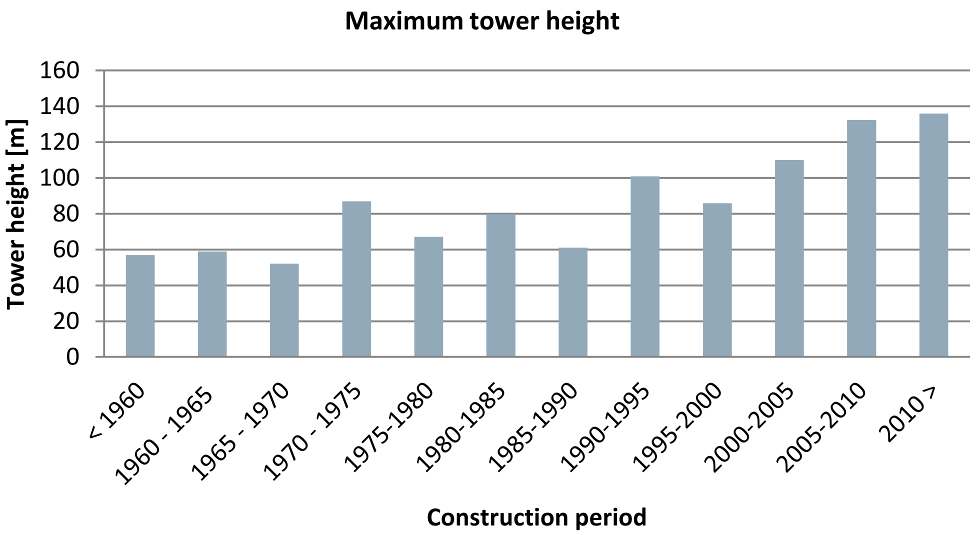


Figure 3.7: Maximum tower height development [Appendix II]

From the height development it can be concluded it took a long time before the barrier of 100 meters was reached. The honour of this achievement is dedicated to our own ATC tower at Amsterdam Schiphol Airport that become operational in 1991. It was also one of the first times an air traffic control tower was constructed of concrete using the slip form technique.

Reasons for an increasing height along the construction period are:

- *New materials and techniques allow to construct higher ATC towers*
- *Airports started to expand (most important factor are the runways) resulting in building new and higher towers in order to have visibility over the entire airport domain. Several examples of these airports are Amsterdam "Schiphol" Airport, Paris "Charles du Gaulle" Airport and Washington "Dulles International" Airport.*

- *Future airport expansion plans becomes more and more important, resulting in higher towers in order to satisfy future airport expansions over the upcoming decades without the actual need at this moment.*

- *Prestige and unique architecture of the ATC tower became more important resulting in higher towers. Several examples are Bangkok "Survarnabhumi" Airport and Jeddah "King Abdul Aziz" airport*

Figure 3.8: Some of the tallest ATC towers around the globe [kobasworld.wordpress.com, 2012]

3.3.2 Architectural and structural aspects

Besides analysing the ATC towers over time, it is also interesting to investigate the architectural and structural aspects of these towers globally. After the first investigation "height distribution" the analysis scope is reduced to 100 towers. Insufficient information is given by Mr Brown, because only the construction date and height are known. Therefore the author of this thesis report made a reduction to 100 towers in order to safe time. These 100 towers are not selected randomly, but are chosen with help of three representative characteristics to towers details; timeline, globe location and height. Since more than 1/3 (100 out 266) of the existing towers is analysed in detail, it can be assumed that the outcomes represent the entire ATC tower industry.

This comprehensive investigation table is presented in Appendix II. Several sources are used for this investigation. The location and layout of the tower on the globe and airport domain is determined by Google Maps. Analyses to determine the structural system and construction material is supported by analysing several images and reading articles. Note that when a certain outcome could not be proven, the outcome is marked as unknown.

Height distribution

The height distribution of all (266) ATC towers around the globe is presented in figure 3.9.

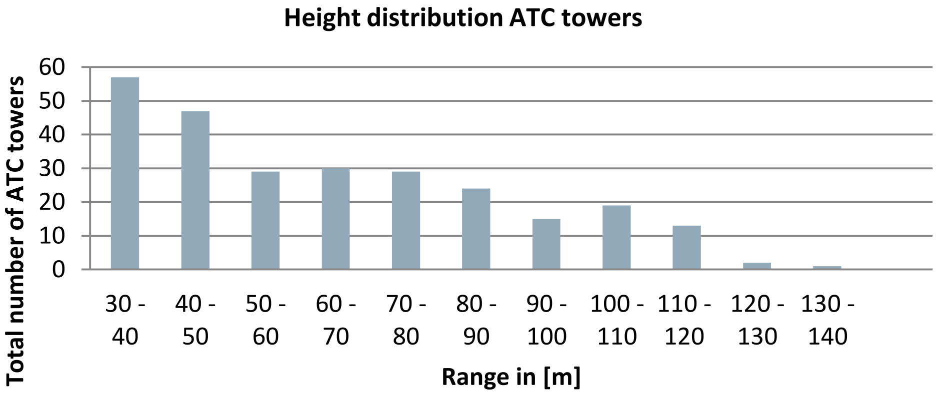


Figure 3.9: Height distribution of ATC towers [Appendix II]

Considering the height distribution, it can be concluded that the height of the majority of the towers, is ranged between 30 and 100 meters. It represents 94 % of the towers. Next, ATC tower experts Nooitgedagt and Marey states that towers higher than 120 meters become prestige projects, because these heights become economical unbeneficial and do not add extra value to the towers visibility.

While nowadays the highest ATC towers are being built, concluded in section 3.3.1, the average height of the ATC towers currently constructed is +- 70 meters. This average number is not changed during the last two decades concluded from table 3.1.

Table 3.1: Average height [Appendix II]

Time line	*Average height in [m]*
< 1990	*59*
1990 – 1995	*62*
1995 – 2000	*64*
2000 – 2005	*72*
2005 – 2010	*73*
2010 >	*72*

The explanation of the 70 meter average height can be found by the visibility principle. The ATC height is mainly determined by the 1° angle visibility requirement. This line of sight is drawn between the ATC tower and runway end.

The visibility domain (radius) calculated from this requirement becomes:

$$\frac{Height}{\tan(min.angle)} = \frac{70}{\tan(1)} = 4000\ meters \tag{3.1}$$

A reasonable domain dimension, when taking into account runway lengths of 4000 meters and the overview over multiple runways in several wind directions.

The explanation of the (small) increase in average height during the time from 64 to 70 meters is caused by the increase of airport domain dimensions and the increase of runway length. Where 3500 meters was the maximum before the year 2000, nowadays the limit is set to 4000 meter in order to receive larger airplanes, such as the Airbus A380.

Functional distribution

The common functional distribution of an ATC tower is, as mentioned in section 3.2.2 a base building – tower shaft with junction level – control cab. Two investigations for the functional distribution are made. The first investigate the presence of junction levels below the control cab. The second investigate whether or not a base building or terminal is linked to the tower shaft.

- Tower shaft with junction levels – 91 %
- Tower shaft without junction levels – 9 %

It can be concluded that almost every tower shaft is accommodated with junction levels and that the tower without junction levels are mainly constructed before the year 1990 (6 of 9). Probably around this period the breakdown of functional requirements in the control cab and tower shaft became more stringent.

- Linked with base building / terminal – 97 %
- Linked without base building – 3 %

Almost every tower shaft is linked to a base building or a terminal. The dimension of the base buildings varies from very small to very large buildings. This size mainly depends on the accommodations placed inside. Small base buildings accommodate only vital equipment to support air traffic control, e.g. UPS, generator and radar rooms. These rooms don't require much space, whereas training and conference rooms do require much space, subsequently increasing the dimensions of the base building significantly.

From the research it can also be concluded that almost every tower shaft is structurally independent with the base building. The base building is often linked to the tower shaft by a small corridor. This is not the case when the tower shaft is constructed on top of terminal. In 7 cases the tower shaft integrated with the terminal, e.g. Zurich Airport and Moscow "Domodedovo" Airport.

Structure

The load bearing structure of the tower shafts is analysed and are presented below.

- Core structure – 88 %
- Core + frame structure – 5 %
- Frame structure – 4 %
- Core + Cable stayed – 2 %
- Tube structure – 1 %

Figure 3.10 ATC tower on terminal Zurich airport [images-google.com, 2013]

Core structures are the most common load bearing structures for ATC towers. An explanation for this significance difference in percentage with other load bearing structures is that core structures are very suitable for slender structures (up to 100 meters) whereas the system provides (relatively) the highest stiffness vs use of construction material, also explained in section 2.2. Next, the simplicity of the structural configuration of the tower shaft plays also a vital role in the choice of load bearing structure. As mentioned before, only the junction levels which are integrated in the upper levels need to be taken into account in the load bearing structure configuration. This results in a very straightforward building design compared with other utility (high rise) buildings. An additional advantage is that the core's outer shell can be used directly as external façade, saving additional materials and cost for façade cladding. An example of a direct external façade is Amsterdam's "Schiphol" ATC tower.

In order to reduce the core diameter and weight, in some cases the core structures are supported by a second load bearing structure. This explains core + frame and core + cable stayed structures.

Figure 3.11 Abu Dhabi tower under construction. [panoramio, 2011]

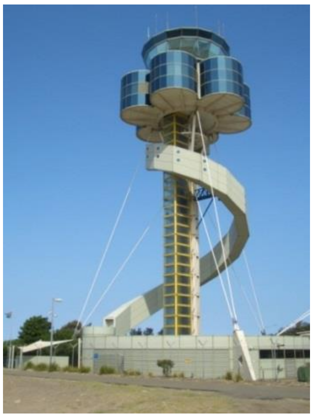


Figure 3.12: Sydney airport [images-google.com]

It is more difficult to determine which type of construction material is used to construct the load bearing structure. Façades are covering the structural system at some projects and insufficient information is available to make proven assumptions. The results below will give a good indication, but still there are several unknowns.

- Concrete 70 %
- Concrete + steel 9 %
- Steel 6 %
- Unknown 15 %

The main reason concrete is the most common used construction material is directly related to the load bearing structure type. The most suitable construction material to construct core structures is concrete. Next, concrete structures have beneficial structural characteristics for slender structures. They provide in relation to steel more structural stiffness, are in general more durable and have better fire resistance properties.

Location

Normally an airport domain is divided into 2 areas, the so called land-side and air-side, based on security restrictions. Land-side is the area where no security measurements are taken, including parking lots, public transportation facilities and access roads. E.g. Amsterdam “Schiphol” Airport.

Airside areas include all areas accessible to aircraft, including runways, taxiways and ramps. Very strict safety and security measures are taken in these areas.

- Land-side – 72 %
- Air-side – 28 %

Approximately 1 out of 4 ATC towers is located on airside. Towers on air-side are not always the most desirable location, because it can add complexities to the building site like safety considerations, accessibility and maintenance restrictions. It also limits the expansion capability of the tower. The main advantage of towers located on air-side areas is the more centralised position on the airport domain, resulting often in lower towers in conformation with the visibility principle.

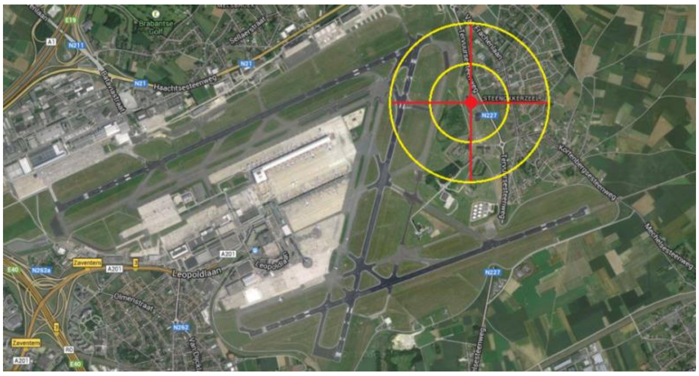


Figure 3.13: Land side ATC tower Brussels Airport [maps.google.com]

3.4 Reference projects

In appendix III several ATC towers are analysed in more detail. Some of the interesting features are described below:

- *Slip forming techniques are often used to construct the concrete core structure. This to reduce the total construction time.*
- *Repetition is used where ever possible to optimize cost and building speed.*
- *Cable stayed structural systems are used to reduce the diameter of the shaft. To provide stability, the cab is horizontally supported by cables.*
- *Outrigger structures + ties systems are used to reduce the overturning bending moment in the shaft and as a result reducing the diameter of the shaft.*
- *Jacking systems are used by the construction of the London Heathrow airport tower. Prefabricated steel elements were assembled on site during the night, to reduce the construction time and nuisance.*
- *Core + frame systems are used to reduce the diameter and mass of the shaft. This to minimize earthquake action on the tower. To minimize the impact of ground movements even further, base isolation (pendulums) is applied in the Istanbul Sabiha Gokcen tower and Taiwan tower.*

3.5 Conclusions

The sub-question elaborated in chapter 3 states “*What are the characteristics of air traffic control towers”* and is answered with the following conclusions.

Air traffic control towers are the most important buildings on the airport domain regarding the guidance and safety of air traffic in the proximity of an airport. This guidance is mainly done by visual observation and these towers give the air traffic controllers the best view over active pavement.

In general ATC towers facilities consists of three basic components;

- Control cab
- Tower shaft
- Base building

The control cab is the most vital component because this is the primary operating space of the controllers.

The tower shaft supports the control cab at a desired height and forms the link between base building and control cab. Junction levels are integrated in the higher regions of the tower in order to provide additional functional space.

The primary function of the base building is to provide additional functional space. In this thesis research the emphasis will not be placed on the design of the base building and will be disregarded, because these base buildings are structurally wise stand-alone buildings.

Air traffic control towers are relatively new buildings and the amount of these towers increase exponentially around the globe. The average height of these towers is 72 meter and the highest ATC tower of the world is Jeddah King Abdul Aziz Airports with a height of 136 meter.

Core structures are the most common load bearing structure for ATC towers. In 88 % of the cases only a core structure is applied and an additional 7 % of the towers are combined core system with rigid or braced frames, making these three bearing structures the most suitable load bearing structure for ATC towers.

The most suitable construction material to construct core structures is concrete. As a result, concrete is also the most used material to construct ATC towers as concluded from the exploratory research.

4. Design methodology ATC towers

4.1 Introduction

In this chapter the design methodology used to design ATC towers around the globe is discussed. This kind of international research is not performed before (as far as the author knows) and it is considered as a complex process because a lot of information is unknown. Therefore first the traditional design process is shortly investigated in order to understand the basic design process in the construction industry that is used in the Netherlands.

Following this approach the first step of the elementary design cycle is the analysis of the air traffic control towers, whereby the requirements and fundamental principles are discussed in architectural and structural perspective. In this chapter the focus is placed on general ATC tower design, meaning these principles are applicable for the entire world.

Addressing the System Engineering approach concludes this chapter. Along the thesis research this other approach is considered and investigated in order to analyse the relations between the ATC tower principles in a more systematic manner.

4.2 Traditional design approach

In the global construction industry usually [JCT, 2014] the traditional design process is used, presented in figure 4.1. The design process starts with the conceptual phase, whereby project orientation and a feasibility research are performed. The conceptual phase is followed by several design phases, the construction phase and after the last phase, project close-out, the operation/maintenance period exists. Each of these design phases is characterized by the elementary design cycle, presented in figure 4.2.

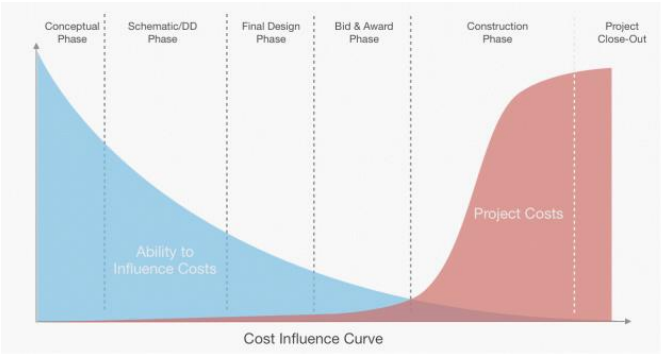


Figure 4.1: Traditional design process versus cost influence curve [Kwame Building Group, 2014]

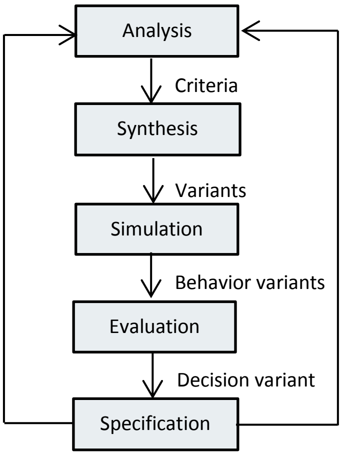


Figure 4.2: Elementary design cycle [Ridder, H.A.J. de, 2008]

In each design phase, the elementary design cycle is used to specify the project in further detail, whereby the focus is put on other aspects each time. At the end of each phase the design must be approved in order to start the next phase. While changing from one phase to the other also often the transition of organisation and responsibilities occur.

This process is sequential which makes it a very clear process, but this traditional process does have a major disadvantage. Many essential design considerations are taken in the earliest phases (conceptual and schematic phases) while often insufficient data is available. Little changes in the (early) design can have a large impact on the total project cost. A schematisation of the controllability on cost is given in figure 4.1.

Next, due to the transitions of organisations and responsibilities along the process, the original and essential thoughts of the design and decision making are fading out. These disadvantages result often in sub-optimal solutions, due to a lack of design consistency between the phases. To limit these disadvantages in this chapter another design approach is analysed in section 4.7.

4.2.1 Chosen design approach

As mentioned in chapter 1, the overall objective of this thesis research is to perform an international investigation regarding the main local influences in order to provide an economical optimal structural methodology for an air traffic control tower which can be constructed anywhere around the globe.

When taking this objective into account and reflecting it against the traditional design process the most important and interesting information will be gathered when the focus of this master thesis is placed on the conceptual design phase. On basis of concepts the initial cost per project can be estimated in an early stage, when the ability in influencing the cost is the highest and can be directly related and modelled with the local influences and conditions around the globe. Further on, by simulating the concepts (case studies) with designs and calculations, the behaviour can be qualified in more detail and evaluated. This gathers more insight of ATC tower design resulting in more optimal designs. Below a scheme is made of the design methodology that will be used in this thesis research and this will be described in chapters 4 until 7.

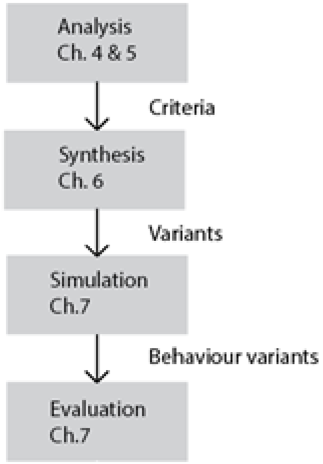


Figure 4.3: Applied design methodology

The analysis is divided in 2 chapters. In chapter 4, sections 4.3 t/m 4.6, the design criteria, divided in requirements, design principles and cost are prepared in a global perspective. In chapter 5 these criteria are specified in detail for the six chosen countries and airports, which will form the basis of the case studies.

In chapter 6 “synthesis ATC towers” the knowledge from the analysis part is translated in several conceptual variants per country in order to obtain optimal solutions.

The variants are simulated by designs and calculations in chapter 7 and the behaviour of the conceptual variants are determined.

4.3 Requirements ATC towers

In general the analysis of a problem starts by defining all the requirements with respect to value in order to be able to define the design space wherein a solution can be found (solution space). These requirements include next to the fundamental requirements also the projects boundary conditions, starting points and desires. Below the philosophy of Mr. De Ridder is elaborated [Ridder, H.A.J. de, 2009].

The fundamental requirements will form the intern lower limit of the value axis and present the minimum specifications of the project. The design must comply with these requirements anyhow.

The external upper limit of the value axis is determined by boundary conditions. These boundary conditions are formed by the local external circumstances of the project and they will influence the project without having control on them. In reality there are several types of boundary conditions; natural, legal, social, financial/economic and environmental.

Within these two outer limits the starting points are defined. These starting points give directions onto the design process in an early phase, which makes it possible to disregard any of the design variables and thereby reducing the design possibilities making the design process less comprehensive.

Desires are determined by the client and describe the expected quality of the design. Desires are no fixed requirements like the other kinds of requirements and represent more an effort obligation the designer must undertake in order to achieve the highest value.

In figure 4.4 the value axis is presented including the requirements limits and the solution space.

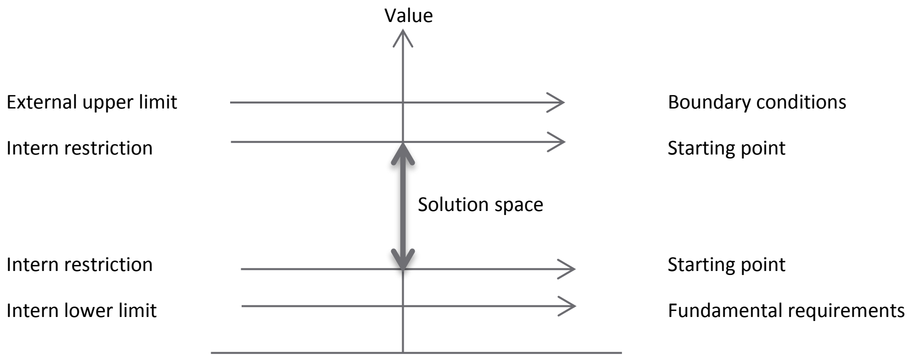


Figure 4.4: Value axis [Ridder, H.A.J. de, 2009]

In this thesis research the same method is adopted as described by Mr. de Ridder to find the solution space. First the fundamental requirements are determined to which the ATC design must fulfil. Next, the local boundary conditions are determined, in order to place the ATC design in the local context, which can differ significantly per country, resulting in different “heights” of the external upper limit per country and solutions spaces. At last several starting points and desires are determined to speed up the design process.

4.3.1 Fundamental requirements

Air traffic control towers are extraordinary and very special equipped buildings. Each country possesses only one or a few towers; as a result countries don't have much own knowledge regarding the essential ATC tower requirements. The Federal Aviation Administration (FAA) and the international Civil Aviation Organization (ICAO), the two global aviation authorities, established fundamental design requirements for ATC towers to guide the design process.

These fundamental requirements are used to establish new ATC's towers, relocation of existing facilities or upgrade projects. All projects around the globe are subjected and must comply with the following fundamental requirements [ICAO, 1984] & [FAA, 2004].

Air traffic control tower

(1) The designer has to review the current and projected future air traffic activity in order to formulate the project scope for the upcoming 10 years [FAA, 2004, chapter 1.2 (11)].

(2) The ATC tower height permits the controller to survey those portions of the airport and its vicinity over which he exercises control [FAA, 2004, chapter 3.1 (40)] & [ICAO, 1984, Part II section 2.1]

(3) The ATC tower ensures structural reliability during its operational lifetime[ICAO, 1984, Part II section 2.2]

(4) The ATC tower ensures reliable communication between controller and aircraft during its operational lifetime. [ICAO, 1984, Part II section 2.1]

Note: requirement (4) will not be elaborated in further detail in this master thesis, because the focus will only be placed on the structural design of the ATC tower.

Control cab

(5) The control cab must provide operational space for controllers [ICAO, 1984, Part II section 2.1]

(6) The control cab allow the controller to have an unobstructed view on active pavement [FAA, 2004, chapter 3.1 (40)] & [ICAO, 1984, Part II section 2.1].

Tower shaft

(7) The tower shaft supports the control cab [FAA, 2004, chapter 3.1 (41)] & [ICAO, 1984, Part II section 2.2].

(8) The tower shaft connect the control cab with ground level by elevators and stairways [FAA, 2004, chapter 3.1 (41)] & [ICAO, 1984, Part II section 2.2].

(9) The tower shaft must provide space for vertical risers [ICAO, 1984, Part II section 2.2].

(10) The tower shaft must provide additional functional space to support all air traffic control operations [ICAO, 1984, Part II section 2.2].

4.3.2 Local boundary conditions

In this thesis research the emphasis will be placed on the geographical and economical boundary conditions. Therefore the following local boundary conditions are found and need to be determined before starting the design process; current and projected future air traffic activity, wind climate, earthquake hazard and the construction industry. All the other boundary conditions will be disregarded in this research.

Current and projected future air traffic activity

Subsequently from requirement (1), the designer has to review the airports master plan in order to formulate the project scope. Aspects such as; amount of runways, runway lengths, tower height and figures of passengers and air traffic movements need to be determined.

Wind climate

In order to obtain wind climate estimation, the basic wind velocity and the peak velocity pressure at the top of the tower need to be determined on basis of local wind maps and metrological data.

Earthquake hazard

The earthquake hazard estimation is performed by the local seismic hazard in m/s^2 and ground type, determined on basis of local earthquake hazards and shear wave velocity maps. These maps are international provided by the United States Geological Survey (USGS).

Construction industry

To get a better understanding of the local construction industry the focus in this thesis research is placed on 4 aspects namely; construction materials, structural systems, knowledge and equipment, material prices and labour cost.

4.3.3 Starting points

The following starting points are determined from the literature study, made during phase I (summarized in chapter 2), and the air traffic control tower research in chapter 3, in order to give directions onto the design process.

- Rigid frames, braced frames and core structures are the most suitable load bearings structures to construct air traffic control towers

- Deep foundations are considered as the foundation system for ATC towers

- The Eurocode will be taken as the normative and used building code

  Note: The reason why the Eurocode is elaborated in more detail; the Eurocode contains the same approach as the other codes [literature study], which make it possible to make good comparisons with other countries.

- The air traffic control tower consists of three basic components;

  - Control cab
  - Tower shaft
  - Base building

- The control cab height is fixed and is determined for future air traffic activity
- The control cab size is fixed and is determined for future air traffic activity
- The control cab is directly connected with the tower shaft
- The control cab is structural dependent on the tower shaft

- The tower shaft height is fixed and is determined for future air traffic activity
- The tower shaft size is fixed and is determined for future air traffic activity
- The tower shaft structurally supports the control cab

- The base building is structural independent of the tower shaft
- The base building is disregarded in the ATC tower design of this research

4.3.4 Desires

In general desires are determined by the client and describe the expected quality of the design. While this research is not conducted for a real client, the author set up the most important and common desires in an economical perspective that will be applicable for an ATC tower around the globe. Note; in reality these desires will be complemented by the client.

- The design should consider optimal cost possibilities
- The design should consider constructability aspects
- The design should consider durability aspects

- Repetition is used wherever possible to optimize cost and building speed.

- The air traffic control tower shall be located where unrestricted visual overview over the entire airport domain is achieved with the highest economic benefits

- When the air traffic control tower is located on the airside domain, minimum nuisance should be considered during construction for the on-going airport operations.

- The control cab should not penetrate the obstacle limitation surface

4.4 Fundamental design principles ATC tower

In section 4.3 the requirements of ATC towers are determined. On basis of these requirements several driving factors regarding the architectural (functional) design of the ATC towers can be specified and are discussed in this section.

4.4.1 ATC tower height

The height is the most important design feature and counts as number one of the primary starting points for the design of the tower. To be more specific, the height of the tower is determined by the height of the operating level in the cab above ground, including the tower shaft. The higher the tower, the more easily the optimum visual surveillance is obtained, but the higher the construction costs and the bigger the chance on penetrating the obstacle limitation surfaces. This is an invisible air path that must be clear of obstacles to secure the safety of in/out bound aircrafts.

The method to determine the required ATC tower height in a quick manner is by using the following steps. Note; in reality the exact height has to be determined by the architect by means of visibility studies, but in fact he will use the same approach.

1. The line of sight drawn between the operating level height and the runway end is minimal 1°
2. The operating level has direct visibility on entire active pavement, including runways, taxiways and platforms. If not, additional height will be added to the tower.
3. The ATC tower height does not interfere the approach surface (if so the tower must be marked).
4. The ATC tower does not interfere the misses approach path (if so the tower must be marked).

The steps are illustrated in the followings figures.

1.

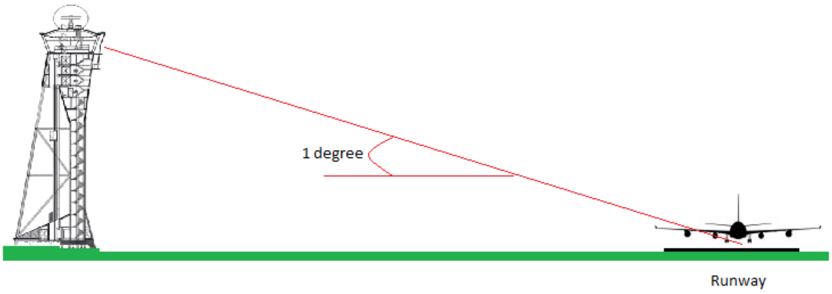


Figure 4.5: Minimum line of sight

2.

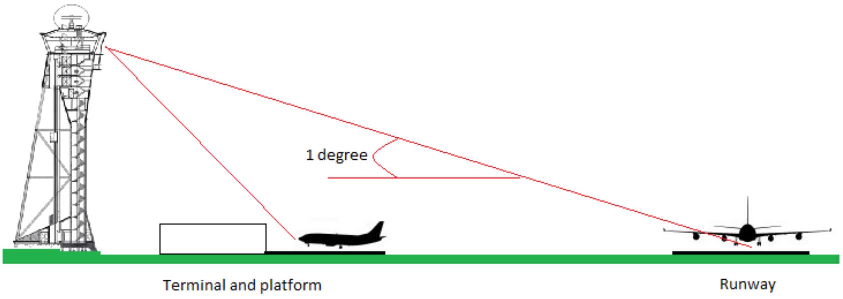


Figure 4.6: Direct visibility on active pavement

3.

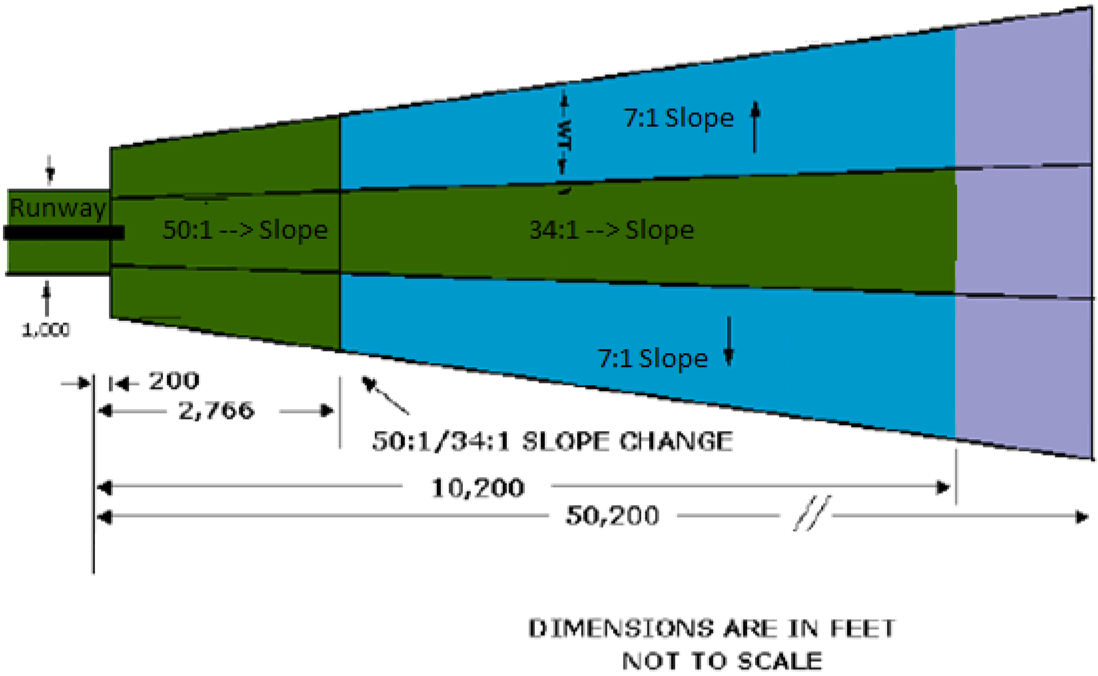


Figure 4.7.: Approach surface [Federal Aviation Regulation Part 77, 2005]

4.

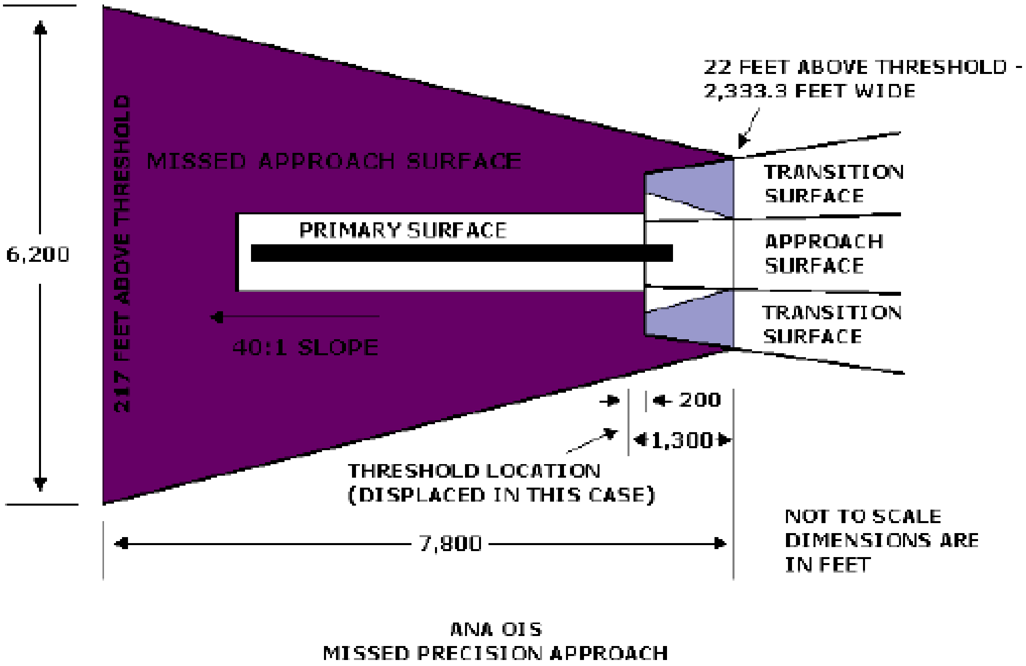


Figure 4.8: Misses approach paths [Federal Aviation Regulation part 77, 2005]

In appendix V a 3D Sketch-up model is presented, which gives the reader more feeling about the approach paths. This model is also used to determine whether or not the tower does interfere with the paths.

4.4.2 Control cab size

The level of activity of the airport is the second most important design feature for the design of the tower. The control cab size of the ATC tower depends on the activity of the airport, to be more specific, the amount of controllers working at the same moment.

The cab size of an air traffic control tower is dependent on the number, location and size of control positions and consoles. Therefore the towers are classified into three main categories by the FAA and ICAO: Low activity, intermediate activity and major activity. It is important for the designer to review the current and projected future air traffic activity, because future expansion of the cab is difficult to realise.

Next to this the layout of the working positions within the tower cab and operating consoles will be determined in relation to the manoeuvring area and the frequently approach direction.

The table below gives indications of the minimum required surface of the control cab in square meter. Note: these values are determined by the ICAO, in reality these values don’t differ much from the FAA categories.

Table 4.1: ATCT design classifications ICAO [ICAO]

Level of activity	Approximate number of personnel	Minimum cab surface m^2
Low	Not more than 6	21
Intermediate	Between 6 and 12	32
Major	More than 12	50

4.4.3 Control cab visibility

The height and the size of the control cab are determined in the previous sections. The third important design feature regarding the control cab is the visibility from the inside of the cab to the outside, overlooking the airport. The aim is to provide maximum transparency and eliminate glass reflections using the following design principles:

- The control cab should have a 360° visibility range
- Avoid structural elements (columns) in the middle of the control cab, preferred only in the façade
- The structural elements in the façade should be integrated with the façade structure and should be multi-functional, e.g. water drainage and utilities
- Limit the number of vertical supports
- The vertical supports should be kept to the smallest feasible diameter
- The ceiling could slope upwards at its perimeter to enhance upward visibility

- The glazing should slope outwards with 15 degrees (recommended) from the vertical to eliminate reflections
- Circular glazing rooms are preferable regarding glass reflection compared with square glazing rooms

4.4.4 Tower shaft size

The size of the tower shaft depends on two different aspects; the required functional and structural dimensions. This section focuses only on the functional principles of the tower shaft. In section 4.4.6 the structural principles of the ATC tower are discussed.

As mentioned the tower shaft connect the control cab with the ground floor and contains elevators, stairways and space for vertical risers. The FAA en ICAO provided several design principles and these are discussed below.

Elevators

The FAA recommends an elevator should be provided inside the tower shaft when the cab floor is 15 meters or more above ground. This recommendation will not be accepted and will be changed, stating that every ATC tower will contain at least one elevator. The main function of the elevator is to transport personnel. The secondary function is the transport of freight, e.g. ATC utility racks, and wounded humans in case of emergency. Both functions are of the same importance. Next there must be an elevator landing at all equipment levels and occupied levels.

The minimum elevator dimensions suitable to transport wheelchairs are presented in table 4.2 and are used in this thesis research.

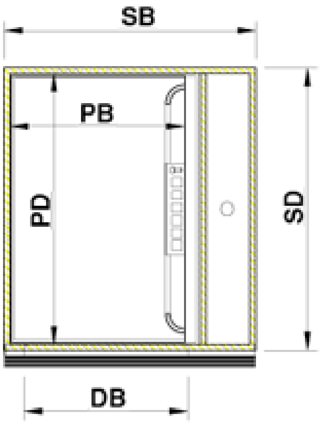


Figure 4.9: Lift layout [Axessliften]

Table 4.2: Lift dimensions [Axessliften]

PB [mm]	PD [mm]	SB [mm]	SD [mm]	DB [mm]	Mass [kg]
1100	1400	1500	1480	1000	400 / 630

Stairs

The width of the stairways depends on the occupant load of the tower and is provided due to fire safety regulations. The FAA made several recommendations for the stairway design and they are adopted in the research. In table 4.3 the minimum required width dimensions are presented and recommended by the FAA. Next the rise of every step shall not exceed 180 mm and the run of 250 mm. Each landing shall have a dimension measured in the direction of travel equal to the width of the stairway. There shall not be more than 3,6 m vertically distance between two landings.

Table 4.3: Stairway width [FAA, 2004]

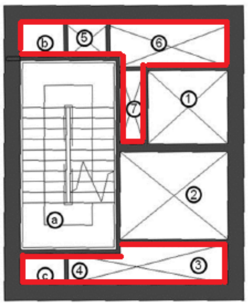
Occupants	Minimum width in millimeters
> 50	1200
10 - 50	1000
< 10	800

The stairway configuration along the height depends on the available space in the tower shaft, the floor to floor height of the occupied level and is in general determined by the architect [M Visscher, Interview report]. During the design several configurations should be considered in order to determine the most optimal solution.

Vertical risers

The tower shaft must provide enough space for vertical risers and are equipped with MEP, smoke exhaust and other ATC utilities. The required space for vertical risers is dependent on a variety of factors and is therefore hard to determine in dimensions, e.g. m^2.

Therefore a rule of thumb as design principle for the required space is determined on basis of two references projects. In figure 4.10 and 4.11 the tower shafts of the Taiwan and Ashgabat ATC towers are presented. Conclusion, the minimal space for the vertical risers is 50 % of the total surface of the tower shaft. This includes the unassigned growth of equipment during the time of 25 %. Note: in reality the architect determines the exact required surface.



a) 樓梯豎板 18 公分，踏面 25 公分 staircase risers 180, tread 250mm
b) 居室樓層排煙 used for smoke exhaust room on occupied levels
c) 居室樓層排煙 used for smoke exhaust room on occupied levels
1) 電梯井 2100x1300 客艙尺寸 Elevator shaft 2100x1300 cabin size
2) 電梯井 1400 X1100 客艙尺寸 Elevator shaft 1400 x1100 cabin size
3) 機械 Mechanical
4) IT/特殊系統（雙重） IT/special systems (redundancy)
5) IT /特殊系統 IT/special systems
6) Ele 火 Ele. Fire
7) 加壓 Overpressure

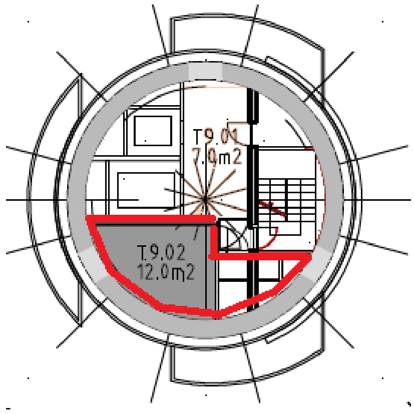


Figure 4.10: Tower shaft Taiwan ATC tower [Royal HaskoningDHV, 2014]

Figure 4.11: Tower shaft Ashgabat ATC tower [Royal HaskoningDHV, 2013]

4.4.5 Junction levels

Directly below the control cab and at the upper levels of the tower shaft the junction levels are located. Each control cab needs supporting facilities and utilities for air traffic control operation and a transfer zone in order to reach the control cab. As mentioned before in sections 4.4.2 and 4.4.3, the size of the control cab is relatively small and customized to the number of operating consoles. Next, due to visibility requirements, no extra facilities are desired in the control cab, giving it's the most optimal 360° visibility range. Due to these reasons junction levels are applied directly below the control cab. Depending on the size and design of the tower, the minimum number of junction levels is two, mainly because of the placing of the elevator equipment room.

The FAA en ICAO provided several design principles for the junction levels and these are discussed below and are used in this thesis research. Note: these principles are divided on the first junction floor and second junction floor, directly below the control cab.

First junction floor

- An top elevator landing lobby
- One break room is required on one of these levels, 1.5 m^2 per occupant
- Mechanical and electronically equipment rooms, 93 m^2 in total (1000 square feet). In addition, 25 % unassigned equipment growth space in ATCT equipment rooms is required.
- Stairs for internal movement. Note; none fire safety and other stair configuration than in tower shaft
- Tower shaft stairs, elevator and risers

Second junction floor

- Elevator equipment room directly above elevator cabin
- Separate toilet rooms (male/female), 1 toilet of 4 m^2 per 10 occupancies
- One break room is required on one of these levels, 1.5 m^2 per occupant
- Mechanical and electronically equipment rooms, 93 m^2 in total (1000 square feet). In addition, 25 % unassigned equipment growth space in ATCT equipment rooms is required.

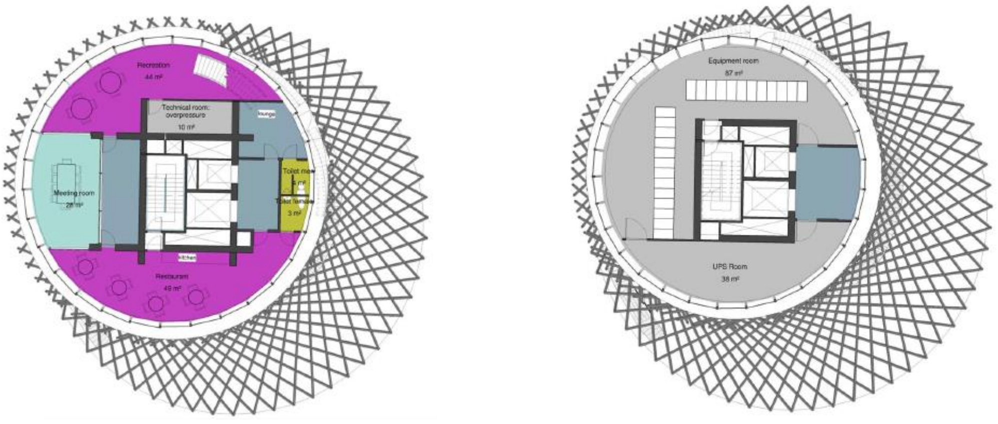


Figure 4.12 & 4.13: Examples of junction floors, sections Taiwan ATC tower [Royal HaskoningDHV, 2014]

4.5 Fundamental structural principles ATC tower

Followed by the architectural design, in this section the driving factors regarding the structural design of the ATC towers are specified and discussed.

4.5.1 Load bearing structure

The load bearing structure of an air traffic control tower is divided into two major parts, the structural shaft and the cab structure. Both structures are structural dependent to each other but can be separately designed with the following principles.

1) The structural shaft provides the stability of the tower and withstands the lateral forces of wind and earthquakes and supports the control cab. The junction levels are supported by the structural shaft. An optimal connection between structural shaft and junction levels must be attempted.

2) The cab structure provides the stability of the control cab and is self-supporting. Due to visibility restrictions the structural elements must be kept to a minimum.

4.5.2 Dead loads

Below tables are given of the dead loads of the construction materials and elements which will be applied in the ATC tower design of this thesis research.

Material	**Weight**
Concrete, cast in-situ	25 kN/m^3
Concrete, prefab	25 kN/m^3
Concrete, light-weight	18 kN/m^3
Reinforcement steel	78.5 kN/m^3
Steel	78.5 kN/m^3

Control cab concrete	**12,85 kN/m^2**
Concrete d = 300 mm	7,5 kN/m^2
Steel structure Roof Columns	0,5 kN/m^2
Façade (perpendicular, vertical)	3,0 kN/m^2
Ceiling + ducts	0,3 kN/m^2
Roof covering	0,3 kN/m^2
Finishing	1,0 kN/m^2
Antenna	0,25 kN/m^2

Staircase concrete	**6,0 kN/m^2**
Concrete d = 200 mm Steps Floor	5,0 kN/m^2
Diverse	1,0 kN/ m^2

Junction level concrete	**11,8 kN/m^2**
Concrete d = 300 mm	7,5 kN/m^2
Façade (perpendicular, vertical)	3,0 kN/m^2
Ceiling + ducts	0,3 kN/m^2
Finishing	1,0 kN/m^2

Control cab composite	**8,35 kN/m^2**
Composite floor	3,0 kN/m^2
Steel structure Roof Columns	0,5 kN/m^2
Façade (perpendicular, vertical)	3,0 kN/m^2
Ceiling + ducts	0,3 kN/m^2
Roof covering	0,3 kN/m^2
Finishing	1,0 kN/m^2
Antenna	0,25 kN/m^2

Staircase steel	**4,0 kN/m^2**
Secondary structure Columns Beams Steps Floors	3,0 kN/m^2
Diverse	1,0 kN/m^2

Junction level composite	**7,3 kN/m^2**
Composite floor	3,0 kN/m^2
Façade (perpendicular, vertical)	3,0 kN/m^2
Ceiling + ducts	0,3 kN/m^2
Finishing	1,0 kN/m^2

Cladding steel structure	1,2 kN/m^2
Façade (inplane, vertical)	1,2 kN/m^2

Tables: 4.4: Applied dead loads [Eurocode 1991-1-1, 2002]

As displayed in the tables above, steel and composite concrete-steel structures contain less self-weight per m^2. Next, in order to bring into account the façade weight, for the ease, the vertical façade loads on the buildings perimeter are translated into vertical loads perpendicular on the associated floor. In figure 4.14 a load schematization is given for the control cab concrete variant. The ratio floor surface / façade surface of the control cab is 1 / 2.5, explaining the increase of the perpendicular projected façade load.

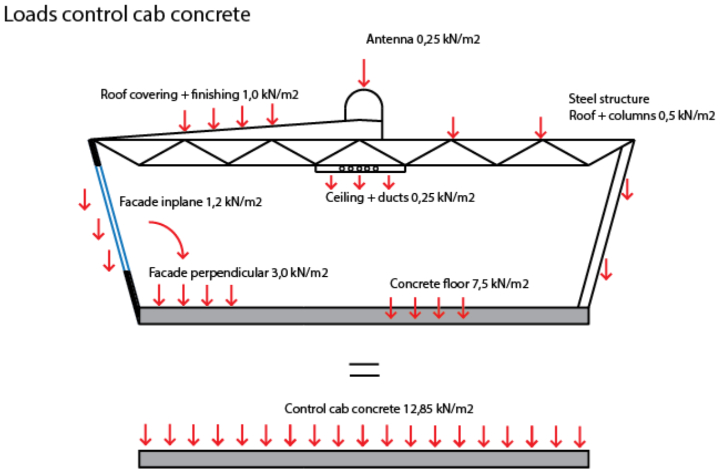


Figure 4.14: Load schematization control cab concrete

4.5.3 Live loads

Live loads are loads superimposed by the intended use and occupancy of the building or area such as, personnel, movable equipment and material, lateral earth pressures, vehicle, and impact loads. Below several tables are given of the live loads which are often applied in the ATC tower design.

Tables: 4.5: Applied live loads [FAA, Eurocode 1991-1-1,2002]

Lateral wind load	
Determined by the eurocode	EN 1991-1-4

Earthquake load	
Determined by the eurocode	EN 1998-1

Control cab	**FAA**	**Eurocode**
Cab roof	Local snow load down	EN 1991-1-3
	Local wind load uplift	EN 1991-1-4
Cab floor	4,8 kN/m^2	5,0 kN/m^2

Junction levels	**FAA**	**Eurocode**
Equipment rooms	7,2 kN/m^2	7,5 kN/m^2
Mechanical and electrical rooms	7,2 kN/m^2	7,5 kN/m^2
Storage space	6,0 kN/m^2	7,5 kN/m^2
Loading dock	9,6 kN/m^2	7,5 kN/m^2
Restrooms	2,4 kN/m^2	2,0 kN/m^2
Locker rooms	2,4 kN/m^2	2,5 kN/m^2
Office areas	2,4 kN/m^2	2,5 kN/m^2
Public areas	4,8 kN/m^2	5,0 kN/m^2

Staircase	**FAA**	**Eurocode**
Stairs and landings	4,8 kN/m^2	4,0 kN/m^2

4.6 Cost principles

This thesis research will be focussed on the global material prices of structural steel and concrete and the labour cost of a construction worker on site, because these figures are considered as the largest proportion of the actual construction costs, which already can be roughly determined in the conceptual phase. This approach is authorized by a cost specialist of Royal HaskoningDHV [Hengstmangers, M., Interview report], keeping in mind that next to the construction costs also other costs aspects exist, which will be disregarded in thesis research in order to reduce the complexity discussed below.

Turner and Townsend is a global management and construction consultancy that is analysing the international construction costs already for several years. After a period of global economic instability the construction markets around the globe are improving slowly and some key markets around the world are showing sustainable signs of growth. They concluded that the construction costs of a country are increasing slowly in line with a country’s inflation along the time. As a result in many countries the costs have barely moved for the last five years. Next to the actual project costs the contractors are taken into account project margins and preliminaries, the aforementioned other costs. Once again these two cost aspects functions as additional information about the international construction market and will not be used in this thesis research.

In developed countries the contractor’s margins have been hit hard by the global financial crises. Very low margins where forced in the hope to pick up work, making it a fierce tendering competition. In the more vibrant countries in e.g. Asia and the Middle East higher margins were seen making these markets much easier and attractive to entry. As a result in the developed countries measures are taken such as lowering all kinds of risks, more focus on efficiency and completing ahead of schedule. Therefore conservative designs and construction methods are preferable. On the other side, when the margins are high a more progressive design approach can be applied. Turner and Townsend gives a global overview for 23 countries. These figures can be used to compare countries with each other, but in case of comparing designs locally in a certain country, an equal margin percentage is taken, making it possible to disregard this cost aspect.

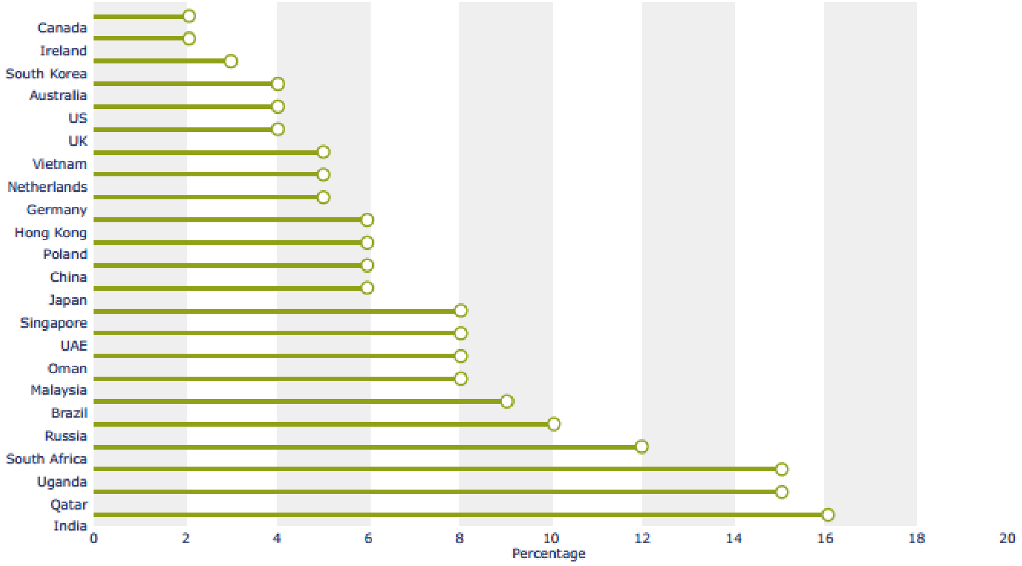


Figure 4.15: Margins contractors worldwide [Turner and Townsend, 2013]

Preliminaries are cost such as supervision, project set-up, temporary facilities and scaffolding and are ranging from 8 to 15 percent displayed in figure 4.16. The height of the preliminaries indicates different requirements between countries, e.g. high-cost countries can have certain safety standards and insurance costs driving the preliminaries cost up. Or they have building sites where space restrictions are present and they would have higher preliminaries due to additional measures. These figures can be used to compare countries with each other, but in case of comparing designs locally in a certain country, an equal margin percentage is taken, making it possible to disregard this cost aspect.

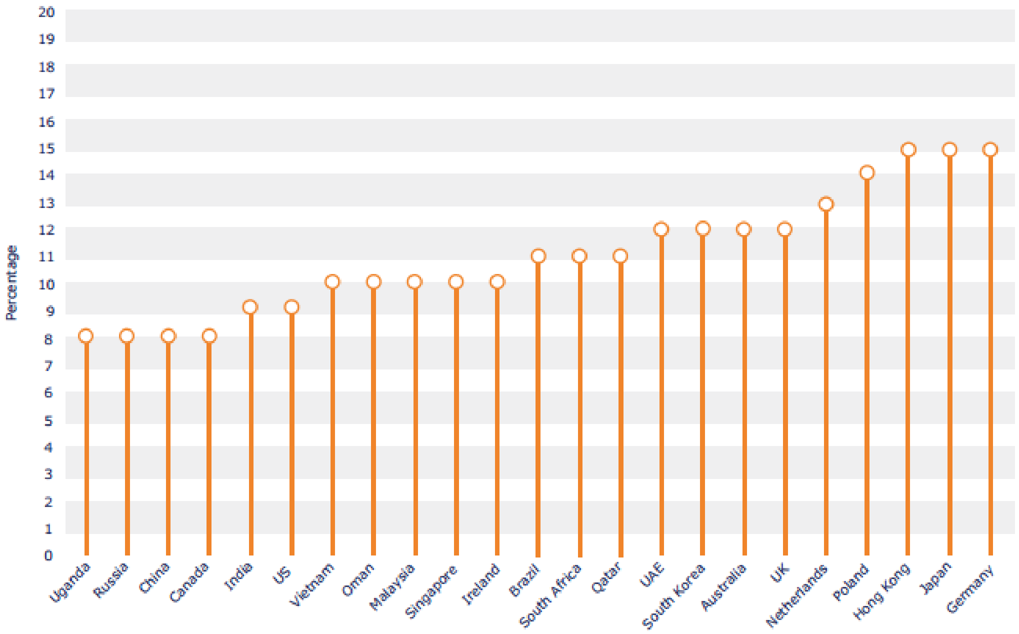


Figure 4.16: Preliminaries worldwide [Turner and Townsend, 2013]

4.6.1 Labour cost

The labour cost is determined by two major aspects; the first is the hourly rate and the second is the productivity of the certain employee. The hourly rates include base wage rate and all related burdens, fringes, statutory payments and contributions, overhead and establishment charges and profit. The height of the rate is determined by dividing the annual salary by the worked hours per year [Compass International Consultants Inc.].

In order to make a proper comparison between countries regarding the labour cost, the productivity of the local construction workers must been taken into account. This productivity is expressed in a factor that can be multiplied with the hourly rate or man-hours. Compass International Consultants Inc. made for every country a productivity index ranging from good, average to poor. Below an example is given for the Dutch construction industry.

	Productivity range	
Good	Average	Poor
0.95	1.15	1.45

Table 4.6: productivity range the Netherlands [Compass International Consultants Inc., 2010]

The productivity factor is measured against the U.S value of 1.00. Meaning a project that took 1000 man-hours to complete in the U.S. will take 1150 man-hours (average) to accomplish in the Netherlands.

Factors that contribute to good productivity are; good access to work; experienced work force; adequate supervision; moderate weather conditions and materials and equipment stored close by the work areas.

Factors that contribute to poor productivity are; overcrowded or tight working conditions, limited education/skills or poor supervision; sophisticated specifications; complex work items; extreme weather conditions; double or triple handling of materials and equipment and small or scattered elements of work.

4.6.2 Concrete price

Concrete prices are different for in-situ and prefab structures, but are both expressed in U.S. dollars per cubic meter (m^3). The price of prefab is 10 % to 20 % higher than in-situ concrete, but the total costs are levelled out by the advantages of prefab above in-situ making both methods very competitive. The major advantages of prefab concrete are; higher concrete quality and increased construction speed.

The concrete price is determined by three major factors; the local concrete price per m^3, reinforcement per tonne and formwork per m^2, subsequently expressed in 1/6, 2/6 and 3/6 of the total price and is verified by a cost specialist [Hengstmangers, M., Interview report] and is also displayed in figure 4.17.

This distribution can be assigned to the related labour load vs material. Pouring concrete is a relatively easy procedure whereby the contribution of labour cost is only 20%. Next stranding reinforcement is more labour intensive making the contribution of labour cost 40 to 50%. At last the formwork is even more labour intensive, resulting in a contribution of 50 – 80 %. This figure is heavily dependent on the local applied formwork materials. In the table below an all-embracing table is presented making above explanation more clearly.

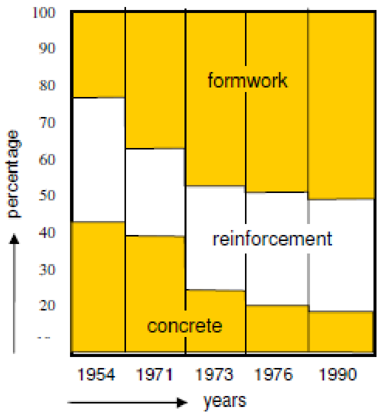


Figure 4.17: Contribution of cost components for concrete works [Horst, A.Q.C van der, 2013]

Concrete in-situ	Material	Labour
Concrete	80 %	20 %
Reinforcement	50 %	50 %
Formwork	30 %	70 %

Table 4.7: Material vs Labour distribution [Hengstmangers, 2014]

It makes sense in countries with high labour cost to optimize man-hour demand, by applying simpler formwork solutions and reinforcement designs. Whereas in countries with high material cost focus must be placed on reducing the material demand.

4.6.3 Steel price

Steel is in comparison with (in-situ) concrete a prefabricated product that is in general assembled on site. The steel price is determined by three major factors; the world steel price, import fees, assembly costs and is expressed in U.S. dollar per tonne. Often the import fees are already included in the local steel prices whereby only the assembly cost must be added. In general the more elements a structure contain the more connections and the longer the assembly time. As a result the labour intensity for braced steel frame is higher than for rigid steel frames, when only the total amount of connections are taking into account. In contrast, rigid joints are in general more complex and require more labour. Therefore is hard to determine which steel structure is more labour intensive, but both steel structures require in general less labour than concrete structures.

4.6.4 Purchasing power parity – secondary price rate

Construction costs between countries cannot be compared on a reliable way using currency exchange rates due to two reasons. First the exchange rates are highly volatile and secondly the local living standards are not taken into account correctly. Turner and Townsend made therefore a secondary price rate, the purchasing power parity (PPP), which is used already in other areas of economics and is a more reliable way of comparing prices. To compare concepts within one country the local prices are suitable to use, whereas the figures of the purchasing power parity must be used when countries are compared with each other, these figures takes the local currency exchange rates and local living standards into account, changing the local prices in some countries significantly. During the thesis research only the PPP figures are used, which is a common used and reliable method [Hengstmangers, interview report].

4.7 System engineering approach

As mentioned in section 4.2 the traditional design process has two major disadvantages. Many essential design considerations are taken in the earliest phases while often insufficient data is available and transition of organizations and knowledge along the design process, often resulting in sub-optimal solutions.

In order to limit these problems and analyze and monitor complex projects “System engineering” (SE) is introduced in the Dutch civil Industry. It is a new design tool promoted by Rijkswaterstaat and Prorail, because in these engineering fields often multidisciplinary and complex projects are commissioned. SE is already implemented for 10 years in the infrastructure sector and application of SE in the other civil sectors is expected to be more common in the nearby future.

One of the challenges in this thesis research is to understand and get grip on the essential design considerations made in the earlier stages. As mentioned before the research is commissioned for Royal HaskoningDHV and NACO, which are both (mainly) located in the Netherlands. This makes it even more difficult to make essential design considerations for a project in a foreign country that is (partly) unknown for the “Dutch” designer and engineer, while using the traditional design approach. Therefore it is interesting to get more insight in SE and determine whether or not it is applicable for this thesis research.

4.7.1 Decomposition

One of the basic principles of system engineering is decomposition. The design process starts often with an abstract client demand, making the design process a very complex process. To reduce the complexity of the main system, decomposition makes it possible to divide the main system into sub-systems that subsequently can be divided in components and elements. This method results in a simplified understanding of the complexity of the system and makes it possible to analyses the relations between system, sub-systems, components and elements. An often decomposition method in the SE is the V-model.

The V-model (figure 4.18) starts at the top left with abstract client demand whereby downward decomposition steps are taken in order to specify concrete design solutions, supported by verification and validation actions. The bottom-up steps of the V-model give the realization of the chosen solutions.

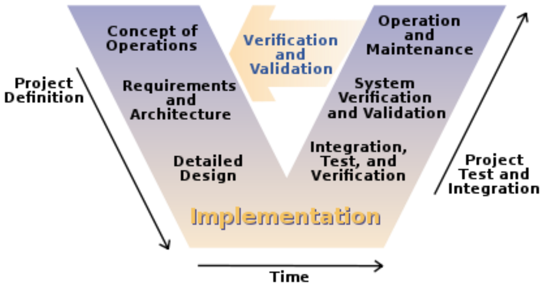


Figure 4.18: V-model [Wikipedia.org]

Each decomposition step is characterized by three analysis processes; requirement analysis, functional analysis and object allocation. From these analysis a design is produced which need to be verified in order to go to the next decomposition layer.

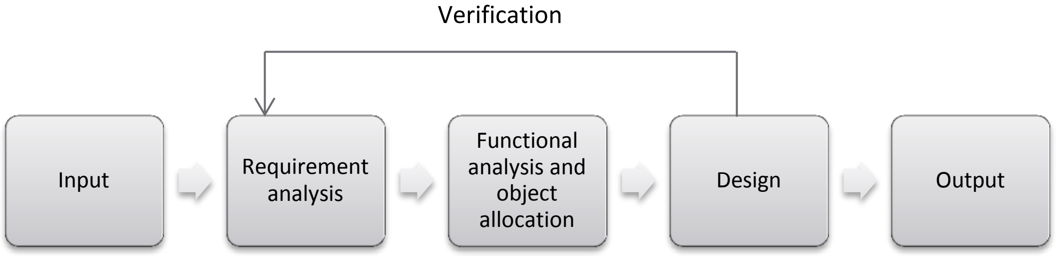


Figure 4.19: Design cycle system engineering

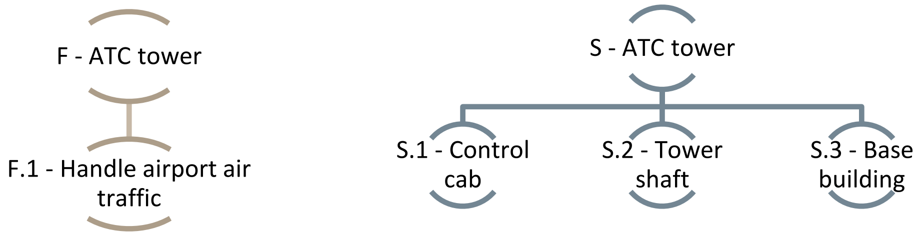
The first step is to derive all the requirements in detail. If needed the requirements must be supplemented and concretized by the client. One of the outcomes is the list of requirements. Decomposing of the requirements is not possible, but requirements at lower levels are derived from the upper system objects and upper requirements.

The second step is to make a functional analysis by allocating the requirements into a function breakdown structure (FBS). Next the functions are allocated into physical objects by a system break down system (SBS) specification. These systems are displayed in section 4.6.2 or appendix IV. This process continues along the design process and starts from very abstract to detail.

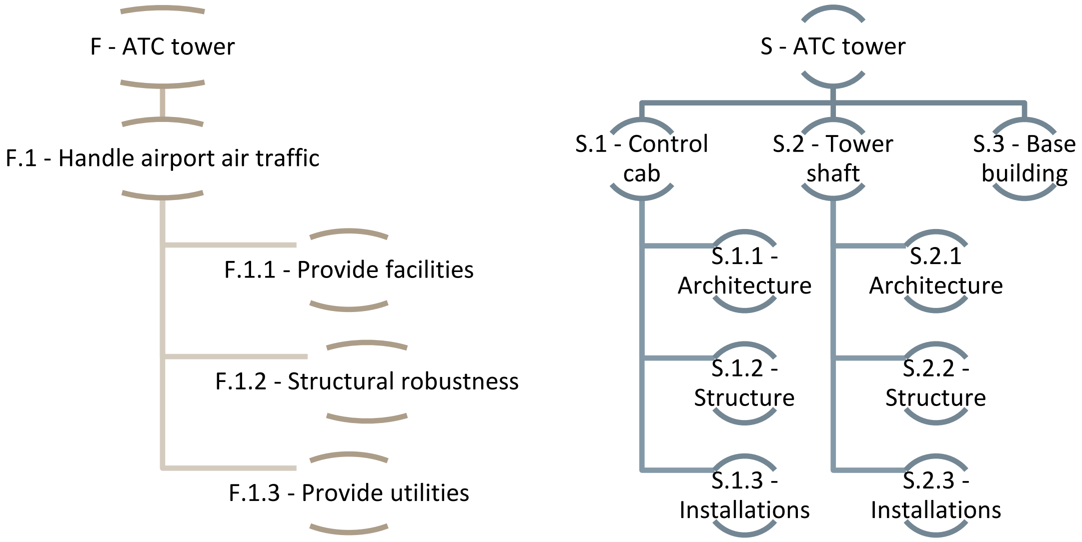
4.7.2 Decomposition analysis ATC tower

Below a general decomposition approach is made in order to analyse ATC towers. The full analysis is attached in appendix IV. On the next page, only the first two decomposition steps are derived. During the analysis only the requirements are analysed, the functions described and the objects allocated. Per decomposition step no design is produced in order to verify the initial requirements. This analysis is not reviewed by SE professionals and as mentioned before the design step is missing. As a result this analysis is not correct and therefore not fully reliable, but it gives more insight in ATC tower design and its components, elements and their mutual relations. This was an additional exercise and added personal knowledge to the author.

Figure 4.20 and table 4.8: Decomposition steps [Appendix IV]



Layer 1	Description	Code	Upper layer	Source / allocation
Requirement	Design optimal ATC tower	R.1	-	Client
Function	Handle airport air traffic	F.1	F	R.1
System	Control cab Tower shaft Base building	S.1 S.2 S.3	S S S	R.1 – R.2 / F.1 R.1 – R. 2 / F.1 R.1 – R. 2/ F.1



Layer 2	Description	Code	Upper layer	Source / allocation
ATC tower	Permit the controller to survey Ensure structural robustness Ensure reliable communication	R.1.1 R.1.2 R.1.3	R.1 R.1 R.1	Client - FAA - ICAO Client - FAA - ICAO Client - FAA - ICAO
Handle airport air traffic	Provide facilities Structural robustness Provide utilities	F.1.1 F.1.2 F.1.3	F.1 F.1 F.1	R.1.1 R.1.2 – R.1.3 R.1.1 – R.1.2
Control cab	Architecture Structure Installations	S.1.1 S.1.2 S.1.3	S.1 S.1 S.1	R.1.1 / F.1.1 R.1.2 – R.1.3 / F.1.2 R.1.1 – R.1.3 / F.1.3
Tower shaft	Architecture Structure Installations	S.2.1 S.2.2 S.2.3	S.2 S.2 S.2	R.1.1 / F.1.1 R.1.2 – R.1.3 / F.1.2 R.1.1 – R.1.3 / F.1.3

4.8 Conclusions

The three key-questions elaborated in chapter 4 are part of the sub-question *"Which steps are taken in order to define and design an economical optimal structural solution?"* and are separately answered with the following conclusions.

Key question one states: *"Which design methodology will be used in order to obtain the thesis research objective"*

The focus is placed on the conceptual design phase of ATC towers and the elementary design cycle will be used to obtain the thesis research objective. The process starts by analysing the design principles and criteria of these towers, followed by synthesis in order to produce variants, resulting in designs and calculations making it possible to evaluate each design.

System engineering is a design approach used to analyse and monitor complex projects. Air traffic control towers are difficult projects but are not so complex in comparison with other civil constriction works. Therefore SE will be too complicated and will not be used any further during this thesis research.

Key question two states *"What are the fundamental criteria and principles for ATC tower design"*.

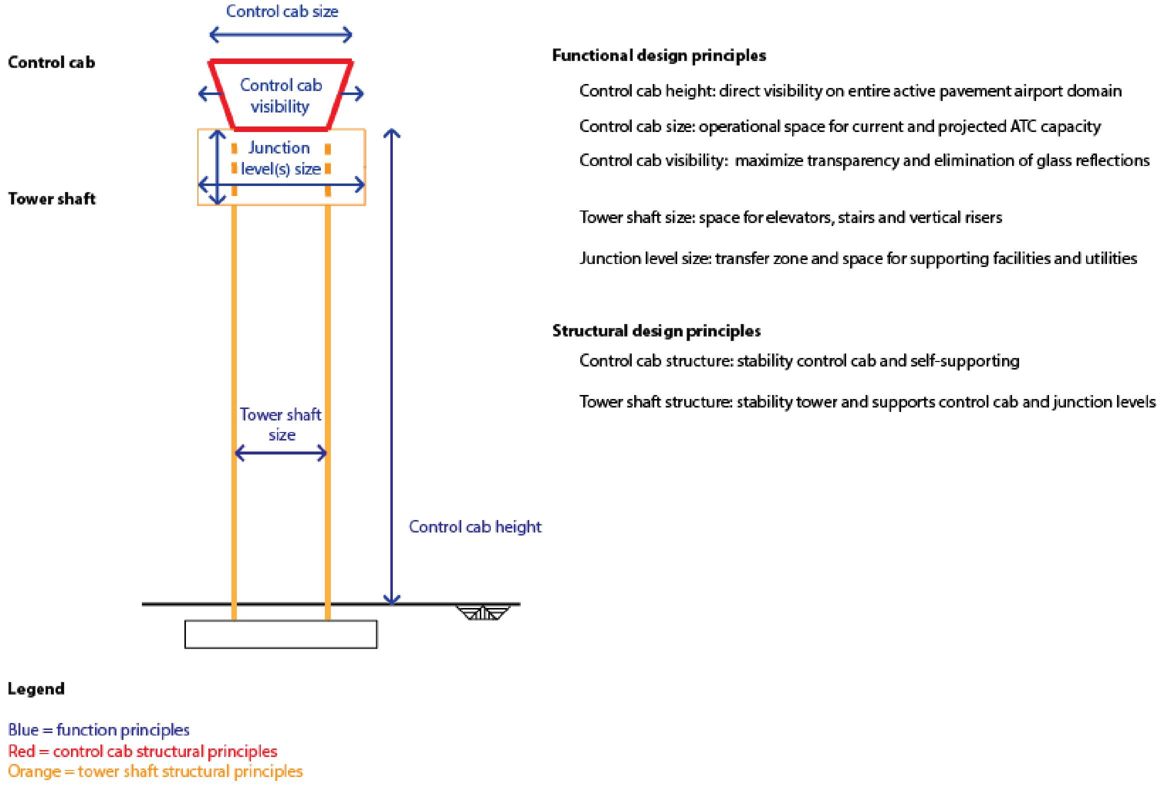
The fundamental requirements for ATC towers facilities are prepared and drafted by the two major aviation authorities in the world, the FAA and ICAO. The towers have to meet their stated requirements, which are applicable anywhere around the globe.

In addition to these requirements, three other design criteria are determined; desires, starting points and boundary conditions. The stated desires and starting points are applicable for every ATC design in a general manner, whereas the local boundary conditions having their own influence and importance on every individual ATC design.

Before starting a design, the following four local boundary conditions are the most important to determine, in both structural as economical perspective:

- Current and projected future air activity airport
- Wind climate
- Earthquake hazard
- Construction industry

The fundamental design principles are divided in functional and structural principles. These principles are displayed and described in an all-embracing overview in figure 4.21.



Functional design principles

Control cab height: direct visibility on entire active pavement airport domain
Control cab size: operational space for current and projected ATC capacity
Control cab visibility: maximize transparency and elimination of glass reflections

Tower shaft size: space for elevators, stairs and vertical risers

Junction level size: transfer zone and space for supporting facilities and utilities

Structural design principles

Control cab structure: stability control cab and self-supporting

Tower shaft structure: stability tower and supports control cab and junction levels

Legend

Blue = function principles
Red = control cab structural principles
Orange = tower shaft structural principles

Figure 4.21: design principles ATC tower

Key question three states *“Which cost aspects influence an economically optimal structural design”*.

Cost estimations of the concepts designs gives important information for the development of the alternatives. The relation between material cost on one hand and the labour cost on the other hand is an important factor in order to obtain an economical optimal solution. These two costs aspects, labour and material, can totally differ for each country, but are all compiled with the same aspects.

The labour cost, expressed in USD per hour, is determined by two major aspects:

- Hourly labour rate
- Productivity factor

The concrete price, expressed in USD per m^3, is determined by three major aspects:

- Local concrete price per m^3
- Reinforcement per tonne
- Formwork per m^2

The structural steel price, expressed in USD per tonne, is determined by three major aspects:

- World steel price m^3
- Import fees
- Assembly cost

5 Local boundary conditions concept designs

5.1 Introduction

In this chapter the starting points for the 6 chosen countries are determined. For these 6 towers, master plans have been developed. The current and future situation for these airports are analysed in order to determine the design starting points for these master plans. The height and the capacity of the proposed towers are defined and the local wind and earthquake hazards are analysed. Also the local construction industry is described shortly on basis of interviews and questionnaires. At last the most important costs are determined per country. This chapter is concluded by a summary presenting a side-by-side overview of the 6 airports.

5.2 Lelystad Airport – Netherlands

5.2.1 Current situation

At this moment Amsterdam Schiphol airport is the main port of the Netherlands with 450.000 air traffic movements per year. In the year 2020 the total air traffic movement in the Netherlands is expected to increase to 580.000 per year, whereby 510.000 are allocated to Schiphol, resulting in a large increase in movements for Schiphol within a short period of time [Schiphol group, 2014].

To handle this increase, Schiphol needs, next to an own airport expansion, a different approach in order to sustain one of the most important an economical hubs of Europe. A master plan is written by “Tafel van Alders” to develop Lelystad Airport as the twin-airport of Schiphol by the year of 2018. In the first phase 10.000 non-main port related air movements will be moved from Schiphol to Lelystad, making it an airport for mainly holiday related flights, executed by Transavia, Arkefly, Corendon, Easyjet and Ryanair.

Lelystad airport is located approximately 40 km from Amsterdam near the city of Lelystad. The airport is currently used by only charter, private and educational aircrafts making it a very small airport, without any commercial facilities or purposes.

The current length of the runway is 1250 meters and the layout of the airport is given in figure 5.1. Below the runway all airport facilities are located, such as small hangers for private use, helipads, offices and fire brigade. Near the red dot the terminal with the air traffic control tower is located. In figure 5.2 the terminal building and the ATC tower are presented. The total height of the current ATC tower is 10 meter and gives space for approximately 3 air traffic controllers. The design classification of the current capacity of the ATC tower is determined as low.

Figure 5.1: Current layout Lelystad Airport [maps.google.com]

Figure 5.2: Left fire brigade, right terminal building with ATC tower [Schiphol group, 2014]

5.2.2 Master plan

The master plan of Lelystad airport is based on the required air traffic capacity and is divided into three phases, resulting in an intended capacity of 45.000 movements around 2043. The first phase will start in 2015 and the current airport layout will be transformed conform the following client's requirements:

- The airport is suitable for receiving Boeing 737 and Airbus A320 aircrafts
- The current runway need to be extended to a total length of 2700 meter and width of 45 meter
- A taxiway parallel to the runway need to be constructed
- A terminal building with a capacity of 4 platforms need to be constructed
- Air traffic control facilities for the future capacity need to be constructed

Below the three phases are expressed in the number of passengers per year and in figure 5.3 the expected market scenarios are presented over time.

I. Maximum capacity of 10.000 air traffic movements and circa 1,5 million passengers per year
II. Maximum capacity of 25.000 air traffic movements and circa 3,7 million passengers per year
III. Maximum capacity of 45.000 air traffic movements and circa 6,7 million passengers per year

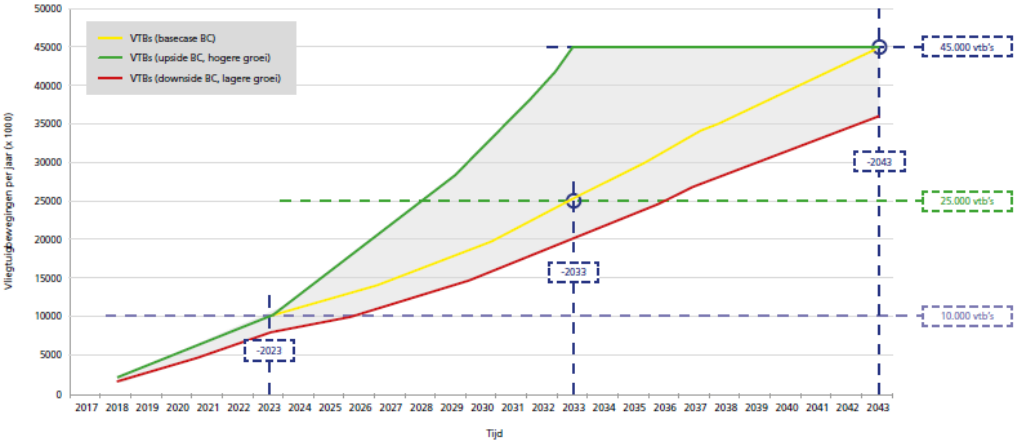


Figure 5.3: Market scenario Lelystad airport [Schiphol group, 2014]

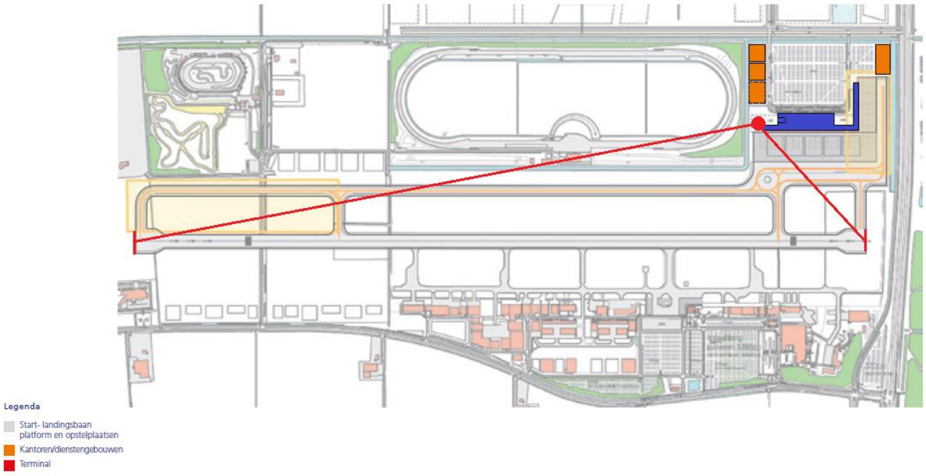


Figure 5.4: Airport layout after phase III [Schiphol group, 2014]

5.2.3 Tower dimensions

The final airport layout, after phase III, is presented in figure 5.4. Comparing with figure 5.1 the runway is doubled in length, a taxiway is placed next to the runway and the terminal and ATC facilities are placed in the right top corner of the airport domain. The ATC tower will be placed near the red dot and is located on the landside of the airport domain.

Tower height

The maximum length between the runway-end and the ATC tower is 2400 meter.

$$\frac{h_{op}}{2400} \geq \tan(1) \tag{5.1}$$

$$h_{op} \geq 2400 \times \tan(1) = 42\, meter \tag{5.2}$$

The total height of the ATC tower is determined by:

$$h_{op} + h_{cab} + h_{sphere} = h_{tower} \tag{5.3}$$

$$42 + 4 + 1 = 47\, meter \tag{5.4}$$

Whereby assumed that

$$h_{cab} = 4\, meter \tag{5.5}$$

$$h_{sphere} = 1\, meter \tag{5.6}$$

The ATC tower will be placed directly next to the terminal building; therefore obstructed view on the aircraft platforms will be prevented. Due to its central location on the airport domain, clear view on taxiways and runways arises and the height meets the direct visibility requirement. As last the ATC tower is checked on interference with the approach surfaces and complies in this respect.

Control cab size

The design classification of the ATC tower is determined as low. The airport contains only one runway and the intended maximum air traffic capacity of the Lelystad airport is 45.000 movements. This amount can be handled by a maximum of 6 controllers; therefore the minimum required cab area is 21 m^2.

5.2.4 Geographical conditions

Wind climate

The basic wind velocity Vb in the Lelystad area is 27 m/s. This results in a maximum basic velocity pressure qb and peak velocity pressure $qp(h_{tower})$ at the top of the tower with the following values:

$$qb = \frac{1}{2} \times \rho \times Vb^2 = 0{,}46 \frac{kN}{m^2} \tag{5.7}$$

$$qp(h_{tower}) = (1 + 7 \times Iv(h_{tower}) \times qb = 1{,}56 \frac{kN}{m2} \tag{5.8}$$

In appendix VI background information is given for this wind pressure calculation.

Earthquake hazard

The local seismic hazard agr for Lelystad airport is 0.4 m/s^2. In cases of very low seismicity, when agr is not greater than 0.39 m/s^2, the provisions of the Eurocode 1998 need not be observed [NEN-EN 1998-1:2005 section, 3.2.1].

In this case the local earthquake hazard is determined as very low and will be neglected in structural design and analysis. In appendix VII background information is given for this earthquake hazard determination.

5.2.5 Dutch construction industry

Information about the Dutch construction industry is gathered by consulting J. Font Freide and other professional of Royal HaskoningDHV.

Construction materials

In the Netherlands all modern construction materials are produced and available. Next, the Dutch construction industry stimulates, in cooperation with universities and research centres, further investigation in construction materials, improving the current quality and reliability of the materials. In the Netherlands prefabricated elements are highly used in tower design. Also high strength concrete and steel are available and in general no additional construction materials need to be imported from abroad.

The following 5 materials are ranked in appearance for general tower design in the Netherlands, with the height range 50m to 150 meters.

1) Concrete
2) Steel
3) Composite concrete/steel
4) Masonry
5) Timber

Structural systems

The most common structural systems for towers with height range 50m – 150m in the Netherlands are core structures. Also many other systems are used, but this is highly depended on the choice of the structural engineer. As mentioned, prefabrication is highly used in the Netherlands and is applicable also for the several structural systems. The following 5 structural systems are ranked in appearance for tower design in the Netherlands.

1) Core structures
2) Shear walls
3) Tube structures
4) Braced frame
5) Rigid frames

As known, the geotechnical conditions in the west of the Netherlands are bad. For tower design often deep foundations in combination with prefabricated piles are used.

Knowledge and equipment

In the Netherlands many contractor firms are active in the construction industry. A few are internationally oriented and others are focusing on local areas in the Netherlands. In general, all firms have a high knowledge standard and using high tech equipment and techniques, therefore pretension, posttension and slip forming are generally used techniques.

Prices and costs

The following numbers are price indications of the Dutch construction materials [Turner & Townsend, 2013].

Table 5.1: Dutch material prices [Turner & Townsend, 2013]

Material	Euro	USD	Purchasing power parity in USD
Concrete 30 MPA per m^3	95	125	158
Reinforcement bar 16 mm per tonne	968	1274	1614
Formwork to soffit of slab	35	46	58
Structural steel beams per tonne	1337	1759	2229

Construction labour hourly rates

The labour cost of a skilled construction worker in the Amsterdam area is varying from $ 48,00 per hour (low range) to $ 55,00 per hour (high range). The average labour cost for an construction worker in Lelystad is set on $ 53,00 per hour. This rate includes base wage rate and all related burdens, fringes, statutory payments and contributions, overhead and establishment charges and profit.

Next to the hourly labour rate the labour productivity of a Dutch construction worker is important. The followings figures (table 5.2) are found and the value of 1.15 is taken in this thesis research. This means a construction task that took 1000 man-hours to complete in the U.S. would take 1150 man-hours to complete in the Netherlands.

Table 5.2: Dutch labour productivity range [Compass International Consultants Inc., 2010]

	Productivity range	
Good	Average	Poor
0.95	1.15	1.45

5.3 Conclusions Lelystad airport

Lelystad airport will contain 1 runway and the new ATC tower requires a minimum height of 47 meters with a low ATC capacity and is located on the landside of the airport domain.

The normative lateral load is wind. The maximum peak velocity pressure at a height of 47 meters is 1,56 kN/m^2. The local earthquake hazard is very low and therefore earthquake loading can be disregarded conform the Eurocode.

Concrete and steel are the most common structural materials used for high and slender buildings and the concrete technology is highly developed. One of the results is that the Dutch are highly experienced with prefabricated concrete structures, resulting that the appearance of concrete core structures and shear wall are the highest.

The Dutch contractors are highly skilled and possess high tech construction techniques and equipment. “Everything is possible” is the main philosophy.

The average labour cost of a skilled construction worker in the Netherlands is $ 53 dollar per hour (approximately €38) and the productivity average is 1.15. This number is low meaning that the Dutch projects and construction workers are relatively inefficient in comparison with American standards.

5.4 Abuja Airport – Nigeria

5.4.1 Current situation

Nnamdi Azikiwe International airport is the main airport near Abuja, the capital city of Nigeria. The airport has one runway with a length of 3600 meters and the layout of the airport is given in figure 5.5. Near the red dot the current ATC tower is presented. The height of the current ATC tower is 50 meters and handles approximately 60.500 air traffic movements per year. The annual passenger's number for Abuja's airport for 2012 was 6.2 million passengers. The design classification of the current capacity of the ATC tower is determined as low.

Figure 5.5: Current Abuja airport layout [maps.google.com]

Figure 5.6: Abuja ATC tower [panoramio, 2013]

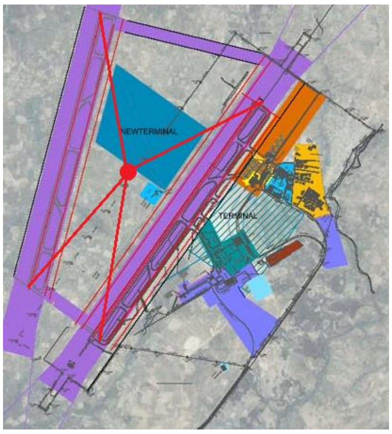


Figure 5.7: Master plan Abuja airport [Aliu, P., PSA online, 2009]

5.4.2 Master plan

At this moment the master plan exists to enlarge the airport activity by constructing a new runway parallel to the existing runway, located left on the airport domain presented in figure 5.7. Between the two runways a new terminal building arises. The current ATC tower is too low to meet the new visibility requirements and should be replaced. The increase of air traffic for the upcoming years is unknown and is taken with an increase of 20 %, resulting in 72.600 movements.

5.4.3 Tower dimensions

The future airport layout is presented in figure 5.7 and the new ATC tower will be placed near the red dot and is located on the airside of the airport domain.

Tower height

The maximum length between the runway-end and the ATC tower is 3000 meter.

$$\frac{h_{op}}{3000} \geq \tan(1) \tag{5.9}$$

$$h_{op} \geq 3000 \times \tan(1) = 53\, meter \tag{5.10}$$

The total height of the ATC tower is determined by:

$$h_{op} + h_{cab} + h_{sphere} = h_{tower} \tag{5.11}$$

$$53 + 4 + 1 = 58\, meter \tag{5.12}$$

Whereby taken that

$$h_{cab} = 4\, meter \tag{5.13}$$

$$h_{sphere} = 1\, meter \tag{5.14}$$

The ATC tower will be placed directly next to the terminal building; therefore obstructed view on the aircrafts platform will be prevented. Due to its central location on the airport domain, clear view on taxiways and runways arises and the height meets the direct visibility requirements. The height of the ATC tower is checked on interference with the (misses) approach surfaces and does not comply. The tower must be marked, meaning the tower must be described in the approach handbooks for pilots and sufficient lighting must be placed on the tower.

Control cab size

The new design classification of the ATC tower is determined as intermediate. The airport is extended by one runway and the air traffic capacity is increased by 20 %. This air traffic will be handled by a minimum of 6 and a maximum of 12 controllers. The minimum required cab area is 32 m^2.

5.4.4 Geographical conditions

Wind climate

The basic wind velocity Vb of the Abuja area is 40,2 m/s. This results in a maximum basic velocity pressure qb and peak velocity pressure $qp(h_{tower})$ at the top of the tower with the following values:

$$qb = \frac{1}{2} \times \rho \times Vb^2 = 1{,}01 \frac{kN}{m^2} \tag{5.15}$$

$$qp(h_{tower}) = (1 + 7 \times Iv(h_{tower}) \times qb = 3{,}61 \frac{kN}{m2} \tag{5.16}$$

In appendix VI background information is given for this wind pressure calculation.

Earthquake hazard

The local seismic hazard agr for Abuja airport is 0.2 m/s^2. In cases of very low seismicity, when agr is not greater than 0.39 m/s^2, the provisions of the Eurocode 1998 need not be observed [NEN-EN 1998-1:2005, section 3.2.1].

In this case the local earthquake hazard is determined as very low and will be neglected in structural design and analysis. In appendix VII background information is given for this earthquake hazard determination.

5.4.5 Nigerian Construction industry

Information about the Nigerian construction industry is gathered by interviews and questionnaires with experts J. Boon, R. Brouwers, P. Gröning and N. Igbedion and is summarized in this section. More information can be found in the interview report.

Construction materials

First, in Nigeria and especially in Africa, not a lot of towers have been constructed. The most common construction material in Nigeria is concrete. The maximum quality is C28/35. Steel is often used to construct large roof spans for industry purposes, like the Heineken breweries. Next to this, hollow bricks (masonry) are also widely used in Nigeria and are mainly used to construct non-load bearing walls and partition walls. The following 5 materials are ranked in appearance for general tower design in Nigeria.

1) Concrete
2) Steel
3) Composite concrete/steel
4) Masonry
5) Timber

Generally, all the common construction materials are available in Nigeria, but locally only concrete and hollow bricks are produced on larger scale. All the other materials are imported through the Nigerian harbour of Lagos. The Nigerians gained sufficient experience in importing materials along the time, wherefore the reliability of delivery is high. An upcoming trend in the global and especially Nigerian construction industry is the use of pre-fabricated buildings. These modular buildings are assembled in foreign countries, shipped in sections by (sea) containers and reassembled in Nigeria. The benefits of constructing structures with this method are; cheaper, in general a shorter construction time and higher qualities of material and structure. This method is very suitable for standard buildings like, industry halls. Air traffic control towers are mainly one of a kind designs and therefore less suitable for pre-engineering.

Structural systems

The most common structural systems for constructing buildings in Nigeria are rigid frames, due to its simplicity and because concrete is already available in the country. The earthquake hazard in Nigeria is very low and can be disregarded; therefore the wind load is normative in the design of the structural system. The following 5 structural systems are ranked in appearance for tower design in Nigeria.

1) Rigid frames
2) Braced frames
3) Core structure
4) Tube structures
5) Shear walls

The most common foundation systems for tower design in Nigeria are deep foundations in combination with bored piles. Shallow foundations are used when the geotechnical conditions are good.

Knowledge and equipment

In Nigeria several large contractor firms are active, often subdivisions of international operating contractors. These larger firms are working in general on the major projects. Next to this also a lot of smaller local firms exist. But all contractors in Nigeria do not have a high knowledge level and don’t possess high tech equipment. In addition the majority of the construction workers are not qualified.

“Keep it simple” is the main focus while designing a building in Nigeria. Royal HaskoningDHV monitors the execution of a project by sending skilled project managers to Nigeria, who are responsible for the work preparation, planning and quality. This method is often the cheapest solution.

Prices and cost

Unfortunately Turner and Townsend did not survey the Nigerian construction materials, but by using questionnaires and interviews the prices are obtained. To check the correctness and credibility of the given prices (given by 3 Royal HaskoningDHV employees) the prices are compared with the Ugandan prices given by Turner and Townsend in order to give a good estimation of the construction prices in this region of the world. In this case no comparisons can be made on basis of the purchasing power parity figures and therefore Nigeria cannot be directly compared with other countries to obtain reliable results.

Table 5.3: Nigerian material prices [Igbedion, N., Interview rapport]

Material	USD
Concrete 30 MPA per m^3	214
Reinforcement bar 16 mm per tonne	1382
Formwork to soffit of slab	15
Structural steel beams per tonne	3808

Construction labour hourly rates

The labour cost of a construction worker in the Lagos area is varying from $ 1,50 per hour (low range) to $ 4,12 per hour (high range). The average labour cost for a construction worker in Abuja is set on $ 3,0 per hour. This rate includes base wage rate and all related burdens, fringes, statutory payments and contributions, overhead and establishment charges and profit.

Next to the hourly labour rate the labour productivity of a Nigerian construction worker is important. The followings figures (table 5.4) are found and the value of 2.25 is taken in this thesis research. This means a construction task that took 1000 man-hours to complete in the U.S. would take 2250 man-hours to complete in Nigeria.

Table 5.4: Nigerian productivity range [Compass International Consultants Inc., 2010]

	Productivity range	
Good	Average	Poor
1.75	2.25	3.35

5.4.6 Conclusions Abuja airport

Abuja airport will be extended with 1 runway and the old ATC tower will be replaced by a new tower with a minimum height of 58 meter with an intermediate capacity. Next the tower will be located on the airside of the airport domain. Reduction of nuisance during construction is preferred.

The normative lateral load is wind. The maximum peak velocity pressure at a height of 58 meters is 3,61 kN/m^2. The local earthquake hazard is very low and therefore earthquake loading can be disregarded conform the Eurocode.

Concrete and hollow bricks are the only construction materials that are produced locally, all the other materials are imported by ship through the harbour of Lagos, but this method is very reliable. As a result these construction materials are the most common construction materials used in tower design in Nigeria, subsequently followed by steel. In general, the most common structural system for constructing buildings in Nigeria are concrete rigid frame structures filled with hollow bricks, because due to the simplicity and the local availability

“Keep it very simple” is the main focus while designing buildings in Nigeria, because the majority of the Nigerian construction workers are not qualified. Next, the contractors in Nigeria do not have a high knowledge level and possesses no high tech equipment.

The average labour cost of a construction worker in Nigeria is $ 3 dollar per hour and the productivity average is 2.25. This number is high meaning that the Nigerian projects and construction workers are inefficient in comparison with American standards.

5.5 Tokyo Narita International airport – Japan

5.5.1 Current situation

Narita International is located approximately 60 km from Tokyo and is the primary international airport of the greater Tokyo area. Narita handles the majority of international passenger traffic of Japan and is the major link between Asia and America. It is the second-busiest airport of Japan. The airport has two runways with a length of 4000 m and 2200 m. Near the red dot the current ATC tower is presented. The height of the current ATC tower is 86 meters and handles approximately 190.000 air traffic movements per year. The annual passenger's number for Tokyo Narita International airport for 2012 was 31.4 million. The design classification of the current capacity of the ATC tower is determined as major.

Figure 5.8: Current Narita airport layout [maps.google.com]

Figure 5.9: Nartia airport tower [airchive.com, 2014]

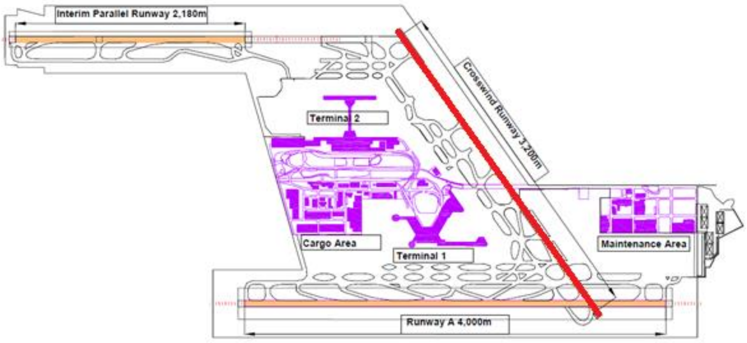


Figure 5.10: Master plan Narita airport [Gamo, M, 2008]

5.5.2 Master plan

The estimated future capacity of Narita airport is 300.000 air movements per year; this is an increase of 60% of the current capacity. In order to be able to handle this new amount an extra runway will be constructed with a length of 3200m marked in figure 5.10. The height of the current tower is sufficient, because the new runway is within the current sight boundaries. Due to the large increase of capacity (60%) the current cab size is considered to be too small and a new tower shall be designed.

5.5.3 Tower dimensions

The new airport layout is presented in figure 6.10 and the ATC tower will be placed next to the existing ATC tower, near the red dot in figure 5.8, and is located on the landside of the airport domain.

Tower height

As mentioned the current height is sufficient, therefore the new height will is also be 86 meters.

Control cab size

The new design classification of the ATC tower is determined as major. The airport is extended by one runway and the air traffic capacity is increased by 60 %. This air traffic will be handled by a minimum of 12 controllers. The minimum required cab area is 50 m^2.

5.5.4 Geographical conditions

Wind climate

The basic wind velocity Vb of the Tokyo area is 38 m/s. This results in a maximum basic velocity pressure qb and peak velocity pressure $qp(h_{tower})$ at the top of the tower with the following values:

$$qb = \frac{1}{2} \times \rho \times Vb^2 = 0{,}88 \frac{kN}{m^2} \tag{5.17}$$

$$qp(h_{tower}) = (1 + 7 \times Iv(h_{tower}) \times qb = 3{,}42 \frac{kN}{m2} \tag{5.18}$$

In appendix VI background information is given for this wind pressure calculation.

Earthquake hazard

The local seismic hazard agr for Narita airport is 9.8 m/s^2. For the structural design and analysis the Eurocode 1998 will be used instead of the Japanese building code Ministry regulation No.14 - 1997. The reason for this decision is; the Eurocode is elaborated in more detail, the Eurocode contain the same approach as the Japanese code [literature study] and the Eurocode makes it possible to make good comparisons with other countries and hazards, while using all the same code.

The ground type of Tokyo airport area is C. Deposits of very dense sand, gravel, or very stiff clay. In appendix VII background information is given for this earthquake hazard determination.

5.5.5 Japanese construction industry

Information about the Japanese construction industry is gathered by reading, scanning the internet and consulting J. Font Freide. The author made the following summary. These results are indications and can be considered as quite reliable.

Construction materials

The following 5 construction materials are ranked in appearance for tower design in Japan with height range 50m – 150m.

1) Steel
2) Composite concrete/steel
3) Concrete
4) Timber
5) Masonry

Structural systems

In general rigid shaped structures are commonly preferred to overcome seismic affects. The following 5 structural systems are ranked in appearance for tower design in Japan with height range 50m – 150m.

1) Rigid frames
2) Braced frames
3) Core structures
4) Shear walls
5) Tube structures

Knowledge and equipment

The Japanese construction industry is widely spread around the pacific area; major contractor firms are active in Indonesia and Philippines and possess high knowledge levels and equipment regarding high tech techniques. Just like the Netherlands, Japan stimulates the construction industry, in cooperation with universities and research centres, for further investigation in materials especially related with earthquake engineering.

Prices and cost

The following numbers are price indications of the Japanese construction materials [Turner & Townsend, 2013].

Table 5.5: Japanese material prices [Turner & Townsend, 2013]

Material	**JPY**	**USD** Exchange rate 97,90	**Purchasing power parity in USD**
Concrete 30 MPA per m^3	11900	122	172
Reinforcement bar 16 mm per tonne	66000	674	956
Formwork to soffit of slab	2680	27	39
Structural steel beams per tonne	80000	817	1159

Construction labour hourly rates

The labour cost of a skilled construction worker in the Tokyo area is varying from \$ 43,20 per hour (low range) to \$ 52,00 per hour (high range). The average labour cost for an construction worker in Tokyo is set on \$ 47,00 per hour. This rate includes base wage rate and all related burdens, fringes, statutory payments and contributions, overhead and establishment charges and profit.

Next to the hourly labour rate the labour productivity of a Japanese construction worker is important. The followings figures (table 5.6) are found and the value of 1.20 is taken in this thesis research. This means a construction task that took 1000 man-hours to complete in the U.S. would take 1200 man-hours to complete in Japan.

Table 5.6: Japanese productivity range [Compass International Consultants Inc., 2010]

	Productivity range	
Good	Average	Poor
1.10	1.20	2.00

5.5.6 Conclusions Tokyo airport

Tokyo Narita airport will be extended with 1 runway. The current ATC tower does not have enough ATC capacity and will be replaced by a new tower with the same height but a larger control cab in order to meet the future growth (major activity). The location of the new tower is on the landside of the airport domain.

The normative lateral loads are both wind and earthquakes. The maximum peak velocity pressure at a height of 86 meters is 3.42 kN/m^2. The local earthquake hazard is very high with a value of 9,8 m/s^2.

Steel is the most common used structural material for high and slender buildings, followed by composite steel/concrete structures. In Japan the steel technology is highly developed, raised from their experiences with the earthquake phenomenon and related earthquake engineering. As a result the most common structural systems are rigid and braced steel frames, subsequently followed by concrete structures.

The Japanese contractors are highly skilled and possess high tech construction techniques and equipment. “Everything is possible” is the main philosophy.

The average labour cost of a skilled construction worker in Japan is \$ 47 dollar per hour and the productivity average is 1.20. This number is low meaning that the Japanese projects and construction workers are relatively inefficient in comparison with American standards.

5.6 Nanjing Lukou International airport – China

5.6.1 Current situation

Nanjing Lukou international airport is the main airport of the city of Nanjing and serving the Yangtze River Delta area. The airport has one runway with a length of 3600 meters. Near the red dot the current ATC tower is presented and has got a height of 50 meters. The airport handles approximately 135.000 air traffic movements per year and the annual passenger's number for Nanjing airport for 2013 was 15 million. The design classification of the current capacity of the ATC tower is determined as intermediate.

Figure 5.11: Current Nanjing airport layout [maps.google.com]

Figure 5.12 Nanjing ATC tower [panoramio , 2014]

Figure 5.13: Master plan Nanjing airport [adp-i, 2013]

5.6.2 Masterplan

A feasibility study has been performed by the Aéroports de Paris Ingénierie (ADPI) and forecasted an increase to 30 million passengers in the year 2020 and 70 million in the year 2040. The feasibility study recommended the construction of a whole new terminal building and 4 parallel positioned runways, this study is presented in figure 5.13.

5.6.3 Tower dimensions

The airport layout is presented in figure 5.13 and the ATC tower will be placed near the red dot and is located on the landside of the airport domain.

Tower height

The maximum length between the runway-end and the ATC tower is 3500 meter.

$$\frac{h_{op}}{3500} \geq \tan(1) \tag{5.19}$$

$$h_{op} \geq 3500 \times \tan(1) = 61\ meter \tag{5.20}$$

The total height of the ATC tower is determined by:

$$h_{op} + h_{cab} + h_{sphere} = h_{tower} \tag{5.21}$$

$$61 + 4 + 1 = 66\ meter \tag{5.22}$$

Whereby assumed that

$$h_{cab} = 4\ meter \tag{5.23}$$

$$h_{sphere} = 1\ meter \tag{5.24}$$

The ATC tower will be placed directly next to the main terminal building, see figure 5.13, therefore obstructed view on the closest aircrafts platforms will be prevented. Due to the large airport domain and the further located second terminal, the direct visibility requirement will not meet for certain parts of active pavement. The height of 61 meters will be increased by 30 meters in order to meet the requirements. The new height of the ATC tower will become 96 meter. As last the ATC tower is checked on interference with the (misses) approach surfaces and complies.

Control cab size

The new design classification of the ATC tower is determined as major. The airport is extended by three runways and the passenger growth will be increased by 466% in the year 2040. This air traffic will be handled by a minimum of 12 controllers. The minimum required cab area is 50 m^2.

5.6.4 Geographical conditions

Wind climate

The basic wind velocity Vb of the Tokyo area is 30 m/s. This results in a maximum basic velocity pressure qb and peak velocity pressure $qp(h_{tower})$ at the top of the tower with the following values:

$$qb = \frac{1}{2} \times \rho \times Vb^2 = 0{,}55 \frac{kN}{m^2} \tag{5.25}$$

$$qp(h_{tower}) = (1 + 7 \times Iv(h_{tower}) \times qb = 2{,}17 \frac{kN}{m2} \tag{5.26}$$

In appendix VI background information is given for this wind pressure calculation.

Earthquake hazard

The local seismic hazard agr for Narita airport is 1.6 m/s^2. For the structural design and analysis the Eurocode 1998 will be used instead of the Chinese building code, GB50011-2001. Due to the same reason as for Japan; the Eurocode is elaborated in more detail, the Eurocode contain the same approach as the Chinese code [literature study] and makes it possible to make good comparisons with other countries and hazards, while using all the same code.

Nanjing airport is located in the Yangtze River Delta. The stratigraphic profile is assumed to be ground type C: deep deposits of dense or medium-dense sand, gravel or stiff clay.

In appendix VII background information is given for this earthquake hazard determination.

5.6.5 Chinese construction industry

Information about the Chinese construction industry is gathered by interviews and questionnaires with experts A. Geelhoed, S. Vorselman, R. Brouwers and L. Fang and is summarized in this section. More information can be found in the interview report.

Construction materials

The most common materials used for tower design with height range 50m – 150m in China are; concrete, steel and composite concrete/steel. They are ranked in appearance. These materials are highly available and the experience is high.

1) Concrete
2) Steel
3) Composite concrete/steel
4) Timber and masonry

Generally all common materials are available in China; only prefabricated concrete elements are not often used in tower design. The quality of the construction materials are in general lower comparing with the Netherlands and are less durable. As a result, buildings appear to be old after a few years of completion. Next the Chinese want to build as fast and cheap as possible, resulting also in a lower building quality.

Structural systems

The most common structural systems for towers with height range 50m – 150m in China are; core structures, shear wall and steel braced structures. The reasons for choosing these structures are the preferable properties regarding wind/earthquake loading, cost and experience. The following 5 structural systems are ranked in appearance for tower design in China.

1) Core structure
2) Shear wall
3) Braced steel structure
4) Rigid frame
5) Tube structures

Deep foundation with pilling is the common foundation system for tower design in most of the areas in China. China contains areas with only earthquake loading or wind loading. Therefore the load action on the building is highly related on its specific location. For the horizontal load, usually the highest load, due to wind or earthquake action will be determined and used for the structural design.

Knowledge and equipment

In the bigger cities of China, like Nanjing, the largest contractor firms of the country are active. These large firms are very experienced in constructing high buildings and complex structures. In general the designers don’t need to make less complex structures to meet the contractor’s knowledge level. Next to this the Chinese contractor firms do possess high tech equipment in order to use pretension, post tension and slip forming.

Prices and cost

The following numbers are price indications of the Chinese construction materials [Turner & Townsend, 2013].

Table 5.7: Chinese material prices [Turner & Townsend, 2013]

Material	**CNY**	**USD** Exchange rate 6.13	**Purchasing power parity in USD**
Concrete 30 MPA per m^3	430	70	129
Reinforcement bar 16 mm per tonne	968	734	1355
Formwork to soffit of slab	90	15	27
Structural steel beams per tonne	8600	1403	2589

Construction labour hourly rates

The labour cost of a construction worker in the Hangzhou area is varying from \$ 4,50 per hour (low range) to \$ 6.00 per hour (high range). These prices indications are suitable because Nanjing is located in the Hangzhou area, but these rates can move significantly up or down at other locations in China. Big differences are seen in the Guanzhou area which is close to Hong Kong and Macao and can be 50 % higher. These costs are low in the remote areas where the rates can be expected as 50 % lower.

The average labour cost for a construction worker in Nanjing is set on \$ 5,00 per hour. This rate includes base wage rate and all related burdens, fringes, statutory payments and contributions, overhead and establishment charges and profit. The labour cost in China is increasing along the years and even faster in the bigger cities; as a result prefabricated structures will become more and more popular in the future, but at this moment intensive design are still preferable.

Next to the hourly labour rate the labour productivity of a Chinese construction worker is important. The followings figures (table 5.8) are found and the value of 2.30 is taken in this thesis research. This means a construction task that took 1000 man-hours to complete in the U.S. would take 2300 man-hours to complete in China.

Table 5.8 Chinese productivity range [Compass International Consultants Inc., 2010]

	Productivity range	
Good	Average	Poor
2.00	2.30	3.00

5.6.6 Conclusions Nanjing airport

Nanjing airport will be heavily extended with 3 runways and the old ATC tower will be replaced with by a new tower with a minimum height of 96 meters and a major ATC capacity. The location of the new tower is on the landside of the airport domain.

The normative lateral loads are both wind and earthquakes. The maximum peak velocity pressure at a height of 96 meters is 2.17 kN/m^2. The local earthquake hazard is moderate with a value of 1.6 m/s^2.

Concrete and steel are the most common structural materials used for high and slender buildings in China. As a result the appearance of concrete core structures, concrete shear walls and steel braced frames are the highest.

The Chinese contractors are highly skilled and possess high tech construction techniques and equipment. “Everything is possible” is the main philosophy.

The average labour cost of a skilled construction worker in the Nanjing Area is \$ 5 dollar per hour and the productivity average is 2.30. This number is very high meaning that Chinese projects and construction workers are inefficient in comparison with American standards.

5.7 Sabiha Gökçen International airport – Turkey

5.7.1 Current situation

Sahiba Gökçen international airport is located approximately 35 km from Istanbul and is one of the two international airports serving the city. The airport has one runway with a length of 3000 meters. Near the red dot the current ATC tower is presented and has got a height of 25 meters. The airport handled in 2013 approximately 18.6 million passengers. The design classification of the current capacity of the ATC tower is determined as low.

Figure 5.14: Sahiba Gökçen ATC towe [panoramio, 2014]

Figure 5.15: Current Sahiba Gökçen airport layout [maps.google.com]

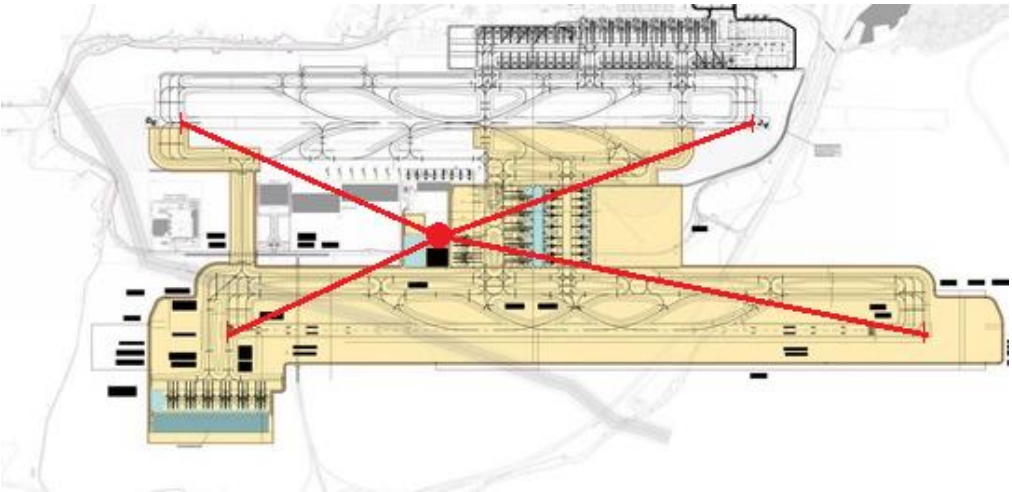


Figure 5.16: Master plan Sahiba Gökçen airport [Arup associates, 2013]

5.7.2 Master plan

By the year of 2023 the airport is planning to handle 25 million passengers per year, an increase of 33 %. In order to be able to handle this increase a master plan is made by Arup. The airport will be provided by an extra runway, located parallel to the existing runway with a length of 3500 m. Next to this, extra terminals and facilities are planned and are presented in figure 5.16.

5.7.3 Tower dimensions

A subdivision of Arup, Arup associates, stated that the master plan should include a new ATC tower with a remarkable height of 115 meters. This height is relatively high, while considering the 2 parallel runways and the “average” size of the airport domain. Probably the design Arup associates can be seen as a prestige project and the beneficial height will be determined by the author and will be used for the research.

The airport layout is presented in figure 5.16 and the ATC tower will be placed near the red dot and is located on the airside of the airport domain.

Tower height

The maximum length between the runway-end and the ATC tower is 2500 meter.

$$\frac{h_{op}}{2500} \geq \tan(1) \tag{5.27}$$

$$h_{op} \geq 2500 \times \tan(1) = 42\, meter \tag{5.28}$$

The total height of the ATC tower is determined by:

$$h_{op} + h_{cab} + h_{sphere} = h_{tower} \tag{5.29}$$

$$42 + 4 + 1 = 47\, meter \tag{5.30}$$

Whereby taken that

$$h_{cab} = 4\, meter \tag{5.31}$$

$$h_{sphere} = 1\, meter \tag{5.32}$$

The ATC tower will be placed in the centre of the airport domain and is not placed next to the current terminal or the future terminal, therefore direct visibility requirements will not be meet for certain parts of active pavement. The height of 42 meters will be increased by 30 meters in order to meet the requirements. The new height of the ATC tower will become 77 meter. The height of the ATC tower is checked on interference with the (misses) approach surfaces and does not comply. The tower must be marked, meaning the tower must be described in the approach handbooks for pilots and sufficient lighting must be placed on the tower.

In order to check whether or not the height of the Arup design is prestige, the following considerations are made. The location of the proposed tower is also placed near the red dot, figure 5.16. It is centrally located on the airport domain, which is preferable to achieve the active pavement requirement, while overlooking all terminals. The sight range with a tower height of 115 meter is 6600 meters, which is 4000 meter more than required. On basis of these considerations it can be assumed that the tower design of Arup is prestige. Furthermore this height will rather lead to a disadvantage for the visibility on closely located active pavement. The visibility will be reduced due to the relative large angle of the line of sight

Control cab size

The new design classification of the ATC tower is determined as intermediate. The airport is extended by one runway and the passenger growth will be increased by 33% in the year 2023. This air traffic will be handled by a minimum of 6 and a maximum of 12 controllers. The minimum required cab area is 32 m^2.

5.7.4 Geographical conditions

Wind climate

The basic wind velocity Vb of the Istanbul area is 27 m/s. This results in a maximum basic velocity pressure qb and peak velocity pressure $qp(h_{tower})$ at the top of the tower with the following values:

$$qb = \frac{1}{2} \times \rho \times Vb^2 = 0{,}46 \frac{kN}{m^2} \tag{5.33}$$

$$qp(h_{tower}) = (1 + 7 \times Iv(h_{tower}) \times qb = 1{,}74 \frac{kN}{m2} \tag{5.34}$$

In appendix VI background information is given for this wind pressure calculation.

Earthquake hazard

The local seismic hazard agr for Sahiba Gökçen airport is 4.8 m/s^2. For the structural design and analysis the Eurocode 1998 will be used instead of the Turkish building code. Due to the same reason as mentioned before; the Eurocode is elaborated in more detail and makes it possible to make good comparisons with other countries and hazards, while using all the same code.

The ground type of Sahiba Gökçen airport area is B. Deposits of very dense sand, gravel, or very stiff clay. In appendix VII background information is given for this earthquake hazard determination.

5.7.5 Turkish construction industry

Information about the Turkish construction industry is gathered by a questionnaire with experts E.B. Kurt and S. Bektaş and is summarized in this section. More information can be found in the interview report.

Construction materials

The most common materials used for tower design with height range 50m – 150m in Turkey are concrete and steel, because of its availability and price. The following 5 materials are ranked in appearance for tower design in Turkey:

1) Concrete
2) Steel
3) Composite concrete/steel
4) Masonry
5) Timber

Nearly, all construction materials are available in Turkey and high strength concrete and steel are also commonly available. Prefabricated concrete elements are not preferred in tower construction. In-situ concrete or steel is generally preferred, since Turkey has a high seismicity hazard and prefabricated structures are believed to be less safe and not requested by owners.

Structural systems

In general, rigid/tube shaped structures and core structures are commonly preferred to overcome seismic effects. The following 5 structural systems are ranked in appearance for tower design in Turkey.

1) Rigid structures
2) Tube structures
3) Core structures
4) Shear wall
5) Braced structures

The common foundation systems for tower design in Turkey are shallow or deep foundations, but are depending on the local geographical conditions.

Knowledge and equipment

The contractors in Turkey do not possess high knowledge and experiences regarding high-tech construction techniques. In general every project is constructed in a traditional way. Contractors follow the intended design and therefore the design should not be too complex.

Prices and cost

Unfortunately Turner and Townsend did not survey the Turkish construction materials, but by using questionnaires and interviews the prices are obtained. To check the correctness and credibility of the given prices the prices are compared with the Russian, Oman, Qatar and United Arab Emirates prices given by Turner and Townsend in order to give a good estimation of the construction prices in this region of the world. Turkish contractors contain the largest market share in these countries. In this case no comparisons can be made on basis of the purchasing power parity figures and therefore Turkey cannot be directly compared with other countries to obtain reliable results.

Table 5.9: Turkish material prices [Kurt, E., Interview rapport]

Material	USD
Concrete 30 MPA per m^3	125
Reinforcement bar 16 mm per tonne	1274
Formwork to soffit of slab	46
Structural steel beams per tonne	1759

Construction labour hourly rates

The labour cost of a skilled construction worker in the Istanbul area is varying from $ 13,25 per hour (low range) to $ 17,50 per hour (high range). The average labour cost for a construction worker in Istanbul is set on $ 15,00 per hour. This rate includes base wage rate and all related burdens, fringes, statutory payments and contributions, overhead and establishment charges and profit.

Next to the hourly labour rate the labour productivity of a Turkish construction worker is important. The followings figures (table 5.10) are found and the value of 1.90 is taken in this thesis research. This means a construction task that took 1000 man-hours to complete in the U.S. would take 1900 man-hours to complete in Turkey.

Table 5.10: Turkish productivity range [Compass International Consultants Inc., 2010]

	Productivity range	
Good	Average	Poor
1.50	1.90	3.00

5.7.6 Conclusions Istanbul airport

Istanbul Sahiba Gökçen airport will be extended with 1 runway and the new ATC tower requires a minimum height of 77 meters with an intermediate ATC capacity and is located on the airside of the airport domain. Reduction of nuisance during construction is preferred.

The normative lateral load is earthquake action. The local earthquake hazard is high with a value of 4.8 m/s^2.

Concrete and steel are the most common structural materials used for high and slender buildings in Turkey. As a result the appearance of concrete rigid frames and steel braced frames are the highest.

“Keep it simple” is the main focus while designing buildings in Turkey. The contractors in Turkey are international orientated, have adequate knowledge and sufficient high tech equipment, but are still some small steps behind the latest construction techniques.

The average labour cost of a skilled construction worker in Turkey is $ 15 dollar per hour and the productivity average is 1.90. This number is high meaning that Turkish projects and construction workers are inefficient in comparison with American standards.

5.8 Soekarno – Hatta international airport – Indonesia

5.8.1 Current situation

Soekarno - Hatta international airport is located near Jakarta and is the main airport serving the greater Jakarta area on the island of Java. The airport has two runways both with a length of 3600 meters. Near the red dot the current ATC tower is presented and has got a height of 50 meters. The airport handles approximately 370.000 air traffic movements per year and the annual passenger's number for Jakarta airport for 2013 was 57.8 million. The design classification of the current capacity of the ATC tower is determined as major.

Figure 5.17: Current Soekarno – Hatta airport layout [maps.google.com]

Figure 5.18: Soekarno - Hatta [panoramio, 2014]

Figure 5.19: Master plan Soekarno – Hatta airport [abut airport planner, 2012]

5.8.2 Master plan

The airport is expecting an air traffic growth in the upcoming decades of 70 %. At this moment terminal 3 is under construction, which will be followed by the construction of the third runway and terminal 4 resulting in total airport capacity of 625.000 air movements per year. The master plan is presented in figure 5.19.

5.8.3 Tower dimensions

Tower height

The maximum length between the runway-end and the ATC tower is 4000 meter.

$$\frac{h_{op}}{4000} \geq \tan(1) \tag{5.35}$$

$$h_{op} \geq 4000 \times \tan(1) = 70\,meter \tag{5.36}$$

The total height of the ATC tower is determined by:

$$h_{op} + h_{cab} + h_{sphere} = h_{tower} \tag{5.37}$$

$$70 + 4 + 1 = 75\,meter \tag{5.38}$$

Whereby taken that

$$h_{cab} = 4\,meter \tag{5.39}$$

$$h_{sphere} = 1\,meter \tag{5.40}$$

The ATC tower will be placed in the centre of the airport domain and is not placed next to the current terminal or the future terminal, therefore direct visibility requirements will not be meet for certain parts of active pavement. The height of 75 meters will be increased by 40 meters in order to meet the requirements. The new height of the ATC tower will become 115 meter. The height of the ATC tower is checked on interference with the (misses) approach surfaces and does not comply. The tower must be marked, meaning the tower must be described in the approach handbooks for pilots and sufficient lighting must be placed on the tower.

Control cab size

The new design classification of the ATC tower is determined as major. The airport is extended by one runway and the air traffic capacity is increased by 70 %. This air traffic will be handled by a minimum of 12 controllers. The minimum required cab area is 50 m^2.

Wind climate

The basic wind velocity Vb of the Jakarta area is 23,33 m/s. This results in a maximum basic velocity pressure qb and peak velocity pressure $qp(h_{tower})$ at the top of the tower with the following values:

$$qb = \frac{1}{2} \times \rho \times Vb^2 = 0{,}33 \frac{kN}{m^2} \tag{5.41}$$

$$qp(h_{tower}) = (1 + 7 \times Iv(h_{tower}) \times qb = 1{,}35 \frac{kN}{m2} \tag{5.42}$$

In appendix VI background information is given for this wind pressure calculation.

Earthquake hazard

The local seismic hazard agr for Jakarta airport is 4.0 m/s^2. For the structural design and analysis the Eurocode 1998 will be used instead of the Indonesian building code. Due to the same reason as mentioned before; the Eurocode is elaborated in more detail and makes it possible to make good comparisons with other countries and hazards, while using all the same code.

The ground type of Jakarta airport area is C. Deposits of dense or medium-dense sand, gravel, or very stiff clay. In appendix VII background information is given for this earthquake hazard determination.

5.8.4 Indonesian construction industry

Information about the Indonesian construction industry is gathered by interviews and questionnaires with experts I. Woudenberg and S. Tano and is summarized in this section. More information can be found in the interview report.

Construction materials

Generally, concrete structures are the most common used construction materials in Indonesia to construct tall buildings. Steel structures are used for industrial facilities and masonry structures are used for the typical residential housing, which are both low-rise structures. The following 5 materials are ranked in appearance for tower design in Indonesia.

1) Concrete
2) Steel
3) Composite
4) Masonry
5) Timber

All materials are available in Indonesia. High strength concrete is mainly used in the infrastructure industry in order to construct bridges and fly-overs. Recently, prefabricated structures are introduced and are mostly used in the infrastructure. In the high rise tower design prefabricated elements are rarely used, since conventional systems are still preferable to minimize the cost.

Structural systems

As mentioned, concrete is the most common used construction material in Indonesia, resulting that rigid frame and shear walls are also the most common structural systems in order to provide stability against the lateral forces. Also a combination of these two systems occurs, which is called a dual system. Recently also core – outrigger systems are used in high-rise structures.

The earthquake force is the major lateral force to be considered in every high-rise structure. For large buildings in Indonesia wind tunnel modelling must be used to consider the wind load.

The following 5 structural systems are ranked in appearance for tower design in Indonesia.

1) Rigid frame
2) Shear wall
3) Core
4) (Eccentrically) braced frame
5) Tube structure

Note: concentric braced frames (CBF) are not very common in tower design, but eccentrically braced frames are. These frames contain bracings, but in between there is a small beam or column part designed, with can act as a plastic hinge in case of an earthquake.

In the Jakarta area, deep foundations using bored piles or diaphragm wall are the most common foundation systems, but also shallow foundation are sometimes used, if the geotechnical conditions are good.

Knowledge and equipment

In Indonesia there are two kinds of contractor firms.

Large professional contractors, these are often side branches from Korean / Japanese / Australian contractors containing much knowledge and high tech equipment and are mostly involved in the largest projects, such as ATC towers. They have knowledge regarding pretension and post-tension, but slip forming is a technique that is not often used in Indonesia

Local contractors often are deployed for smaller projects. For these projects the designs are kept simple, because of the lower knowledge level of the contractor and available equipment.

Prices and cost

Unfortunately Turner and Townsend did not survey the Indonesia construction materials, but by using questionnaires and interviews the prices are obtained. To check the correctness and credibility of the given prices (given by 2 Royal HaskoningDHV employees) the prices are compared with the Malaysian, Vietnamese and Singaporean prices given by Turner and Townsend in order to give a good estimation of the construction prices in this region of the world. In this case no comparison can be made on basis of the purchasing power parity figures and therefore Indonesia cannot be directly compared with other countries to obtain reliable results.

Table 5.11: Indonesian material prices [Woudenberg, I. Interview rapport]

Material	USD
Concrete 30 MPA per m^3	90
Reinforcement bar 16 mm per tonne	1081
Formwork to soffit of slab	20
Structural steel beams per tonne	1531

Construction labour hourly rates

The labour cost of a skilled construction worker in the Jakarta area is varying from $ 5,05 per hour (low range) to $ 7.20 per hour (high range). The average labour cost for a construction worker in Jakarta is set on $ 6,00 per hour. This rate includes base wage rate and all related burdens, fringes, statutory payments and contributions, overhead and establishment charges and profit.

Next to the hourly labour rate the labour productivity of an Indonesian construction worker is important. The followings figures (table 5.12) are found and the value of 2.80 is taken in this thesis research. This means a construction task that took 1000 man-hours to complete in the U.S. would take 2800 man-hours to complete in Indonesia.

Table 5.12: Indonesian productivity range [Compass International Consultants Inc., 2010]

	Productivity range	
Good	Average	Poor
2.50	2.80	3.20

5.8.5 Conclusions Jakarta airport

Jakarta airport will be extended with 1 runway and the new ATC tower requires a minimum height of 115 meters with a major capacity and is located on the airside of the airport domain

The normative lateral loads are wind and earthquakes. The maximum peak velocity pressure at a height of 115 meters is 1,35 kN/m^2. The local earthquake hazard is intermediate with a value of 4,0 m/s^2.

Concrete is the most common structural material used for high and slender buildings, subsequently followed by steel. For building design in general rigid frames and shears walls are applied, whereas for high rise structures concrete core structures are used.

The Indonesian contractors, often side branches of international contractors, are intermediate to highly skilled and possess high tech construction techniques and equipment. In general "Everything is possible" is the main philosophy.

The average labour cost of a skilled construction worker in Jakarta is $ 6 dollar per hour and the productivity average is 2.90. This number is very high meaning that Indonesian projects and construction workers are inefficient in comparison with American standards.

5.9 Summary airports

To summarize this chapter, all the findings of each airport are listed side by side in an overview, presented below in table 5.13. This allows making quick comparisons between the airports, countries and construction industries. The most striking comparisons are described in more detail.

Table 5.13: Overview boundary conditions 6 countries

Boundary condition	Property	Unit	Lelystad	Abuja	Tokyo	Nanjing	Istanbul	Jakarta
Current situation	Amount of runways	-	1	1	2	1	1	2
	Length	m	1250	3600	2500 4000	3600	3000	3600 3600
	Tower height	m	7	50	86	50	25	50
	Passengers	per year	0	6.200.000	31.400.000	15.000.000	18.600.000	57.800.000
	Movement	per year	0	60.500	190.000	135.000	133.000	370.000
	Tower capacity	-	Low	Low	Major	Intermediate	Low	Major
Master plan	Amount of runways	-	1	2	3	4	2	3
	Length	-	2700	3600 3600	2500 3200 4000	4 x 3600	3000 3500	3 x 3600
	Tower height	m	47	58	86	96	79	115
	Passengers	per year	6.700.000	7.500.000	50.240.000	70.000.000	25.000.000	98.260.000
	Movements	per year	45.000	72.600	300.000	630.000	180.000	625.000
	Tower capacity	-	Low	Intermediate	Major	Major	Intermediate	Major
	Tower location	-	Landside	Airside	Landside	Landside	Airside	Landside
Tower dimensions	Tower height	m	47	58	86	96	77	115
	Minimum cab size dimension	m^2	21	32	50	50	32	50
Wind load	Basic wind speed	m/s	27	40	38	30	27	23,33
	Peak velocity pressure	kN/m^2	1,56	3,61	3,42	2,17	1,74	1,35
Earthquake load	Hazard	m/s^2	0,4	0,2	9,8	1,6	4,8	4,0
	Ground type	-	-	-	C	C	B	C
Construction materials	Availability materials	Local fabricated	Yes, all materials	No only concrete, others imported	Yes, all materials	Yes, all materials	Yes, all materials	Yes, all materials
	Rank of appearance in tower design 50m – 150m	1	Concrete	Concrete	Steel	Concrete	Concrete	Concrete
		2	Steel	Masonry	Composite concrete /steel	Steel	Steel	Steel
		3	Composite concrete/ steel	Steel	Concrete	Composite concrete/ steel	Composite concrete/ steel	Composite concrete/steel
		4	Masonry	Timber	Timber	Timber and masonry	-	Masonry
		5	Timber	Composite concrete/ steel	Masonry	-	-	Timber
	Prefabrication	Often applied	Yes, high experienced	No, sometimes pre-engineering modular buildings from abroad	No	No, only infrastructure	No	No, only infrastructure

Boundary condition	Property	Unit	Lelystad	Abuja	Tokyo	Nanjing	Istanbul	Jakarta
Structural system	Normative load action	-	Wind	Wind	Earthquake	Wind and Earthquake	Earthquake	Earthquake and wind
	Rank of appearance in tower design 50m – 150m	1	Core structure	Rigid frames	Rigid frames	Core structures	Rigid frame / tube structures	Rigid frames
		2	Shear walls	Braced frames	Braced frames	Shear walls	Core structures	Shear walls
		3	Tube structures	Core structures	Core structures	Braced frames	Shear walls	Core structures
		4	Braced frames	Tube structures	Shear walls	Rigid frames	-	(Eccentrically) Braced frames
		5	Rigid frames	Shear walls	Tube structures	-	-	Tube structures
	Foundation	Often applied	Deep foundation with pilling	Shallow foundation or bored piles	Deep foundation with pilling	Deep foundation with pilling	Shallow and deep foundations	Deep foundations with bored piles or diaphragm walls
Knowledge and equipment	Contractors knowledge	Capacity	High	Low	High	High	Intermediate	Intermediate / high
	High tech techniques	Availability	Yes	No	Yes	Yes	No	Intermediate
	Philosophy	-	Everything is possible	Keep it very simple	Everything is possible	Everything is possible	Keep it simple	Everything is possible
Prices and costs	Labour hourly rates	USD	53	3	47	5	15	6
	Productivity range	-	1.15	2.25	1.20	2.30	1.90	2.80
	Concrete 30 MPa per m^3	USD	125	214	122	70	125	90
		Purchasing power parity	158	*dna*	172	129	dna	dna
	Reinforcement per tonne	USD	1274	1382	674	734	1274	1081
		Purchasing power parity	1614	*dna*	956	1355	*dna*	*dna*
	Formwork	USD	46	15	27	15	46	20
		Purchasing power parity	58	*dna*	39	17	*dna*	*dna*
	Structural steel beams per tonne	USD	1759	3808	817	1403	1759	1531
		Purchasing power parity	2229	*dna*	1159	2589	dna	dna

The lowest tower investigated in this thesis research is 47 meter and the highest 112 meter, forming a sufficient scatter in order to investigate the height regarding the structural design characteristics. The height of the tower is (in general) directly related with the size of the airport. The more runways an airport contains, the larger the airport domain and the higher the tower in order to overview the entire active pavement, as noticed in table 5.13. Next, larger airports require in general more air traffic control, resulting also in larger control cabs.

Near Abuja and Tokyo the highest basic wind speeds are measured. Whereas the basic wind speeds near Lelystad, Istanbul and Nanjing have approximately the same value of 27 m/s. The lowest basic wind speed occurs near Jakarta. The peak velocity pressures, related with the height, are proportional to the basic wind speed for each design. In figure 5.20 the wind figures are once more displayed.

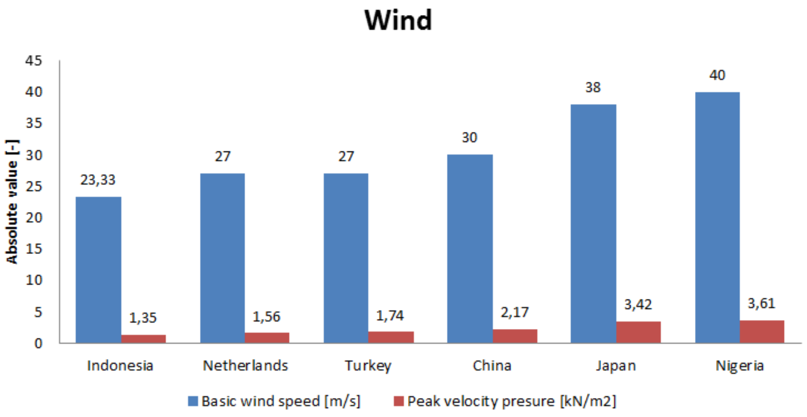


Figure 5.20: Wind parameters

Mentioned in chapter 2 and from the wind engineering consultant [Graaf, S., Interview report], the wind force on a structure is predominantly determined by the peak velocity pressure and the shape factor. As a result the contribution of the shape factor becomes also more decisive for designs with a high peak velocity pressure.

For Lelystad and Abuja airport the earthquake loading can be neglected. For Tokyo the highest earthquake hazard is determined with a value of 9.8 m/s^2. Followed by Istanbul and Jakarta with respectively the same hazard. Near Nanjing the lowest (apart from Lelystad and Abuja) hazard is determined with a value of 1.6 m/s^2.

The most common used construction material for high and slender tower design is concrete. In 5 of the 6 countries this is the case. In these countries steel is the second applied material. Only in Japan steel is more applied than concrete. These results are obtained by conducting questionnaires and interviews with experts from Royal HaskoningDHV around the globe. Therefore the nature of this information and the rank of appearance are subjective. However by taking an overall view it can be concluded concrete and steel are the only two major applied construction materials in high and tall building design.

Only in the Netherlands prefabrication of concrete structures is highly used in the building industry. In China and Indonesia prefabrication is only applied in the infrastructure where in the other remaining countries only in-situ concrete is used.

The appearances of structural systems are randomly divided over the six countries. These results are also obtained by conducting questionnaires and interviews with experts from Royal HaskoningDHV around the globe making them subjective. In addition a different terminology of structural systems is noticed during the investigation, making the results even more unreliable. Therefore the information gathered about the appearances of the structural systems is not taken into account in the further research.

“Everything is possible” is the design philosophy in the Netherlands, China, Japan and Indonesia, because the local (international) contractors do possess a high construction knowledge level and equipment. In Nigeria this is totally different, whereas everything must be kept as simple as possible.

The height of labour cost of an average construction worker varies considerably per country. Whereas in countries like the Netherlands and Japan the hourly labour rates are around $ 50, the figures are very low in Nigeria, China and Indonesia, as displayed in figure 5.21.

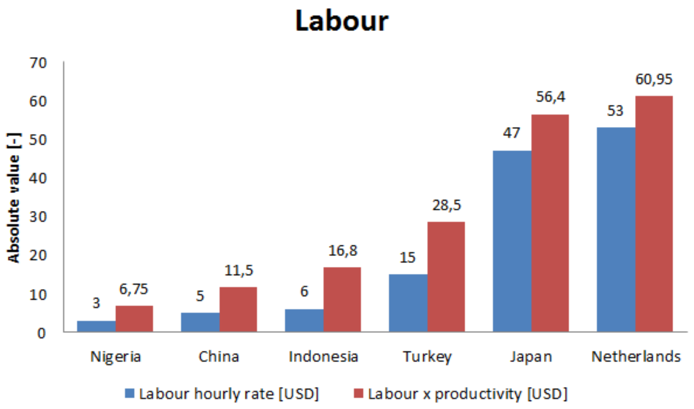


Figure 5.21: Labour figures

The productivity factors are used in order to compare national labour costs with each other. The figures in red represents labour x productivity. It can be seen that a Dutch construction worker is 9x more expensive as an Nigerian construction worker. Other comparisons regarding the Dutch labour cost are presented in table 5.14 in order to have an feeling of the differences.

Table 5.14: Labour comparisons

Country	Factor
Netherlands	1,0
Japan	1,08
Turkey	2,14
Indonesia	3,63
China	5,3
Nigeria	9,03

Below, in figure 5.22 until 5.25, the global construction cost are determined for concrete, structural steel, reinforcement and formwork, expressed in the purchasing power parity allowing to make reliable comparisons. The world average (blue column) is calculated on basis of 23 countries presented by Turner and Townsend. Using this number as global stardard makes it possible to determine whether or not a material in a certain country is cheap (displayed in green) or expensive (displayed in red) in a global understanding.

For Nigeria, Turkey and Indonesia no purchasing power parity figures are known and are replaced by figures of simular countries, respectively Uganda, Russia and Malaysia. The purpose is to make also for these countries rough estimatons in a global perspective. Rough estimations are justified because these countries do have similar livings standards, construction material prices and are close geographically positioned to each other.

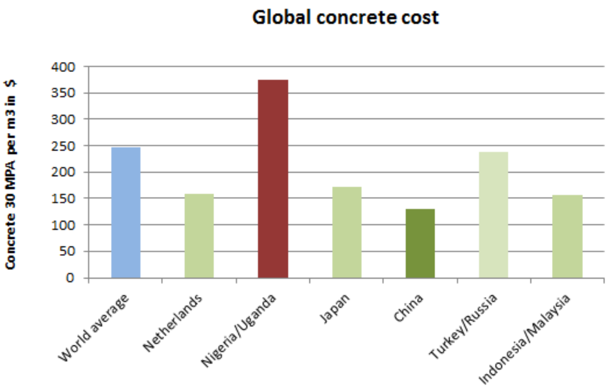


Figure 5.22: Global concrete cost

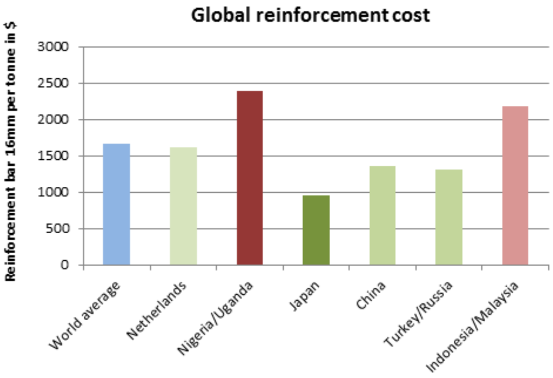


Figure 5.23: Global reinforcement cost

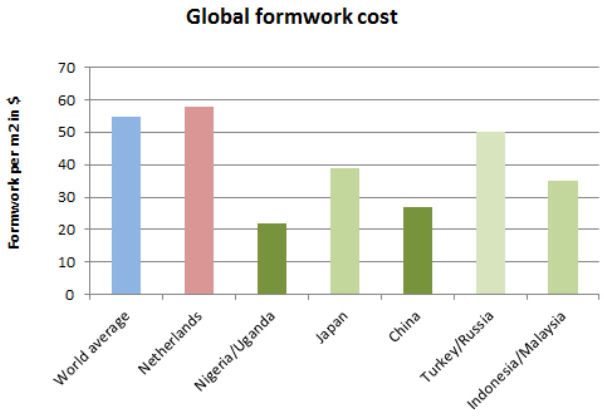


Figure 5.23: Global reinforcement cost

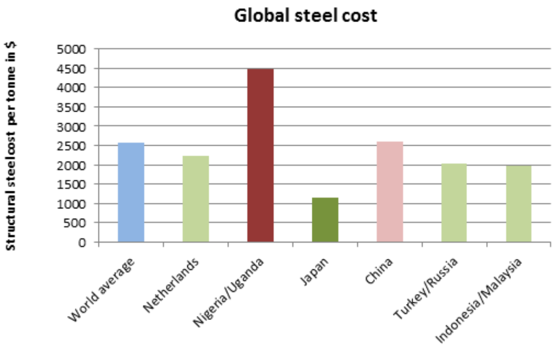


Figure 5.24: Global formwork cost

5.10 Conclusions

The key-question *"What are the local boundary conditions of the six chosen countries"* is elaborated in this chapter and is answered with the summary table in 5.13 (section 5.9) and the following conclusions.

Larger airport domains, which are mainly directly related on the amount of runways, require higher ATC towers. Subsequently higher ATC capacities are required, resulting in larger control cabs.

In Japan and Nigeria the largest wind speeds are measured. For these countries more emphasis should be placed on the aerodynamic characteristics of the towers.

For Lelystad and Abuja airport earthquake loading can be neglected, whereas for Tokyo the highest hazard is followed by Istanbul, Jakarta and Nanjing. For these four countries more emphasis should be placed on the tower's characteristics to reduce the earthquake load.

Several similarities and differences can be determined regarding wind and earthquake loads.

- Japan and Nigeria have the same basic wind speed (approx. 40 m/s), but a total different earthquake hazard
- Indonesia and Turkey have the same earthquake hazard (approx. 4,0 m/s^2) but a small difference in basic wind load
- The Netherlands, Turkey and China have the same wind load (approx. 28 m/s), but a total different earthquake hazard

The most common used construction material for high and slender tower design in these countries is concrete, followed by steel. Only in Japan steel is more applied than concrete.

Prefabrication of concrete in the building industry is only used in the Netherlands.

For countries with high material cost the focus is placed to minimize material demand whereas for countries with high labour cost the focus is placed to optimize man-hour demand and productivity.

- In Japan and the Netherlands the material cost are (relatively) cheap and the labour cost very high, therefore the focus must be placed on minimizing labour.
- In the Netherlands only formwork is slightly more expensive in relation with the world average, therefore reduce the amount and complexity of formwork.
- In Japan it is preferable to build steel structures. First steel is very cheap and secondly steel structures contain good properties regarding earthquake loading.
- In China it is preferable to build concrete structures. Concrete is cheap and steel relative expensive in relation with the world average steel prices.
- In Nigeria the material cost is very high, except for formwork, and the labour cost very low, therefore the focus must be placed on reducing material demand by applying labour intensive solutions.
- In Indonesia and China the material cost are (relatively) cheap and the labour cost low. In these countries it is possible to place more focus on different construction aspects, such as innovation and safety.

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6 Synthesis concept designs

6.1 Introduction

After the preceding analysis, in this chapter several concept designs are developed with the aim to achieve satisfied results regarding optimal structural design versus the local boundary conditions. Per country an “x” number of designs are developed, which are subsequently modelled in chapter 7, but first the synthesis approach is clarified in the next section.

6.2 Synthesis approach

After a diverge process, elaborated in chapter 4 and 5, wherein all the necessary information is gathered in order to design an ATC tower, the point comes where the process will be turned around into a converge process (displayed as the dotted line in figure 6.1). Choices are made to converge the solution range in order to achieve targeted optimal economical design solutions.

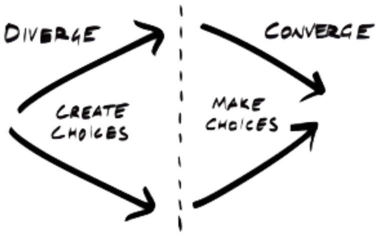


Figure 6.1: Diverge / converge process
[Lensink, B., bartlensink.nl]

This converge process is realized on basis of three main aspects; structural optimum solutions, labour optimum solutions and material optimum solutions.

Structural optimum solutions: These are design (typology) solutions based on the local structural characteristics in order to achieve an economical optimal design.

Labour optimum solutions: These are *construction (execution*) solutions based on the local labour aspects in order to achieve an economical optimal design.

Material optimum solutions: These are design (characteristic) solutions based on the local material aspects in order to achieve an economical optimal design.

These three aspects; structural, labour and material, are chosen because these are seen as the most important, independently and influential aspects in the preparation of a design. As a result the solutions of the three main aspects are of a different type. Time (construction speed) could be implemented as the fourth aspect. Time will be disregarded as a main aspect in order to reduce the complexity, but time is coherent with labour and material and will be included within these two aspects.

Per aspect, variables are drafted by the author and these form the input of the converge process. These input variables are directly related with the boundary conditions for ATC tower design discussed in chapter 4 and determined in chapter 5 for the chosen countries.

The specified variables for the structural optimum solutions aspect are:

- Structural height
- Wind load
- Earthquake hazard

The specified variables for the labour optimum solutions aspect are:

- Labour cost
- Contractors knowledge
- Availability equipment

The specified variables for the aspect, material optimum solutions, are:

- Material cost
- Availability material
- Experiences

After each variable is determined the next step is to follow a “passage”. This passage is a systematic method which starts by filling in the input variables. Along the passage a certain strategy is chosen that gives design directions to acquire optimal design solutions, resulting in several outputs. In figure 6.2 the passage method is displayed.

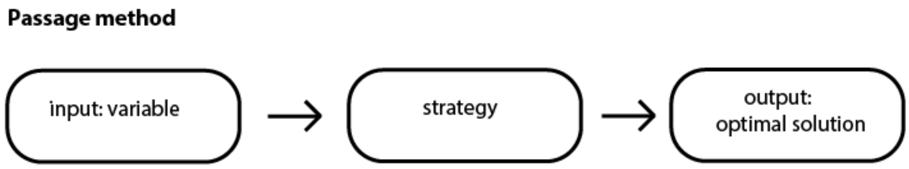


Figure 6.2: Passage method

This converge process is graphically displayed in figure 6.3 and explained in more detail. This figure contains three circles, each representing one main aspect. For each aspect the input variables are written, which subsequently results in optimal design solutions, as mentioned before. These solutions are placed within their own circle. As a result, if two circles are overlapping, in that case for both aspects the same (related) optimal solution is found, forming a sub-optimal solution.

The aim is to produce optimal solutions that will overlap all three circles, making these solutions the most suitable concept designs to investigate. For some countries, also sub-optimal solutions are elaborated in more detail. These additional concepts are considered by the author as almost equally to optimal and therefore interesting to investigate, with the advantage to gain more results.

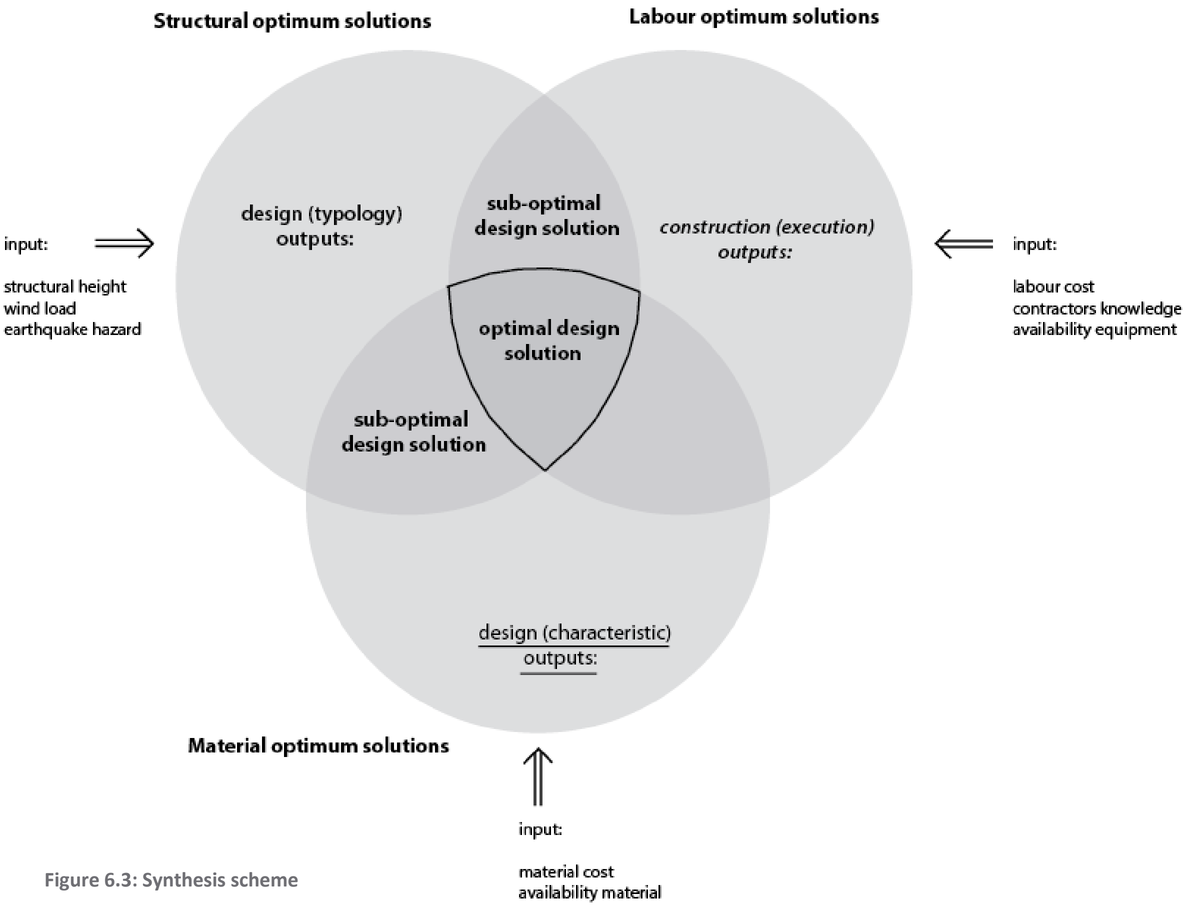


Figure 6.3: Synthesis scheme

In the next sections the passages from the input "variables" to the output "optimal solutions" are displayed per aspect following their own strategy. These passages are prepared on basis of the preceding chapters with their conclusions, which makes them realible. Therefore the outputs are seen as the most likely optimal solutions for each variable. This method is suitable to add more variables and/or strategies in order to gain more outputs, when necessary. For example; steel core structures do exist, but are not optimal for ATC towers design and are therefore disregarded.

6.2.1 Structural aspects

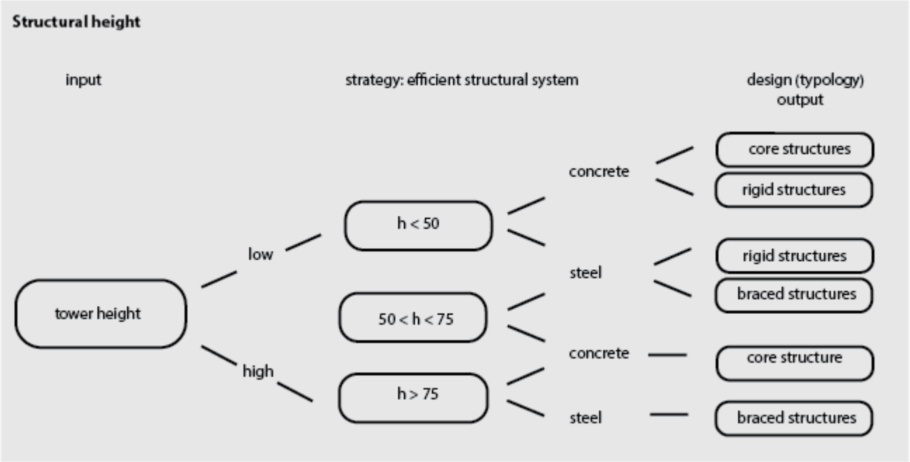


Figure 6.4: Passage structural height

The height passage starts by filling in the required ATC tower height. The strategy is to achieve an efficient load bearing system. The height is divided into three ranges, based on the load bearing structures figures of Hoenderkamp in chapter 2.2. However, the values of the three ranges are scaled down by 25%. This reduction has been done, because in reality the structural section of an ATC tower's load bearing structure, or its slenderness, is significantly smaller than the load bearing sections in Hoenderkamp's classifications. Assuming that the larger the structural section, the larger the moment of inertia and the stiffer the building resulting in higher optimal heights.

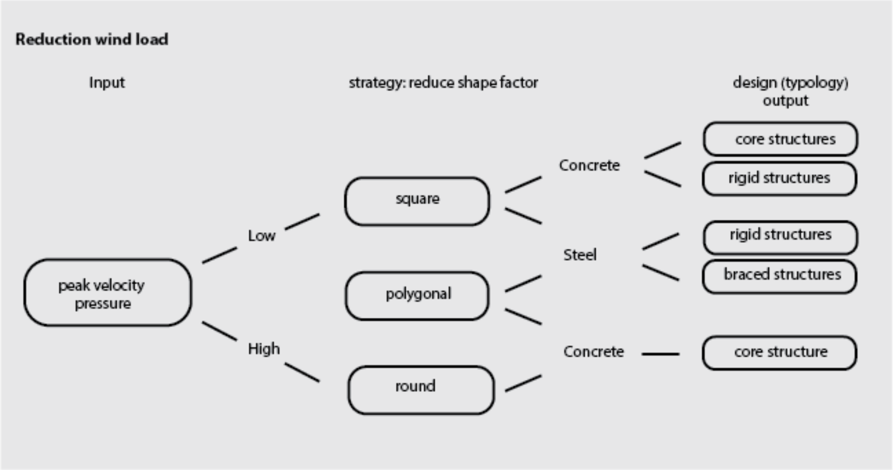


Figure 6.5: Passage reduction wind load

The wind force on a structure is predominantly determined by the peak velocity pressure and the shape factor. As a result the contribution of the shape factor becomes also more decisive for designs with a high peak velocity pressure and the strategy is to reduce the shape factor. To reduce the wind force, aerodynamically shapes are more preferable resulting in polygonal or round solutions.

In the next passage the local earthquake hazard is taken into account. In countries with very low earthquakes hazards this passage can be "neglected" and no additional measures are needed to take into account. The strategy of this passage is to minimize the (internal) earthquake load by applying three methods; ductility, damping and reducing mass. The applied method is highly depended on the (first) natural period of the structure.

The behaviour factor "q" is an approximation of the ductile behaviour of the structure. The factor is used to reduce forces obtained from a linear analysis in order to account for the non-linear response of a structure associated with the materials, the structural system and the design procedures. The larger the behaviour factor the more ductile the structure and the larger the capacity of the structure to dissipate energy. Structures are classified into three categories; low, medium and high dissipative structures. In this thesis research the emphasis is placed on high dissipative structures only. These figures and background information about this subject are elaborated in the literature report section 3.3.4 page 76.

Base isolation is a passive damping system, placed between the building and its foundation, which is very suitable for earthquake action. The main effect (purpose) of base isolation is the relocation of the building vibration period on the elastic response spectra, from the unfavourable part, 0 to 1 second to the more favourable part, 1 to 2 seconds.

The most efficient method is by reducing the entire building mass, especially at higher altitudes.

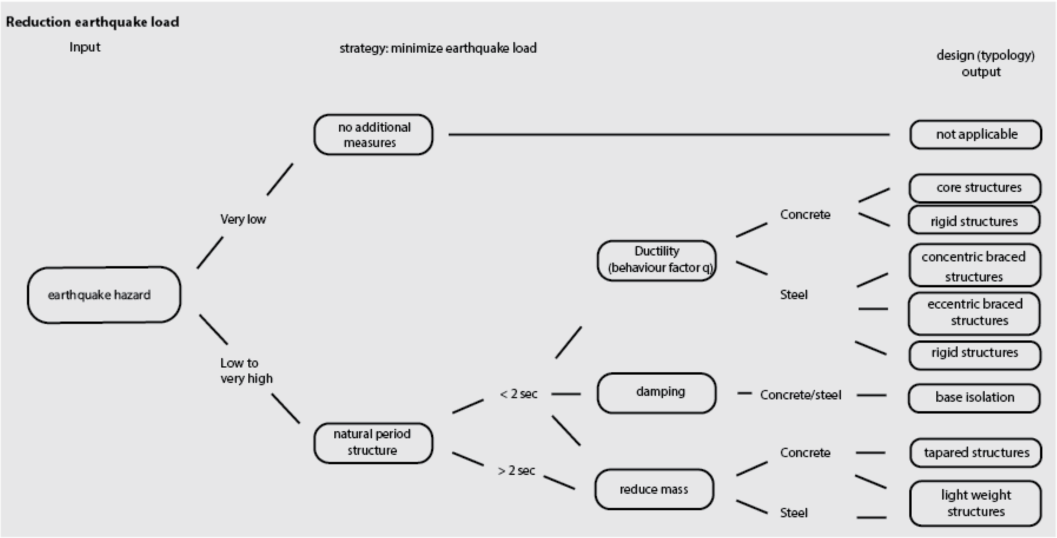


Figure 6.6: Passage reduction earthquake load

6.2.2 Labour aspects

The labour cost in this thesis research is determined by multiplying the hourly rate with the labour productivity. The strategy is to use the labour in an efficient manner, to minimize the total cost of the concept. When the labour cost is low, the focus must be placed on reducing materials with the use of more labour. This is the other way around when the labour cost is high, the focus must be placed on minimize labour and increasing the building speed by optimizing materials. Several construction solutions are written by the author below.

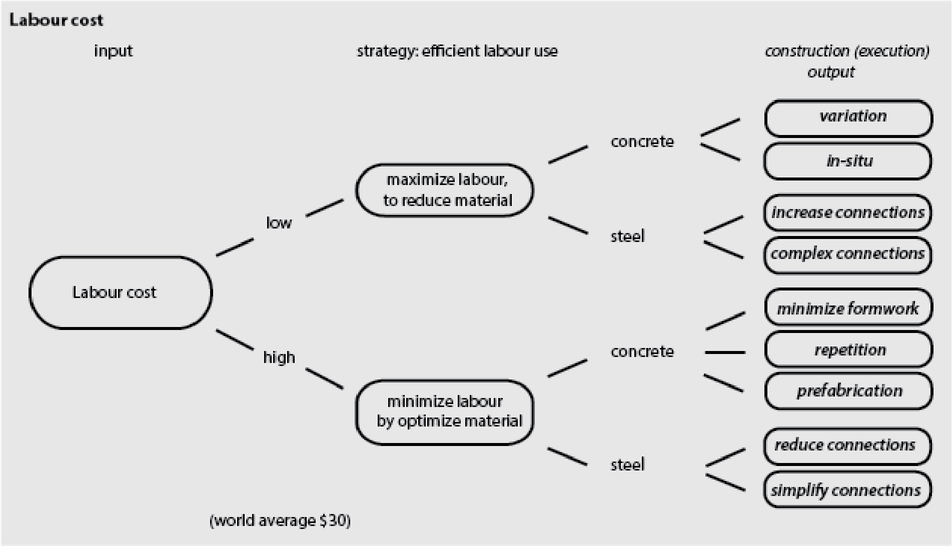


Figure 6.7: Passage labour cost

When designing an ATC tower it is of major importance to know what kind of contractor is selected and what their abilities are. The strategy is to maximize local construction possibilities to construct the concept in an efficient manner. The knowledge can vary from highly skilled contractors with high educated workers and possibilities of equipment to low skilled contractors with construction workers recruited from the streets, without any structural background. Two philosophies are mentioned in this passage; “everything is possible” and “keep it simple” and several construction solutions per philosophy are written by the author.

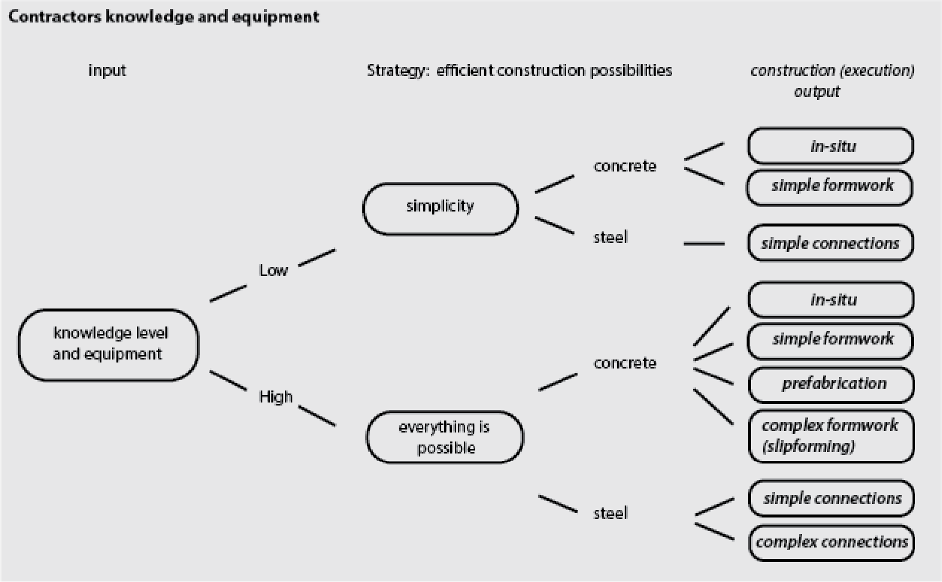


Figure 6.8: Passage contractor’s knowledge and equipment

6.2.3 Material aspects

First the availability of the material is determined, because the designer must know whether or not the foreseen construction materials are available. Most likely in every country concrete and steel is available, but the quality can vary significantly. The strategy is to choose the most efficient local construction material. The materials form the input of this passage, which can be produced locally or otherwise imported from abroad. If the material is limited available certain restrictions can occur, whereby the preference should be to minimize this material.
The “material passage” has another scheme structure as the structural and labour aspects. Whereas in the preceding aspects, concrete and steel were components of the passage, now the materials are the direct object of the scheme, this also counts for the “material cost passages” elaborated on the next page.

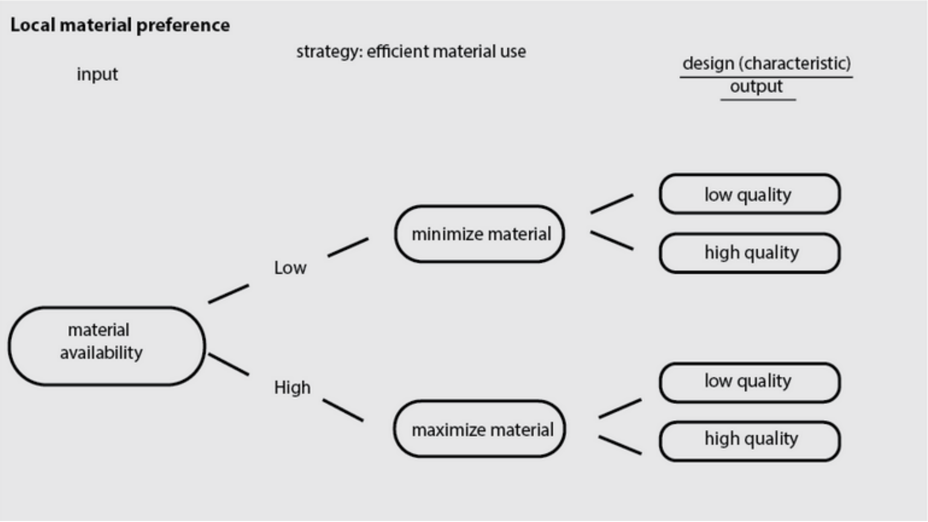


Figure 6.9: Passage local material preference

In the last passage the construction material prices are taken into account and these prices are highly related with the locally availability. The strategy is to use the material in an efficient manner, to minimize the total cost of the concept. The local prices are compared with the world average price for a certain material. This makes it possible to determine whether or not the price is low or high in a global perspective. When a material price is low, maximizing the specified construction material in order e.g. to reduce labour or other materials is preferable. Also in case the material price is high, minimizing the material by optimizing the design will be the main focus. Below the passages are divided for both construction materials, steel and concrete.

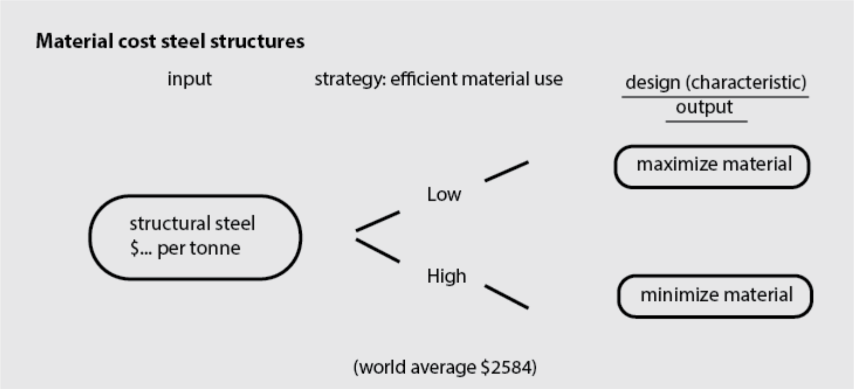


Figure 6.10: Passage material cost steel structures

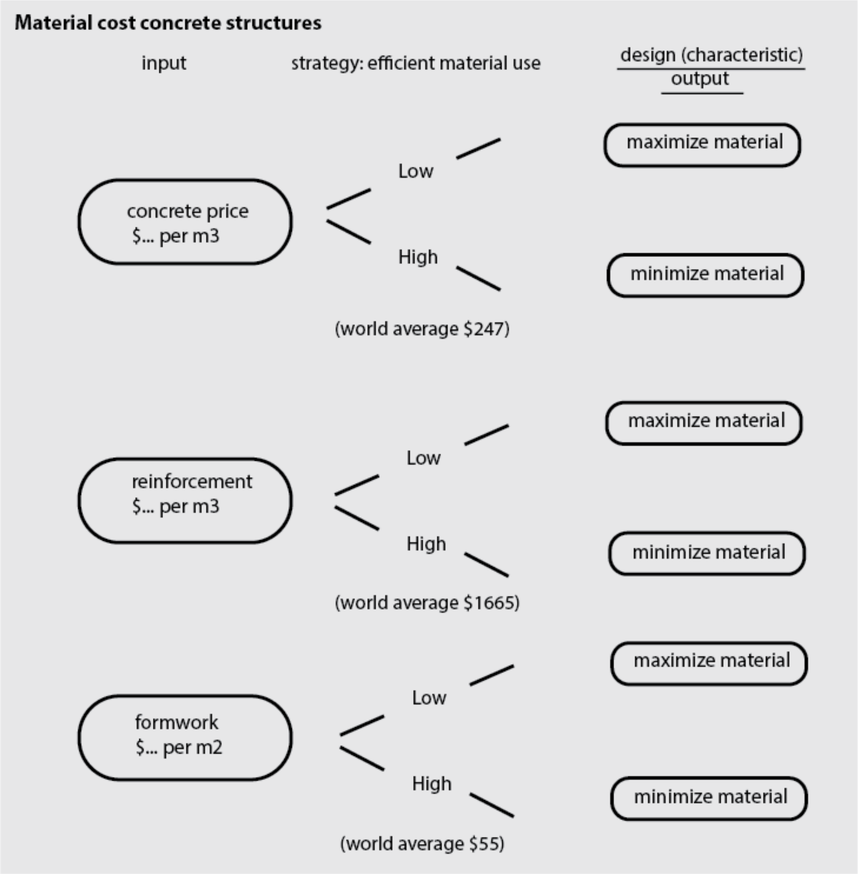


Figure 6.11: Passage material cost concrete structures

6.3 Lelystad airport – Netherlands

The main focus points for the Dutch design are:

- Low wind load, no aerodynamically preferences
- Very low earthquake load, no earthquake engineering aspects
- High labour cost, optimize material to reduce labour
- High experienced on concrete design, prefabrication
- High knowledge level contractors, everything is possible

As a result, displayed and numbered sequentially in figure 6.12, the following two solutions are concluded (based on of the passage method appendix VIII) to be the most likely optimal solutions:

- Square concrete core in-situ
- Square concrete core prefab

In chapter 7 these two solutions will be elaborated in more detail with a conceptual design as the final result. Afterwards these designs can be compared, whereby the emphasis is placed on the role of in-situ versus prefabrication.

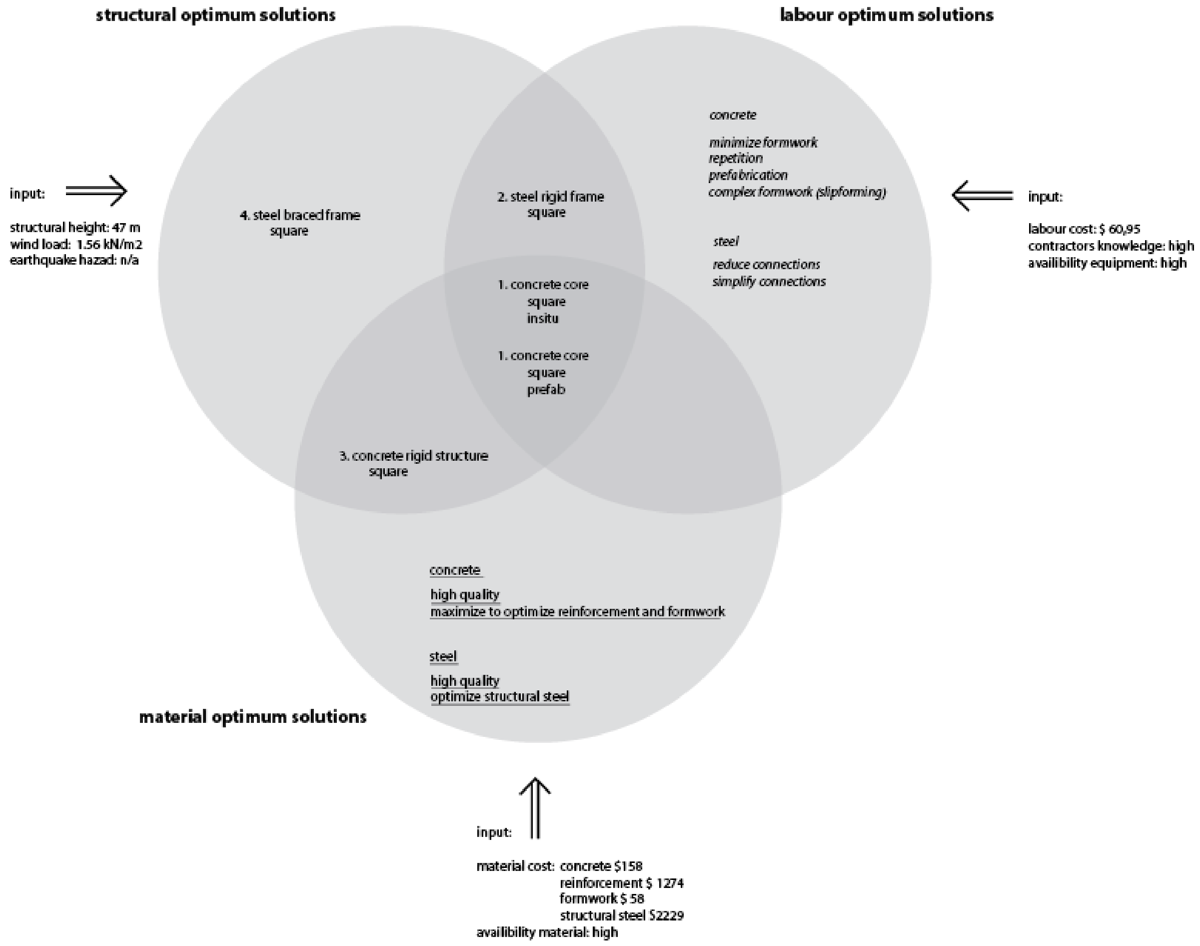


Figure 6.12: Synthesis Lelystad airport

6.4 Abuja Airport – Nigeria

The main focus points for the Nigeria design are:

- High wind load, aerodynamically preferences
- Very low earthquake load, no earthquake engineering aspects
- Low labour cost, optimize labour to reduce material
- High material cost, optimize labour to reduce material
- Low knowledge level contractors, keep it very simple

As a result, displayed and numbered sequentially in figure 6.13, the following solution is concluded (based on of the passage method appendix VIII) to be the most likely optimal solution:

- Round concrete core insitu, tapered

In chapter 7 this solution will be elaborated in more detail with a conceptual design as the final result. Afterwards this design can be compared with other countries with comparable boundary conditions.

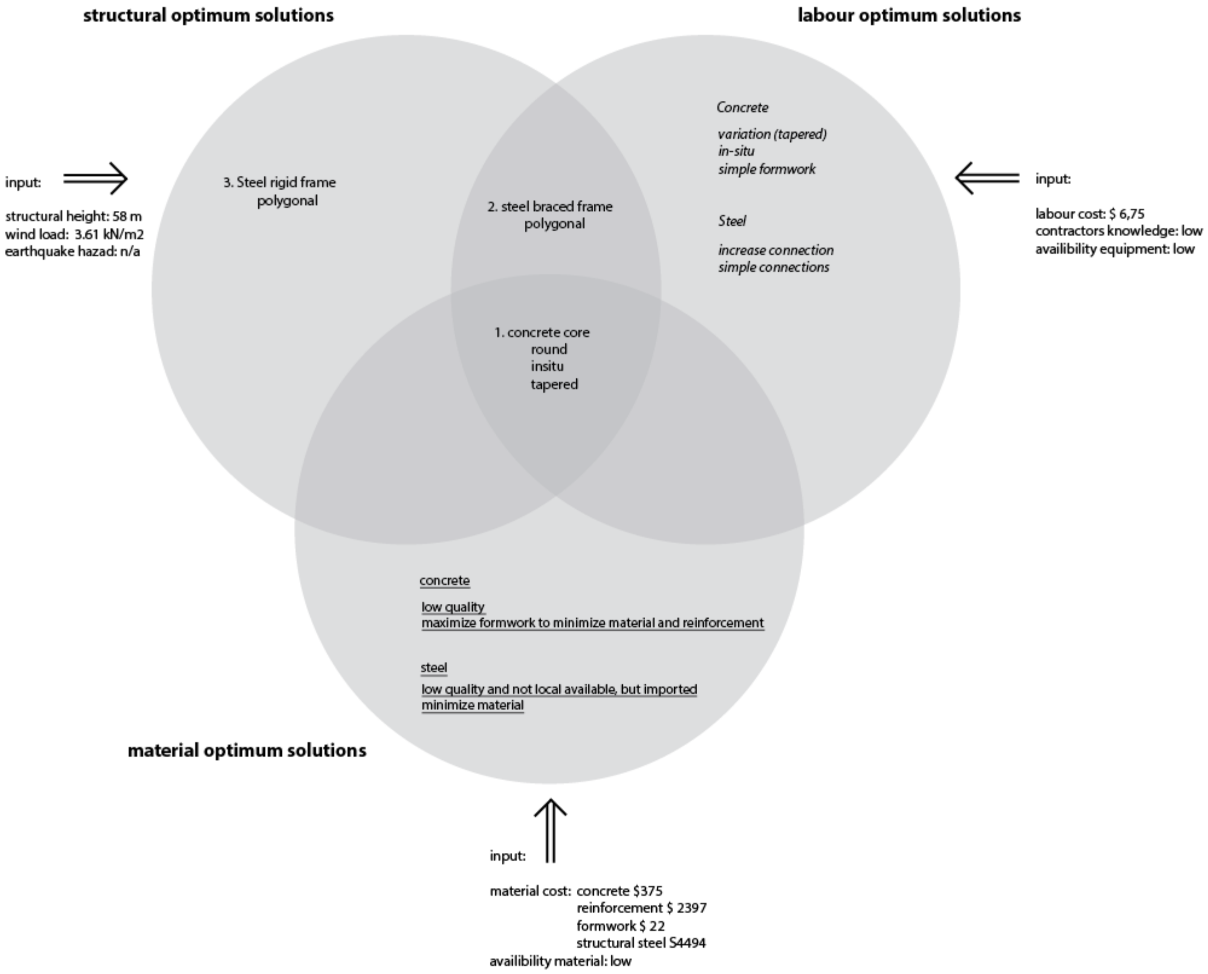


Figure 6.13: Synthesis Abuja airport

6.5 Tokyo Airport – Japan

The main focus points for the Japanese design are:

- High wind load, aerodynamically preferences
- High earthquake load, earthquake engineering aspects
- High labour cost, optimize material to reduce labour
- High experienced on steel design, widely adopted
- High knowledge level contractors, everything is possible

As a result, displayed and numbered sequentially in figure 6.14, the following three solutions are concluded (based on of the passage method appendix VIII) to be the most likely optimal solutions:

- Polygonal eccentric steel braced frame, with base isolation and light weight structures
- Round concrete core in-situ, with base isolation and light weight structures
- Polygonal concentric steel braced frame, with base isolation and light weight structures

In chapter 7 these three solutions will be elaborated in more detail with a conceptual design as the final result. Afterwards these designs can be compared, whereby the emphasis is placed on the role of the structural system versus the applied earthquake load.

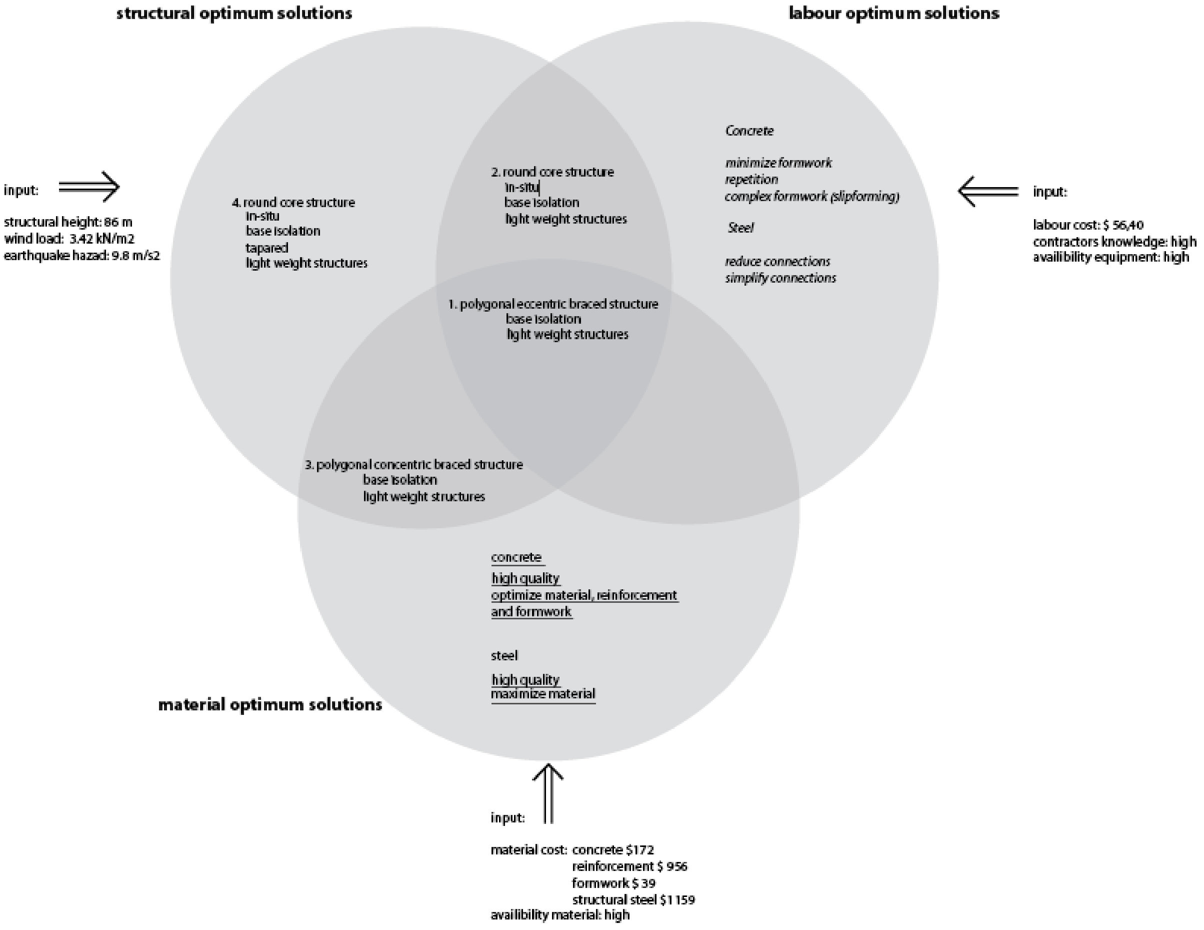


Figure 6.14: Synthesis Tokyo airport

6.6 Nanjing Airport – China

The main focus points for the Chinese design are:

- Intermediate wind load, aerodynamically preferences
- Low earthquake load, earthquake engineering aspects
- Low labour cost, optimize labour to reduce material
- High experienced on concrete design, widely adopted
- High knowledge level contractors, everything is possible

As a result, displayed and numbered sequentially in figure 6.15, the following three solutions are concluded (based on of the passage method appendix VIII) to be the most likely optimal solutions:

- Round concrete core in-situ, with light weight structures
- Round concrete core in-situ, tapered and light weight structures
- Polygonal eccentric steel braced frame, with light weight structures

In chapter 7 these three solutions will be elaborated in more detail with a conceptual design as the final result. Afterwards these designs can be compared, whereby the emphasis is placed on the role of the structural system versus the applied earthquake load and structural system versus the reduction of material.

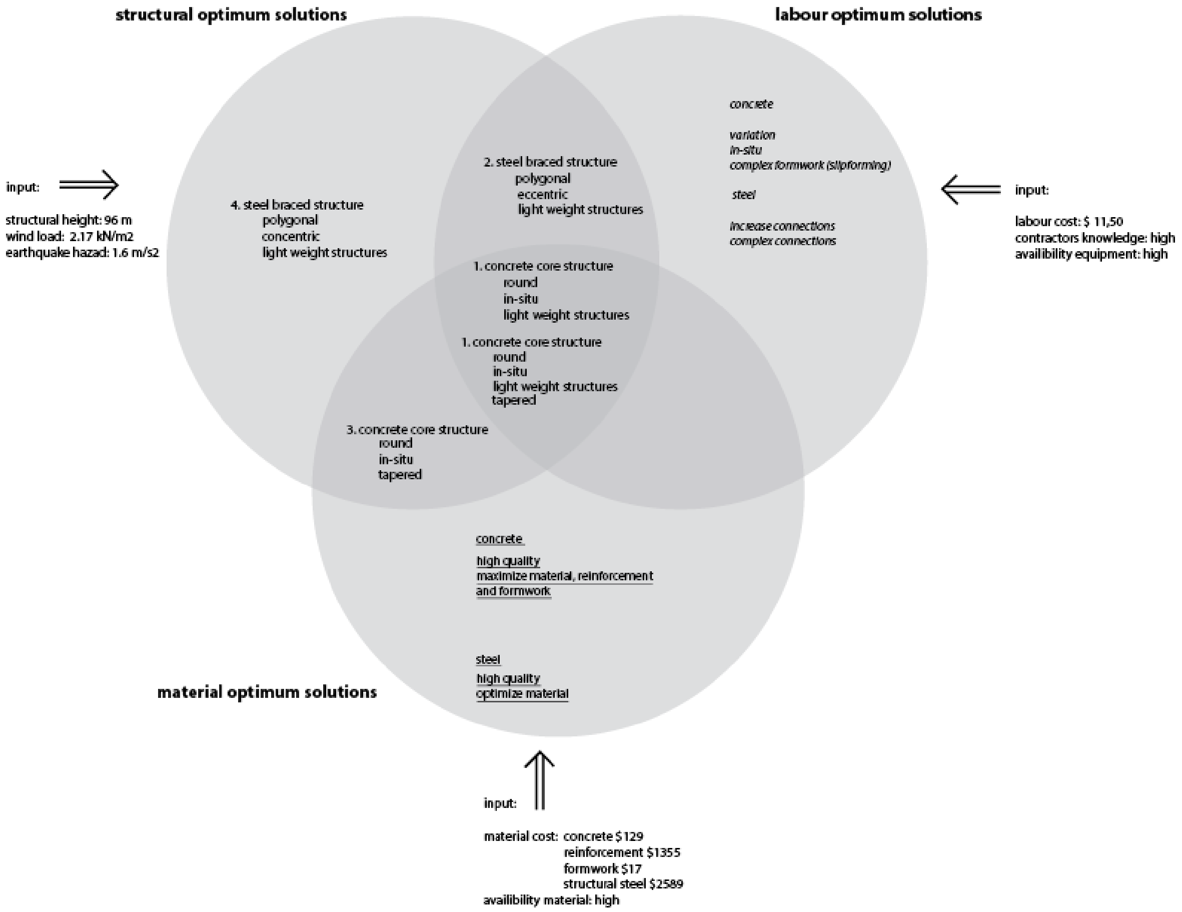


Figure 6.15: Synthesis Nanjing airport

6.7 Istanbul Airport – Turkey

The main focus points for the Turkish design are:

- Low wind load, no aerodynamically preferences
- High earthquake load, earthquake engineering aspects
- High labour cost, optimize material to reduce labour
- Intermediate knowledge level contractors, keep it simple

As a result, displayed and numbered sequentially in figure 6.16, the following two solutions are concluded (based on of the passage method appendix VIII) to be the most likely optimal solutions:

- Round concrete core in-situ, with base isolation and light weight structures
- Polygonal concentric steel braced frame, with base isolation and light weight structures

In chapter 7 these two solutions will be elaborated in more detail with a conceptual design as the final result. Afterwards these designs can be compared, whereby the emphasis is placed on the role of the structural system versus the applied earthquake load.

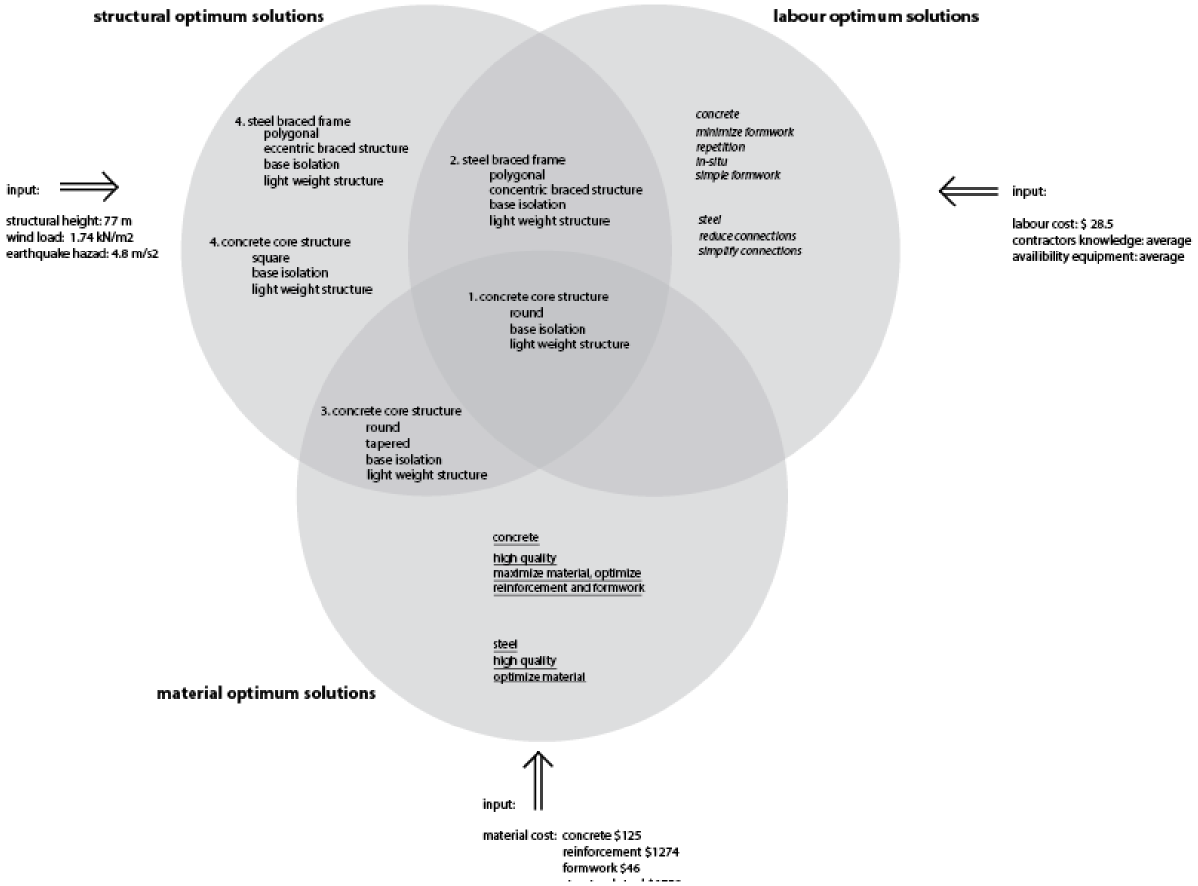


Figure 6.16: Synthesis Istanbul airport

6.8 Indonesia Airport – Jakarta

The main focus points for the Indonesian design are:

- Low wind load, no aerodynamically preferences
- Intermediate / High earthquake load, earthquake engineering aspects
- Low labour cost, optimize labour to reduce material
- High knowledge level contractors, everything is possible

As a result, displayed and numbered sequentially in figure 6.17, the following three solutions are concluded (based on of the passage method appendix VIII) to be the most likely optimal solutions:

- Round concrete core in-situ, tapered and with light weight structures
- Polygonal eccentric steel braced frame, with light weight structures
- Round concrete core in-situ, with light weight structures

In chapter 7 these three solutions will be elaborated in more detail with a conceptual design as the final result. Afterwards these designs can be compared, whereby the emphasis is placed on the role of the structural system versus the applied earthquake load and structural system versus the reduction of material.

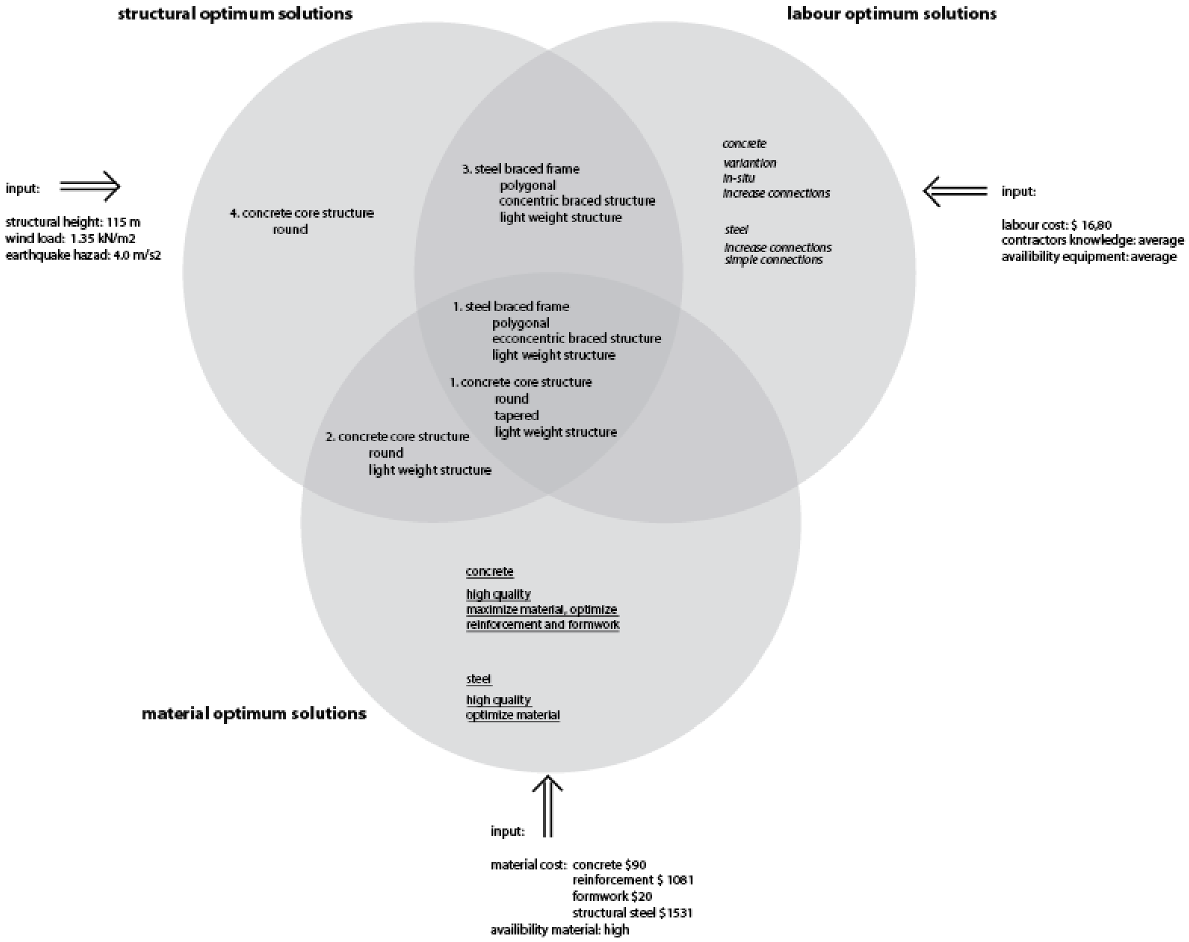


Figure 6.17: Synthesis Jakarta airport

6.9 Conclusions

The key-question *"Which concept design must be investigated in order to achieve satisfiying results regarding optimal structural design versus local conditions"* is elaborated in this chapter and is answered by the following conclusions.

A systematic process is used and elaborated in this chapter to converge the solution range, to achieve targeted optimal design solutions with the aim to limit the amount of design possibilities. This converge process is based on three main aspects; structural, labour and material optimum solutions.

For the six airports the following concept designs are though as the most likely optimal solution.

Lelystad – The Netherlands

- Square concrete core in-situ
- Square concrete core prefab

Abuja - Nigeria

- Round concrete core in-situ, tapered

Tokyo - Japan

- Polygonal eccentric steel braced frame, with base isolation and light weight structures
- Round concrete core in-situ, with base isolation and light weight structures
- Polygonal concentric steel braced frame, with base isolation and light weight structures

Nanjing - China

- Round concrete core in-situ, with light weight structures
- Round concrete core in-situ, tapered and light weight structures
- Polygonal eccentric steel braced frame, with light weight structures

Istanbul - Turkey

- Round concrete core in-situ, with base isolation and light weight structures
- Polygonal concentric steel braced frame, with base isolation and light weight structures

Jakarta - Indonesia

- Round concrete core in-situ, tapered and with light weight structures
- Polygonal eccentric steel braced frame, with light weight structures
- Round concrete core in-situ, with light weight structures

In chapter 7 these 14 concepts designs will be elaborated in more detail.

7. Concept simulations

7.1 Introduction

In the final chapter of this thesis research the 14 optimal concept designs, conducted in chapter 6, are worked out on a conceptual base, whereby the most important strength, stability and stiffness calculations are made including drawings and sketches of the design. The main purpose making these conceptual designs is to understand and qualify how the local boundary conditions relate with the structural design characteristics. Per country the concept designs are addressed shortly followed by a summary, wherein the differences and comparisons between designs and the relations are elaborated. The entire calculation and design approach of all designs is attached in appendix IX.

7.2 Lelystad airport – Netherlands

7.2.1 Concrete core in-situ

The shaft diameter of the tower is minimized to the required minimal functional surface of 12 m^2. The inner length of the core is 3600 mm and an outer length of 4100 mm, whereby the wall thickness is 250 mm. The height of the concrete core is 42 meters which contains 14 stories with a floor to floor height of 3,0 meter. The tower possesses 2 junction levels, each with a surface of 90 m^2. On top of the tower shaft the control cab is located, erected from steel that could be determined in later design phase. In figure 7.1 an overview is given of the concrete core in-situ and in table 7.1 the most important key-figures of this design are displayed.

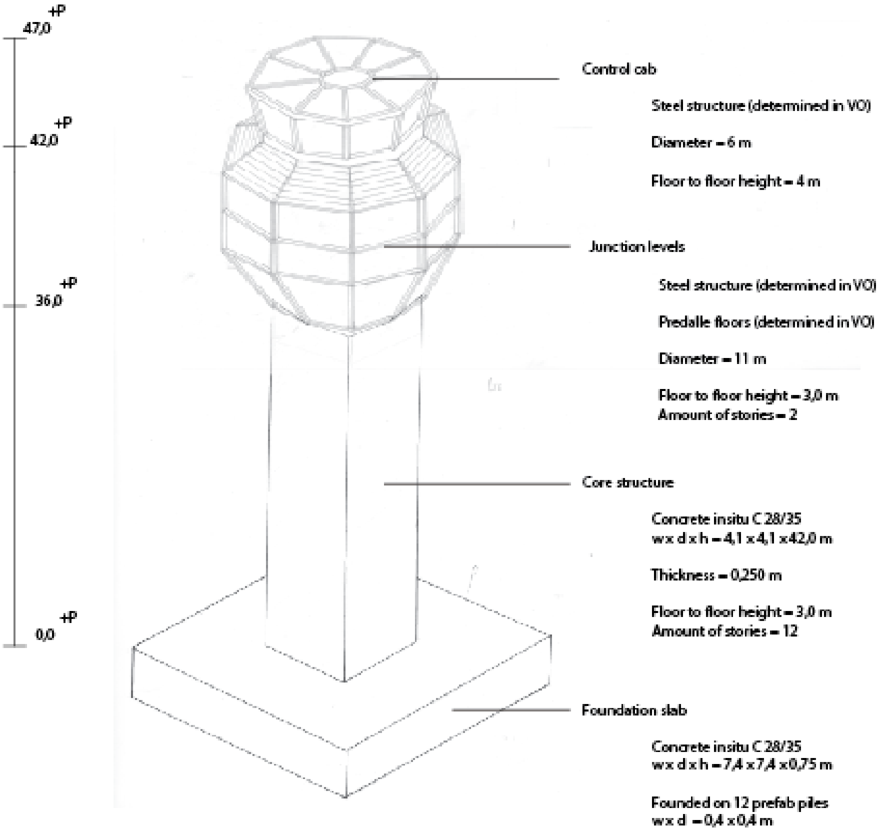


Figure 7.1: Concept design Lelystad airport, concrete core in-situ

7.2.2 Concrete core prefab

Also for the prefab concept design the shaft diameter of the tower is minimized to the required shaft dimension of 12 m^2, resulting in an inner length of 3600 mm and an outer length of 4160 mm, whereby the wall thickness is 280 mm. The same height is adopted which contains also 12 stories and 2 Junction levels. In figure 7.2 an overview is given of the concrete core prefab concept and in table 7.1 the most important key-figures are displayed of this design.

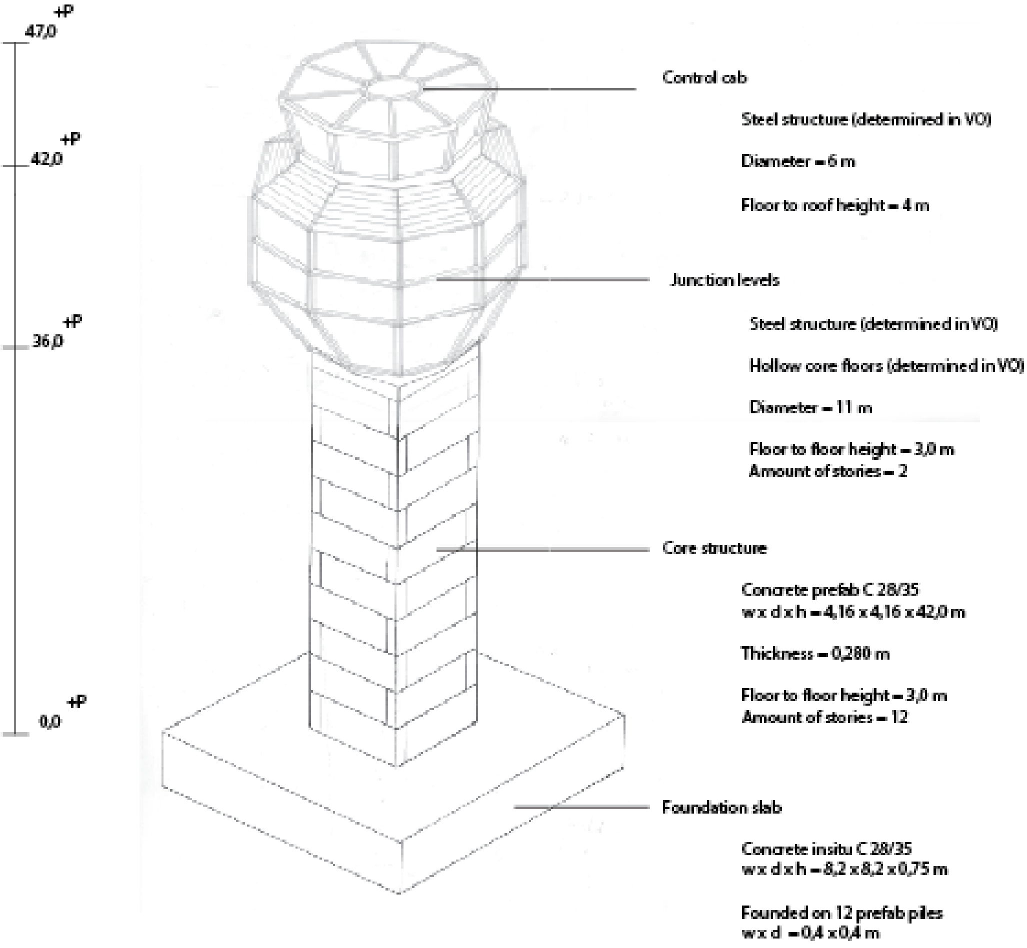


Figure 7.2: Concept design Lelystad airport, concrete core prefab

7.2.3 Summary Lelystad concepts

Both concept designs are very similar while comparing figure 7.1 with 7.2, e.g. the core height and the inner length of the core. The major difference between the two towers is the concrete wall thickness, which can be dedicated to the relation in-situ versus prefabrication.

In the prefab concept, the concrete core is constructed by separate concrete walls and these are stack on each other, resulting in numerous joints along the tower’s height. Disadvantageous these joints reduce the moment of inertia of the tower, making it less stiff. In order to provide enough stiffness subsequently the moment of inertia can be increased, resulting in a thicker concrete wall when the same concrete class is used. In table 7.1 the most important figures are displayed for both concepts designs.

Table 7.1: Design figures Lelystad airport

Aspect	Concrete core in-situ	Concrete core prefab	Value
Structural properties			
Inner length	3600	3600	mm
Wall thickness	250	280	mm
Moment of inertia	7,64 E+12	6,58 E+12	mm^4
First Eigen-period	1,57	1,74	sec
Normative structural requirement	Stiffness, wind	Stiffness, wind	-
Material volumes			
Concrete core	162	182	m^3
Concrete foundation slab	41	50	m^3
Concrete total	203	232	m^3
Foundation piles (400 x 400)	12	12	-
Weight			
Upper structure	10529	11154	kN
Foundation	1232	1513	kN
Total	11761	12667	kN
Relatively between concepts	93	100	%
Wind load			
Distributed wind load	12,28	12,46	kN/m
Moment wind	14131	14289	kNm
Relatively between concepts (moment)	99	100	%
Functional			
Number of stories	14	14	-
Floor to floor height	3,0	3,0	m
Surface core	13,0	13,0	m^2
Surface elevator + stairs	8,0	8,0	m^2
Surface risers (remaining)	5,0	5,0	m^2

First, an increase of the wall thickness results in a direct increase of the concrete volume and weight of the core structure. In this specific case the concrete volume and weight is increased by approximately 10 %. In order to bear this additional weight a larger foundation is needed. Due to a proper redistribution of the piles, still for both designs 12 foundation piles are sufficient.

Next, due to the increase of the outer length (60 mm) of the concrete core, subsequently the wind load and the overturning moment also increase, resulting in higher tensile and compression stresses in both the concrete wall as foundation piles and larger deflections. The increase of 1 % can be neglected in this specific case.

Another solution, not increasing the core’s perimeter, is to use a higher concrete class. In the deflection requirement the reduction of the moment of inertia will be compromised by the increase of the modulus of elasticity of the concrete. The usage of higher concrete classes for prefab concrete elements is a common and very suitable solution.

In appendix IX.I both designs are calculated and elaborated in more detail.

7.3 Abuja airport – Nigeria

7.3.1 Tapered concrete core in-situ

Due to the high wind load, the tower has an aerodynamically round shape. The shaft diameter of the tower is minimized to the minimal inner diameter of 6,0 meter, which is significantly larger than square cores. This increase is caused by the inefficient fitting of rectangular functions, e.g. elevators and stairs, in a circular section, resulting automatically in an additional increase of space for the vertical risers.

The height of the concrete core is 54 meters which contains 18 stories, with a floor to floor height of 3,0 meter. The thickness of the core wall is tapered and varies in three steps of a thickness of 250 mm in the lower sections to 150 mmm in the top sections. The tower possesses 2 junction levels, each with a surface of 100 m^2. On top of the tower shaft the control cab is located, erected from steel which could be determined in later design phase. In figure 7.3 an overview is given of the tapered concrete core and in table 7.2 the most important key-figures are displayed of this design.

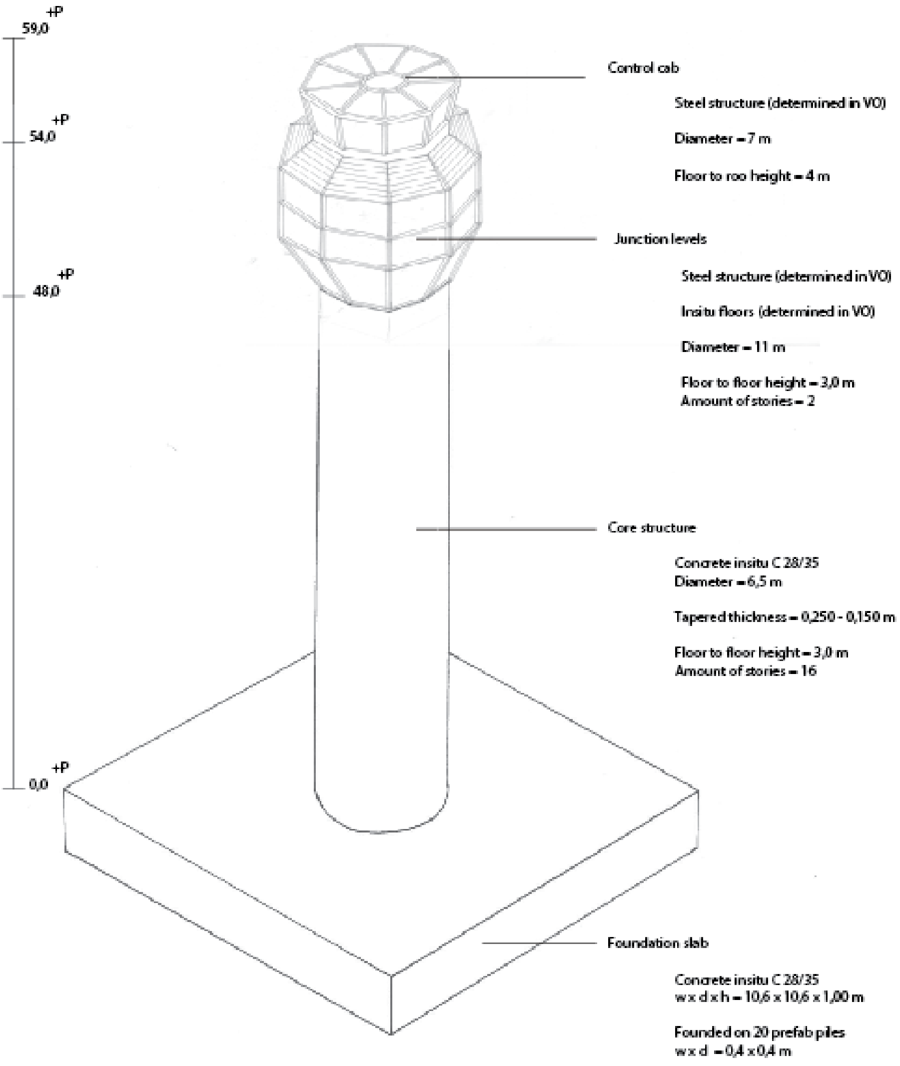


Figure 7.3: Concept design Abuja airport, tapered concrete core in-situ

7.3.2 Summary Abuja concepts

Table 7.2: Design figures Abuja airport

Aspect	Tapered concrete core in-situ	Value
Structural properties		
Inner length	6300 - 6000	mm
Wall thickness	150 - 250	mm
Moment of inertia, average	1,57 E+13	mm^4
First Eigen-period	1,81	sec
Normative structural requirement	Stiffness, wind	-
Material volumes		
Concrete core	214	m^3
Concrete foundation slab	112	m^3
Concrete total	326	m^3
Foundation piles (400 x 400)	20	-
Weight		
Upper structure	13451	kN
Foundation	3371	kN
Total	12667	kN
Wind load		
Distributed wind load	16,89	kN/m
Moment wind	33199	kNm
Functional		
Number of stories	18	-
Floor to floor height	3,0	m
Surface core	28,3	m^2
Surface elevator + stairs	10,3	m^2
Surface risers (remaining)	18,0	m^2

First, the decrease of the wall thickness along the height results in a direct decrease of the concrete volume and weight of the core structure, resulting subsequently in a smaller foundation.

Next, due to the decrease of the wall thickness also the stiffness along the height reduces, resulting in larger deflections. For the determination of the stiffness an average moment of inertia along the height is taken, which should be defined in more detail in a later design phase. At last, the cross-sectional area of the concrete wall reduces, resulting in a decrease of compression and tension strength capacity.

In the specific case the concrete core would be of constant thickness of 250 mm along the height, 265 m^3 concrete would be necessary, resulting in a volume and weight increase of approximately 20 %.

In the specific case the concrete core perimeter would not be round but square, the distributed wind load along the height would be 3x times larger, resulting in much larger upper structure and foundation.

In appendix IX.II the design is calculated and elaborated in more detail.

7.4 Tokyo airport – Japan

7.4.1 Eccentric steel braced frame

Due to the high wind load, the tower has an aerodynamically shape. Unfortunately, it is not possible to make a perfect round perimeter with a steel structure; therefore the round perimeter is approached by a hex-decagon with a maximum diameter of 14400 mm. The shaft diameter of the tower is determined on basis of stiffness requirements, making the tower shaft surface significantly larger than functional required.

The height of the braced frame is 86,4 meters which contains 24 stories, with a floor to floor height of 3,6 meter. The steel grid along the height is 7,2 meter, resulting in exactly 2 floors per section. The columns and beams are constructed with HE500M elements, whereas smaller sections are used for the diagonals, namely HE320M. The columns and diagonals are connected in an eccentric manner, improving the ductility of the structure. In comparison with a concrete core an additional cladding is used to make the tower wind and water tight, resulting in additional weight. Next the tower is provided with a base isolation system, in order to reduce the earthquake load. In figure 7.4 an overview is given of the eccentric steel braced frame and in table 7.3 the most important key-figures are displayed of this design.

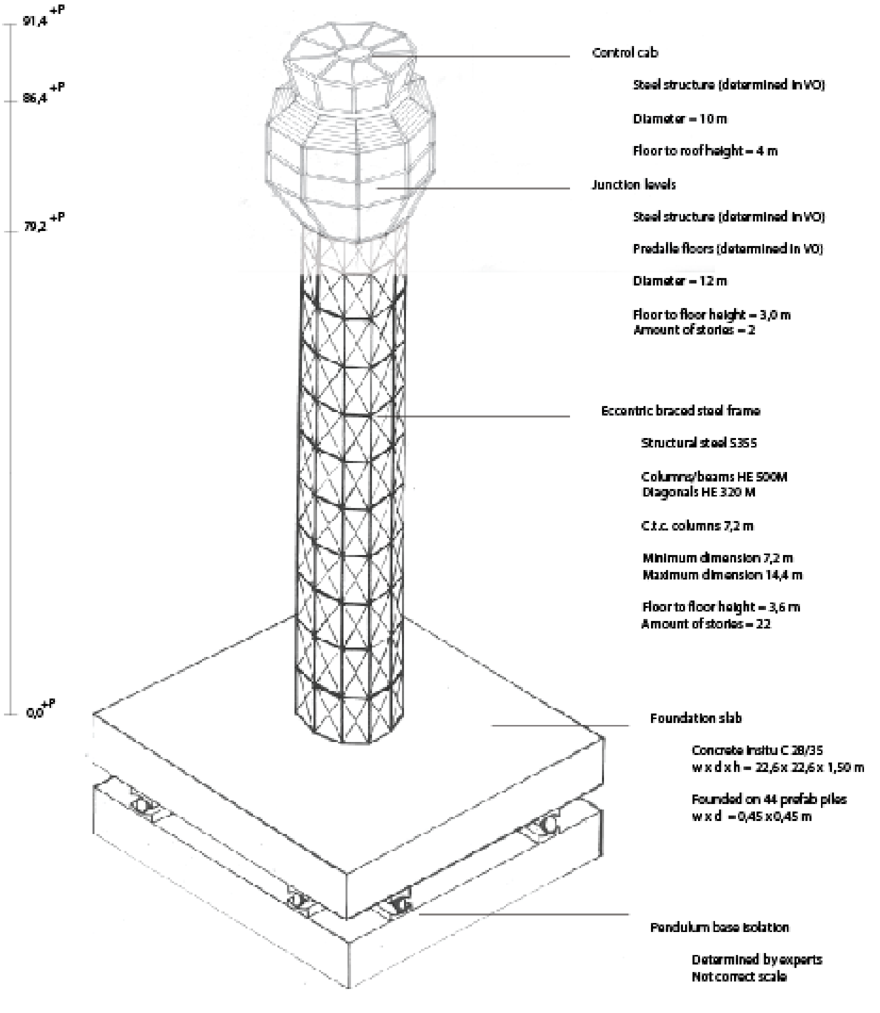


Figure 7.4: Concept design Tokyo airport, eccentric steel braced frame

7.4.2 Concrete core in-situ

Also for the concrete variant, the shaft diameter of the tower is determined on basis of structural requirements, making the tower shaft surface significantly larger than functional required. The inner length of the core is 11000 mm and an outer length of 12300 mm, whereby the wall thickness is 650 mm. The height of the concrete core is 81 meters which contains 27 stories, with a floor to floor height of 3,0 meter. Also this concept is provided with a base isolation system, in order to reduce the earthquake load. In figure 7.5 an overview is given of the concrete core in-situ and in table 7.3 the most important key-figures are displayed of this design.

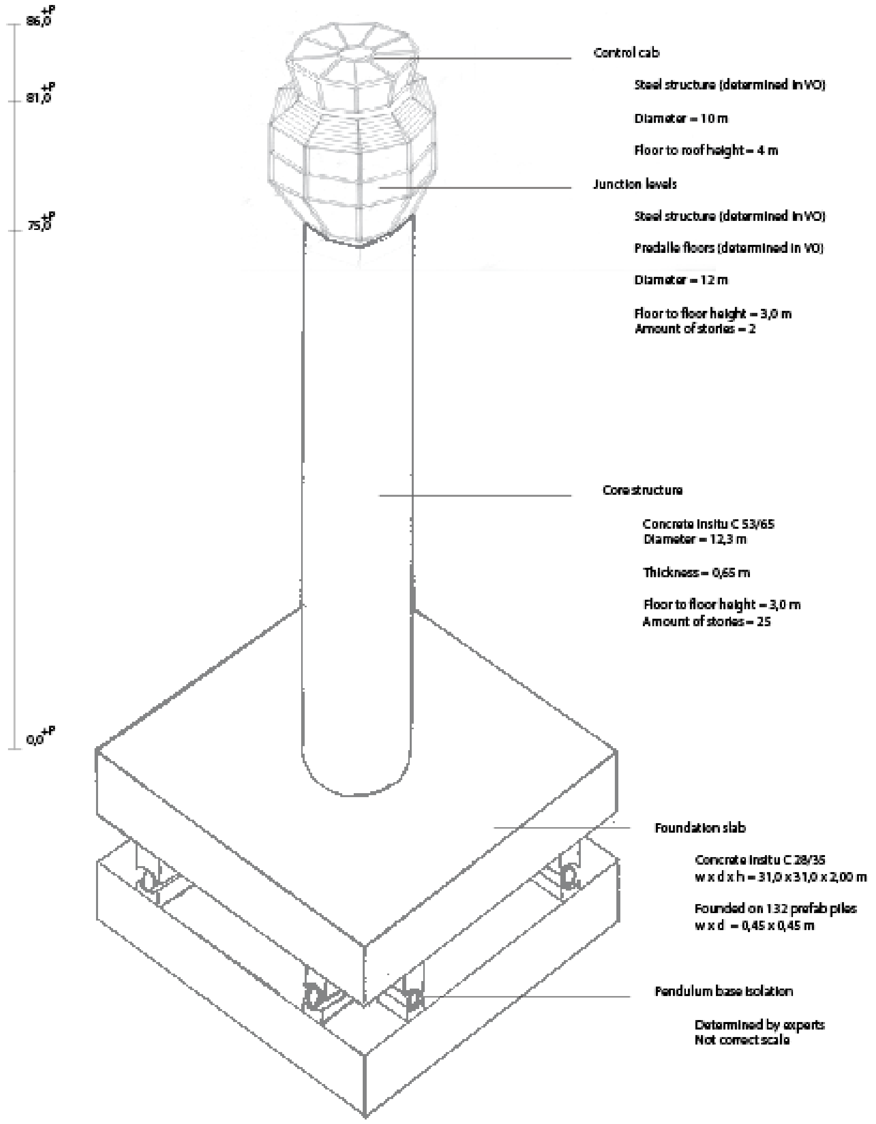
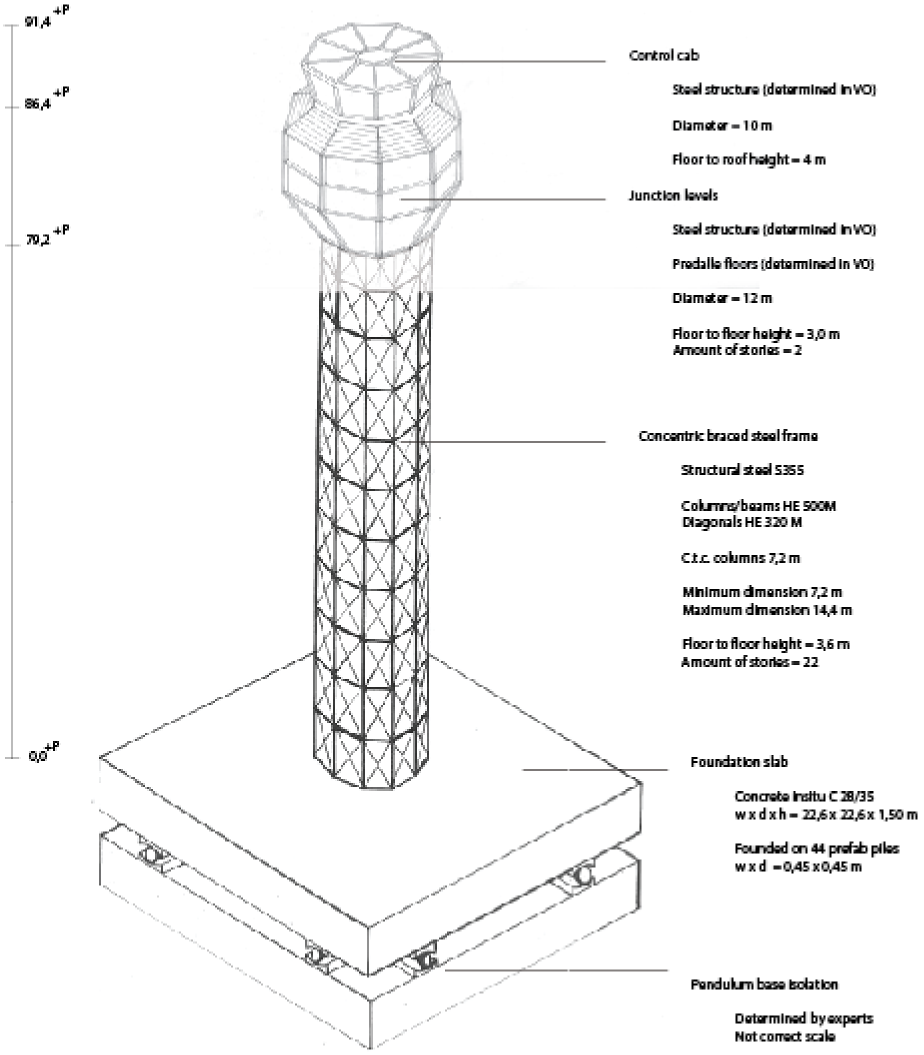


Figure 7.5: Concept design Tokyo airport, concrete core in-situ

7.4.3 Concentric steel braced frame

The design of this steel braced frame tower is almost the same as the tower elaborated in section 7.4.1. The main difference between both towers is the connection between the columns and diagonals. By this design the connections are concentrated in the centre of the nodes, reducing its ductility. In figure 7.6 an overview is given of the concentric steel braced frame and in table 7.3 the most important key-figures are displayed of this design.



Control cab

Steel structure (determined in VO)

Diameter = 10 m

Floor to roof height = 4 m

Junction levels

Steel structure (determined in VO)

Predalle floors (determined in VO)

Diameter = 12 m

Floor to floor height = 3,0 m
Amount of stories = 2

Concentric braced steel frame

Structural steel S355

Columns/beams HE 500M
Diagonals HE 320 M

C.t.c. columns 7,2 m

Minimum dimension 7,2 m
Maximum dimension 14,4 m

Floor to floor height = 3,6 m
Amount of stories = 22

Foundation slab

Concrete insitu C 28/35
w x d x h = 22,6 x 22,6 x 1,50 m

Founded on 44 prefab piles
w x d = 0,45 x 0,45 m

Pendulum base isolation

Determined by experts
Not correct scale

Figure 7.6: concept design Tokyo airport, concentric steel braced frame

7.4.4 Summary Tokyo concepts

Table 7.3: Design figures Tokyo airport

Aspect	Eccentric steel braced frame	Concrete core in-situ	Concentric steel braced frame	Value
Structural properties				
Inner length	14400	11000	14400	mm
Wall thickness	-	650	-	mm
Beams / columns	HE 500M	-	HE 500M	-
Diagonals	HE 320M	-	HE 320M	-
Moment of inertia (80 %), average	4,46 E+12	3,24 E+13	4,46 E+12	mm^4
First Eigen-period	2,00 No base isolation suitable	1,533	2,0 No base isolation suitable	sec
Behaviour factor	6	5,4	4	-
Normative structural requirement	Stiffness, wind	Strength, earthquake	Stiffness, wind	-
Material volumes				
Concrete core	-	1927	-	m^3
Concrete foundation slab	766	1922	766	m^3
Concrete total	766	3849	766	m^3
Structural steel	798	-	798	tonne
Foundation piles (400 x 400)	44	132	44	-
Weight				
Upper structure	22875	64738	22875	kN
Foundation	22984	57660	22984	kN
Total	45859	122398	45859	kN
Relatively between concepts (total)	37	100	37	%
Wind load				
Distributed wind load	53,34	30,52	53,34	kN/m
Moment wind	213328	113066	213328	kNm
Relatively between concepts (moment)	100	54	100	%
Earthquake load				
Base shear load	6398	18108	6898	kN
Moment earthquake	412210	955286	444424	kNm
Relatively between concepts (moment)	43	100	47	%
Relatively moments				
Moment wind	52	12	48	%
Moment earthquake	100	100	100	%
Functional				
Number of stories	24	27	24	-
Floor to floor height	3,6	3,0	3,6	m
Surface core	180	95	180	m^2
Surface elevator + stairs	10	10	10	m^2
Surface risers (remaining)	170	85	170	m^2

First the two steel concepts designs are compared. The main difference between an eccentric and concentric design is the location and detailing of the connection between the beams and diagonals, expressed in different behaviour factors. In figure 7.7, both designs are displayed, whereas in the right figure extra plasticity zones are created (darker marked) to improve the ductility of the structure, more information is given in literature part 3.3.4 page 76.

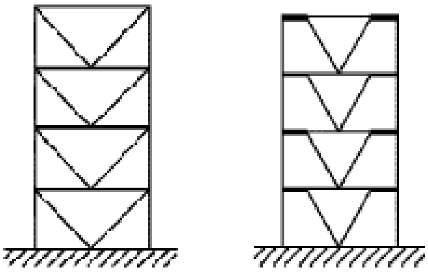


Figure 7.7: Difference concentric (left) and eccentric (right) steel braced frame

Both concept designs have an Eigen-period of 2 seconds, meaning that both towers are classified in the lowest part of the design spectrum. The effect to apply base-isolation to reduce earthquake loads becomes negligible, assuming that base-isolation is only effective by Eigen-periods significantly lower than 2 seconds, and are disregarded in both designs.

Due to a higher structural behaviour factor (6 versus 4) and therefore ductility, the base shear load and bending moment of the eccentric concept design is approximately 10 % lower than the concentric concept design.

When comparing the eccentric steel concept design with the concrete concept design the main difference is the weight, which is expected. Due to the increase of mass, subsequently the internal earthquake reaction load increases, resulting in a negative vicious design cycle. In this specific case the concrete upper structure becomes 2,8 times heavier, resulting in a significantly larger foundation and increase of foundation piles.

Due to the higher base shear loads and bending moments for the concrete variant, the normative structural requirement is strength for earthquake action, whereas for the steel structures the wind deflection is decisive.

The concept design with the lowest maximum bending moment is in structural perspective the optimal solution, making the eccentric steel braced frame for Tokyo airport the most optimal structural design solution. This is matching with the synthesis analysis made in chapter 6, resulting that this solution is expected to be in economically prospect the best solution.

For all concept designs the inner surface is significantly larger than functionally required. For the steel concepts, the inner diameter is 3400 mm larger than the concrete concept, making the steel concepts even less functional efficient. In addition, as already mentioned before, increasing the tower’s diameter resulting in an increase of the wind load.

In appendix IX.III the designs are calculated and elaborated in more detail.

7.5 Nanjing airport – China

7.5.1 Concrete core in-situ

The shaft diameter of the tower is minimized to the minimal inner diameter of 6,0 meter in order have sufficient space for the rectangular elevators and staircases. The outer length of the core is 7300 mm, whereby the wall thickness is 650 mm. The height of the concrete core is 93 meters which contains 31 stories with a floor to floor height of 3,0 meter. In figure 7.8 an overview is given of the concrete core in-situ and in table 7.4 the most important key-figures are displayed of this design.

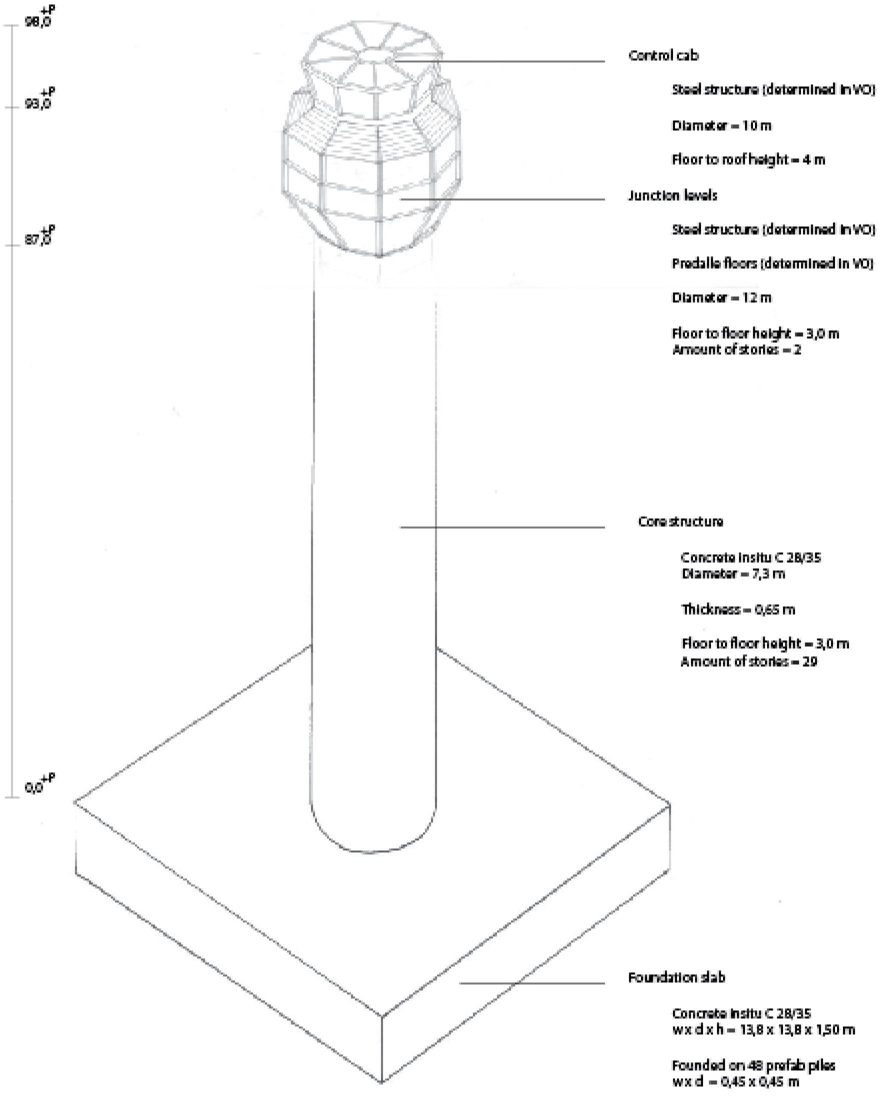


Figure 7.8: Concept design Nanjing airport, Concrete core in-situ

7.5.2 Tapered concrete core in-situ

Also the shaft diameter of this concept design is minimized to the minimal inner diameter of 6,0 meter in order to have sufficient space for the rectangular elevators and staircases. The outer length of the core is 7300 mm. The thickness of the core wall is tapered and varies in three steps of a thickness of 650 mm in the lower sections to 450 mm in the top sections. The height of the concrete core is also 93 meters and contains as well 31 stories with a floor to floor height of 3,0 meter. In figure 7.9 an overview is given of the tapered concrete core in-situ and in table 7.4 the most important key-figures are displayed of this design.

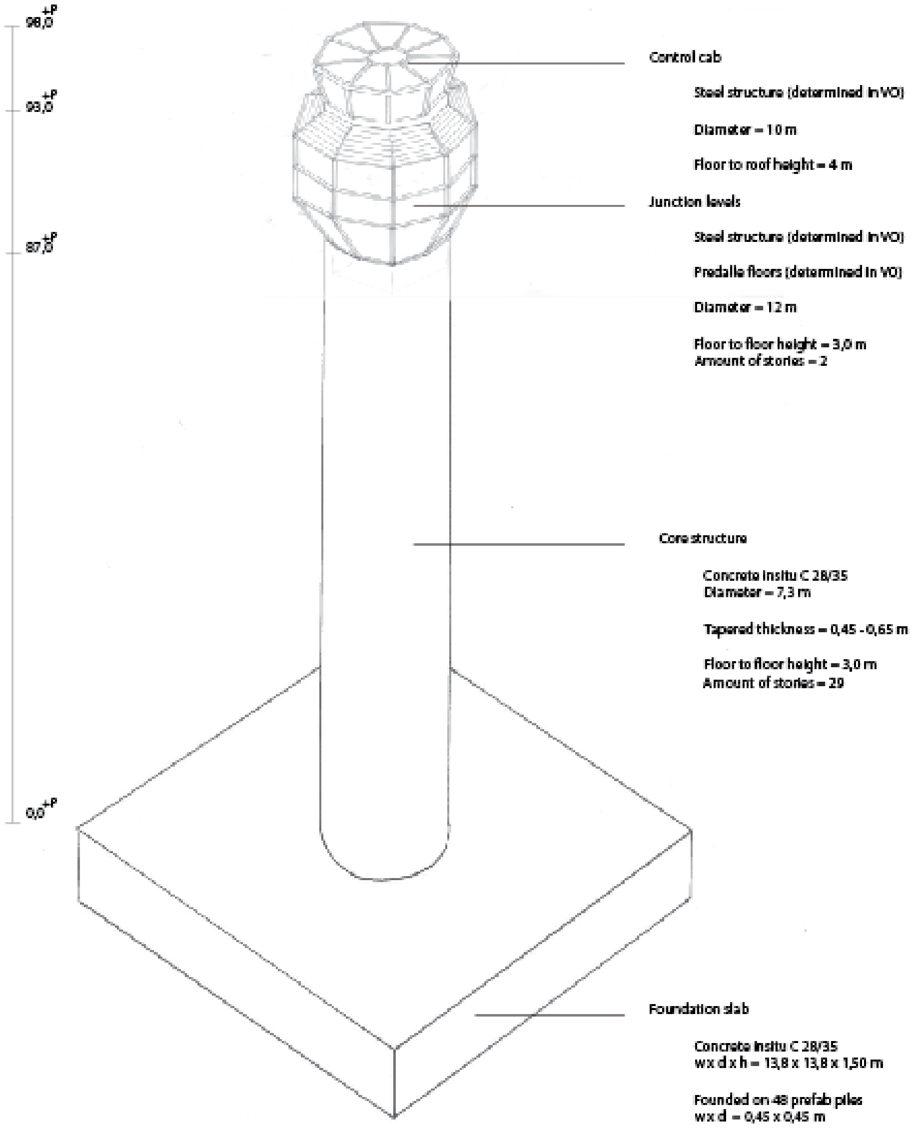


Figure 7.9: Concept design Nanjing airport: Tapered concrete core in-situ

7.5.3 Eccentric steel braced frame

The shape of the steel braced frame is octagonal in order to approach the aerodynamically round perimeter with a maximum length of 10800 mm. The shaft diameter of the tower is determined on basis of structural requirements, making the tower shaft surface larger than functional required. This is the opposite of the concrete concepts, where the diameter was determined on basis of functionality.

The height of the braced frame is 93,6 meters which contains 26 stories, with a floor to floor height of 3,6 meter. The columns and beams are constructed with HE900M elements, whereas smaller sections are used for the diagonals, namely HE500M. The columns, beams and diagonals are connected in an eccentric manner, improving the ductility of the structure. In comparison with a concrete core an additional cladding is used to make the tower wind and water tight, resulting in an additional weight. In figure 7.10 an overview is given of the eccentric steel braced frame and in table 7.4 the most important key-figures are displayed of this design.

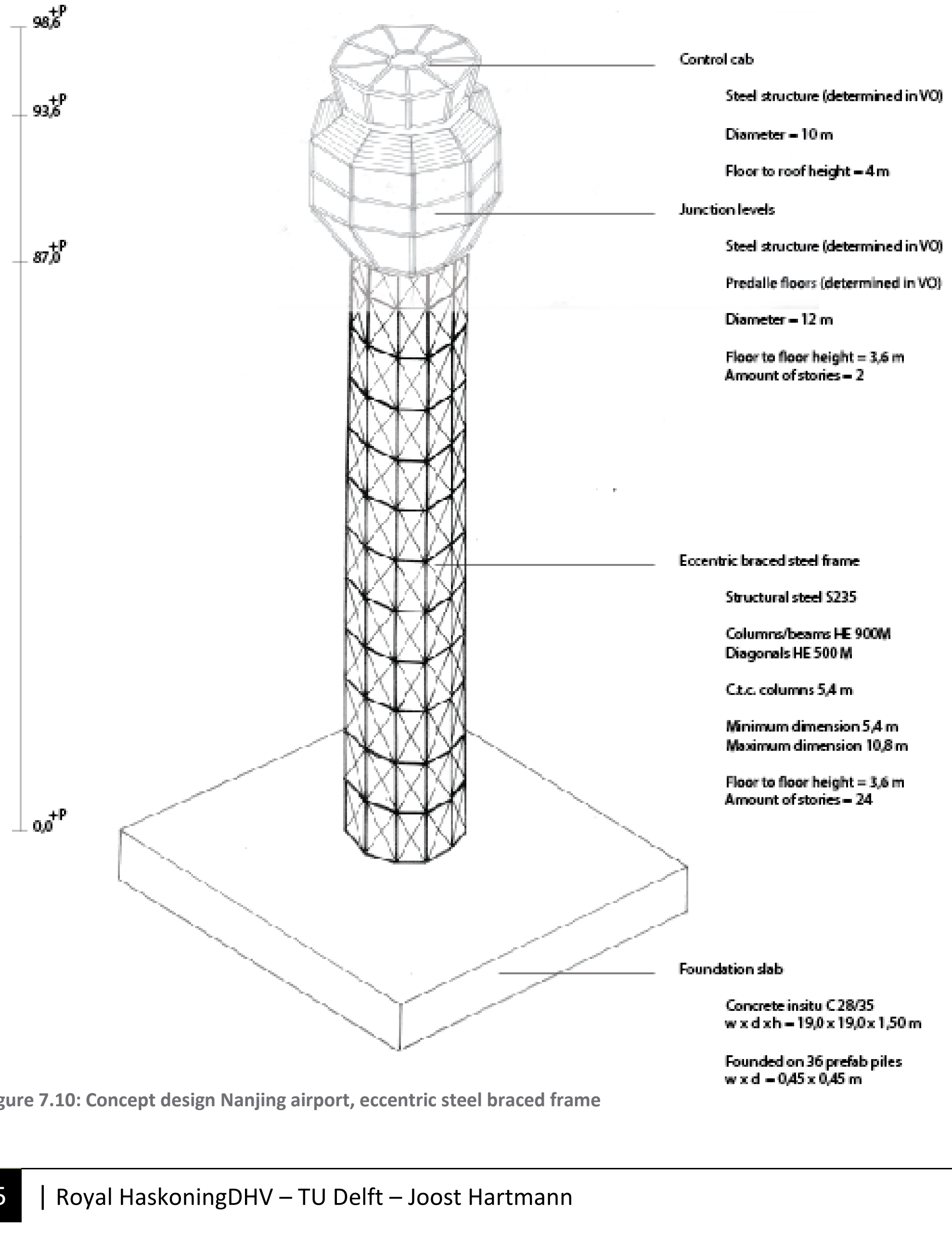


Figure 7.10: Concept design Nanjing airport, eccentric steel braced frame

7.5.4 Summary Nanjing concepts

Table 7.4: Design figures Nanjing airport

Aspect	Concrete core in-situ	Tapered concrete core in-situ	Eccentric steel braced frame	Value
Structural properties				
Inner length	6000	6600 – 6000	10800	mm
Wall thickness	650	450 - 650	-	mm
Beams / columns	-	-	HE 900M	-
Diagonals	-	-	HE 500M	-
Moment of inertia	6,06 E+13	5,33 E+13	3,08 E+12	mm^4
First Eigen-period	3,9	3,9	2,8	sec
Behaviour factor	5,4	5,4	6	-
Normative structural requirement	Stiffness, earthquake	Stiffness, wind	Stiffness, wind	-
Material volumes				
Concrete core	1262	1083	-	m^3
Concrete foundation slab	286	286	542	m^3
Concrete total	1548	1369	542	m^3
Structural steel	-	-	798	tonne
Foundation piles (400 x 400)	48	48	36	-
Weight				
Upper structure	45161	39756	23771	kN
Foundation	8570	8570	16245	kN
Total	53731	48326	40016	kN
Relatively between concepts (total)	100	87	75	%
Wind load				
Distributed wind load	11,46	11,46	36,56	kN/m
Moment wind	59544	59544	169900	kNm
Relatively between concepts (moment)	35	35	100	%
Earthquake load				
Base shear load	2062	1806	1086	kN
Moment earthquake	129800	113329	72847	kNm
Relatively between concepts (moment)	100	87	56	%
Relatively				
Moment wind	46	53	100	%
Moment earthquake	100	100	43	%
Functional				
Number of stories	31	31	24	-
Floor to floor height	3,0	3,0	3,6	m
Surface core	28	28	180	m^2
Surface elevator + stairs	10	10	10	m^2
Surface risers (remaining)	18	18	85	m^2

When comparing the tapered concrete core concept with the eccentric steel concept design, the main difference is the weight of the upper structure, which is expected. In this specific case the concrete upper structure is 1,7 times heavier. Remarkably this is not the case for the foundation, which is 1,9 times lighter. As a result of the large bending moment caused by the wind, the foundation of the steel concept is significantly larger in order to provide enough stability. Concluding; steel structures are not on beforehand the most optimal structural solution in earthquake regions.

Comparing both concrete structures, the tapered concept design contains 13 % less concrete, resulting in 13 % less weight and a reduction of 13 % of the earthquake moment. In this case the same foundation is used, whereby in general the tensile forces in the piles are increased and the compression forces decreased.

The reduction of the stiffness of the tower, caused by the tapering, is not directly unbeneficial. By reducing the weight along the height, subsequently the earthquake shears forces and bending moment reduces, reversing the negative vicious cycle. As a result, the reduction of stiffness does not lead to an additional increase of the earthquake deflection. However, the wind deflection does increases.

The concept design with the lowest maximum bending moment is in structural perspective the optimal solution, making the tapered concrete core in-situ for Nanjing airport the most optimal structural design solution. This is matching with the synthesis analysis made in chapter 6, resulting that this solution is expected to be in economically prospect the best solution.

The concrete concepts are designed as slender as possible, regarding the functionally requirements. The perimeter of the steel concept is significantly larger and therefore less optimal.

In appendix IX.IIII the designs are calculated and written in more detail.

7.6 Istanbul airport – Turkey

7.6.1 Concrete core in-situ

The shaft diameter of the tower is determined on basis of structural requirements, making the tower shaft surface larger than functionally required. The inner length of the core is 7500 mm and an outer length of 8800 mm, whereby the wall thickness is 650 mm. The height of the concrete core is 68,4 meters which contains 21 stories, with a floor to floor height of 3,6 meter. The tower possesses 2 junction levels, each with a surface of 100 m^2. On top of the tower shaft the control cab is located, erected from steel which could be determined in later design phase. In figure 7.11 an overview is given of the concrete core in-situ and in table 7.5 the most important key-figures are displayed of this design.

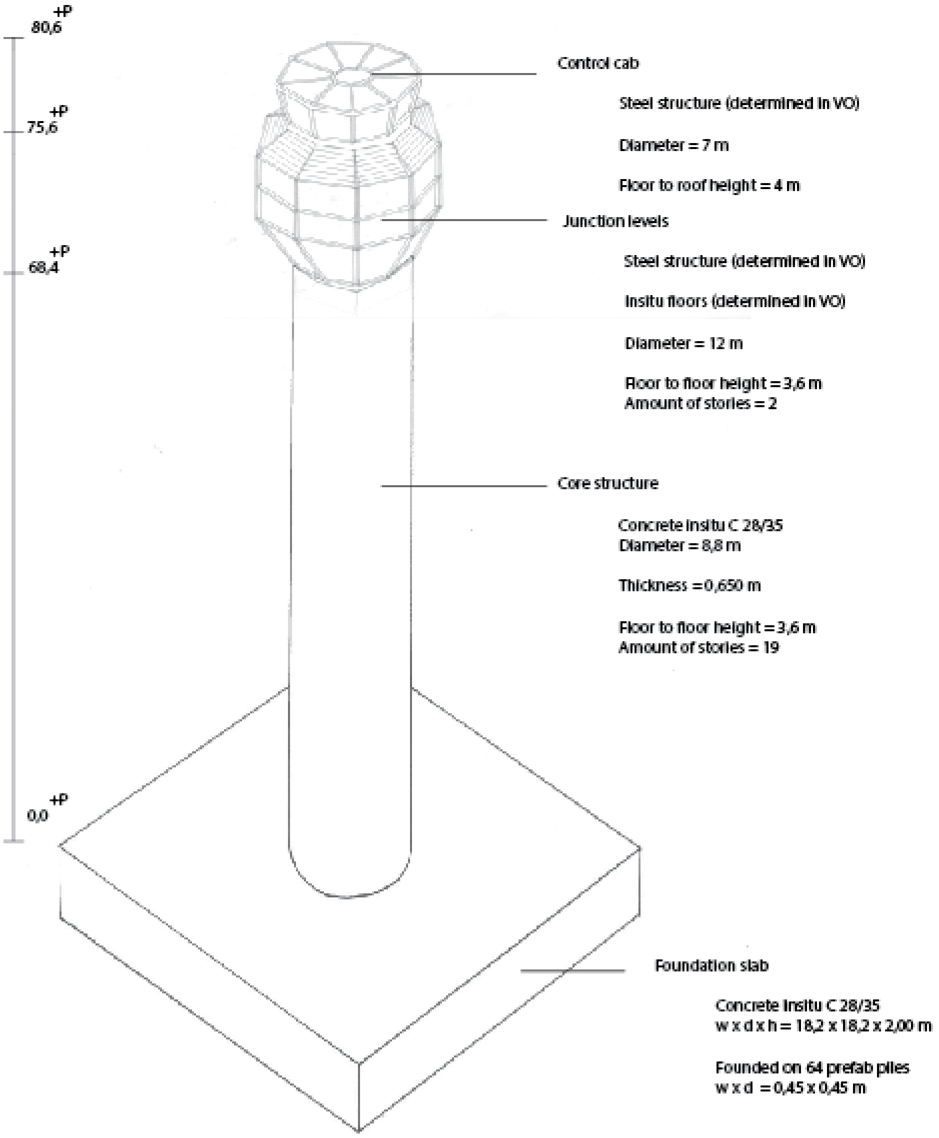


Figure 7.11: Concept design Istanbul airport, concrete core in-situ

7.6.2 Concentric steel braced frame

The shape of the steel braced frame is octagonal in order to approach the aerodynamically round perimeter with a maximum length of 10800 mm. The shaft diameter of the tower is determined on basis of structural requirements, making the tower shaft surface larger than functional required.

The height of the braced frame is 72,0 meters which contains 20 stories, with a floor to floor height of 3,6 meter. The steel grid along the height is 7,2 meter, resulting in exactly 2 floors per section. The columns and beams are constructed with HE260M elements, whereas smaller sections are used for the diagonals, namely HE180M. In figure 7.12 an overview is given of the concentric steel braced frame and in table 7.5 the most important key-figures are displayed of this design.

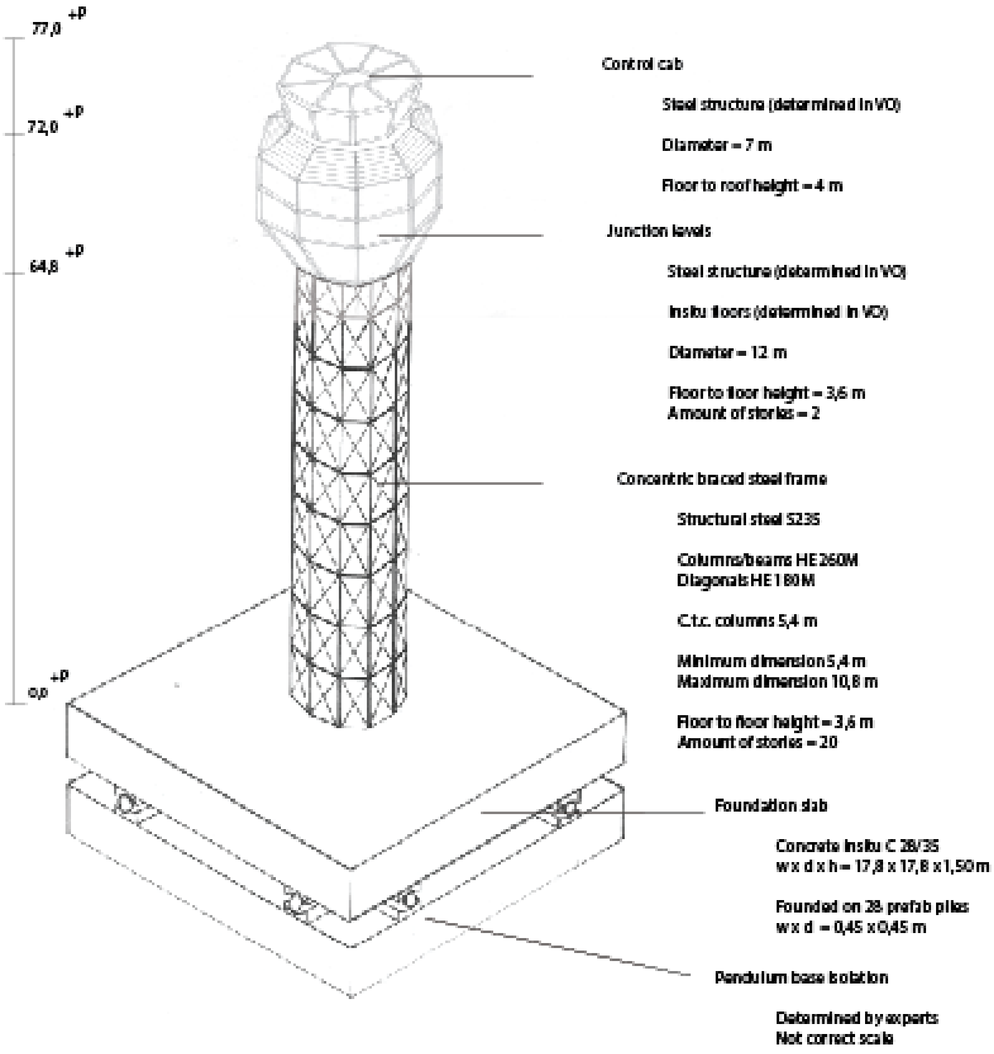


Figure 7.12: Concept design Istanbul airport, concentric steel braced frame

7.6.3 Summary Istanbul concepts

Table 7.5: Design figures Istanbul airport

Aspect	Concrete core in-situ	Concentric steel braced frame	Value
Structural properties			
Inner length	7500	10800	mm
Wall thickness	650	-	mm
Beams / columns	-	HE 260M	-
Diagonals	-	HE 180M	-
Moment of inertia (80 %), average	1,11 E+14	1,60 E+12	mm^4
First Eigen-period	2,01	1,9	sec
Behaviour factor	5,4	4	-
Normative structural requirement	Stiffness earthquake		
Material volumes			
Concrete core	1258	-	m^3
Concrete foundation slab	663	475	m^3
Concrete total	1921	475	m^3
Structural steel	-	301	tonne
Foundation piles (400 x 400)	64	36	-
Weight			
Upper structure	43452	13204	kN
Foundation	19874	14258	kN
Total	63326	27462	kN
Relatively between concepts	100	43	%
Wind load			
Distributed wind load	11,02	29,32	kN/m
Moment wind	38028	81999	kNm
Relatively between concepts	46	100	%
Earthquake load			
Base shear load	5953	1980	kN
Moment earthquake	292158	110625	kNm
Relatively between concepts	100	38	%
Relatively			
Moment wind	13	74	%
Moment earthquake	100	100	%
Functional			
Number of stories	21	24	-
Floor to floor height	3,6	3,6	m
Surface core	44	180	m^2
Surface elevator + stairs	10	10	m^2
Surface risers (remaining)	34	85	m^2

When comparing the concrete concept design with the concentric steel concept design, the main difference is the weight of the upper structure, which is expected. In this specific case the concrete upper structure is 2,3 times heavier.

The concept design with the lowest maximum bending moment is in structural perspective the optimal solution, making the concentric steel braced frame for Istanbul airport the most optimal structural design solution. This does not match with the synthesis in chapter 6, resulting that this solution would not be necessarily optimal in economically perspective as well. Further investigation is required in order to determine which solution will be most optimal.

7.7 Jakarta airport – Indonesia

7.7.1 Tapered concrete core in-situ

The shaft diameter of the tower is determined on basis of structural requirements, making the tower shaft surface larger than functionally required. The outer length of the core is 13600 mm. The thickness of the core wall is tapered and varies in three steps of a thickness of 800 mm in the lower sections to 300 mm in the top sections. The height of the concrete core is 111.6 meters which contains 31 stories with a floor to floor height of 3,6 meter. In figure 7.13 an overview is given of the tapered concrete core in-situ and in table 7.6 the most important key-figures are displayed of this design.

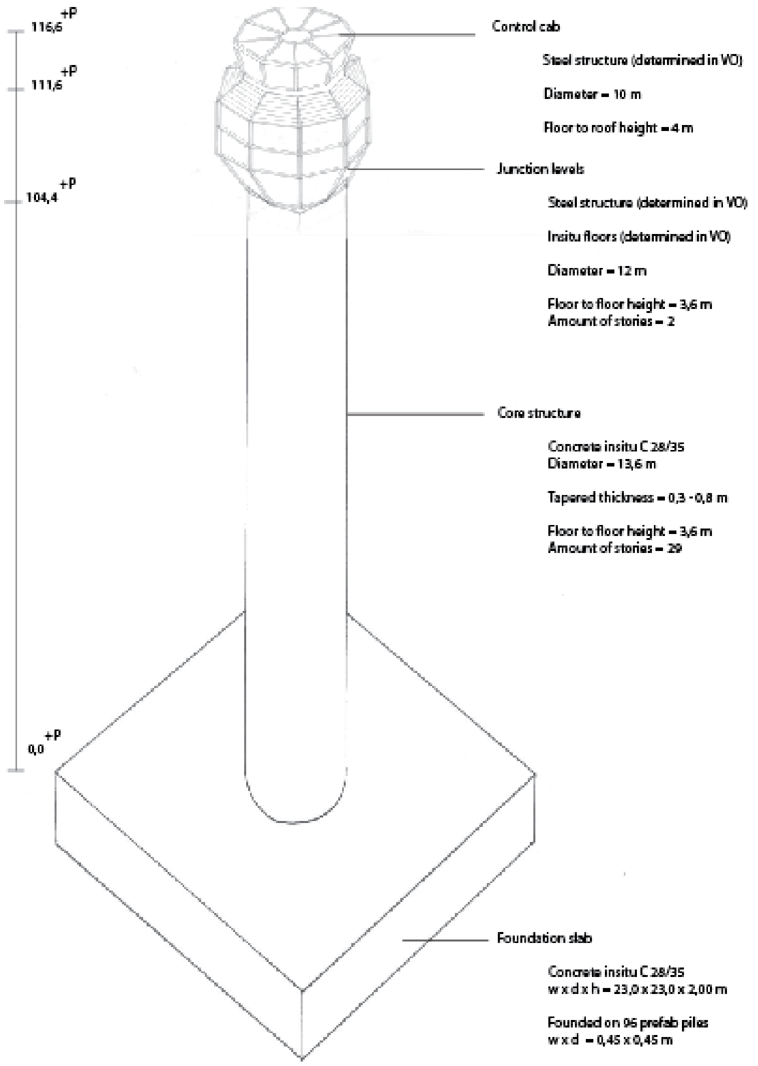


Figure 7.13: Concept design Istanbul airport, concrete core in-situ

7.7.2 Eccentric steel braced frame

The shape of the steel braced frame is octagonal in order to approach the aerodynamically round perimeter with a maximum length of 14400 mm. The shaft diameter of the tower is determined on basis of structural requirements, making the tower shaft surface larger than functional required.

The height of the braced frame is 115,2 meters which contains 32 stories, with a floor to floor height of 3,6 meter. The columns and beams are constructed with HE 600M elements, whereas smaller sections are used for the diagonals, namely HE180M. In figure 7.14 an overview is given of the concentric steel braced frame and in table 7.6 the most important key-figures are displayed of this design.

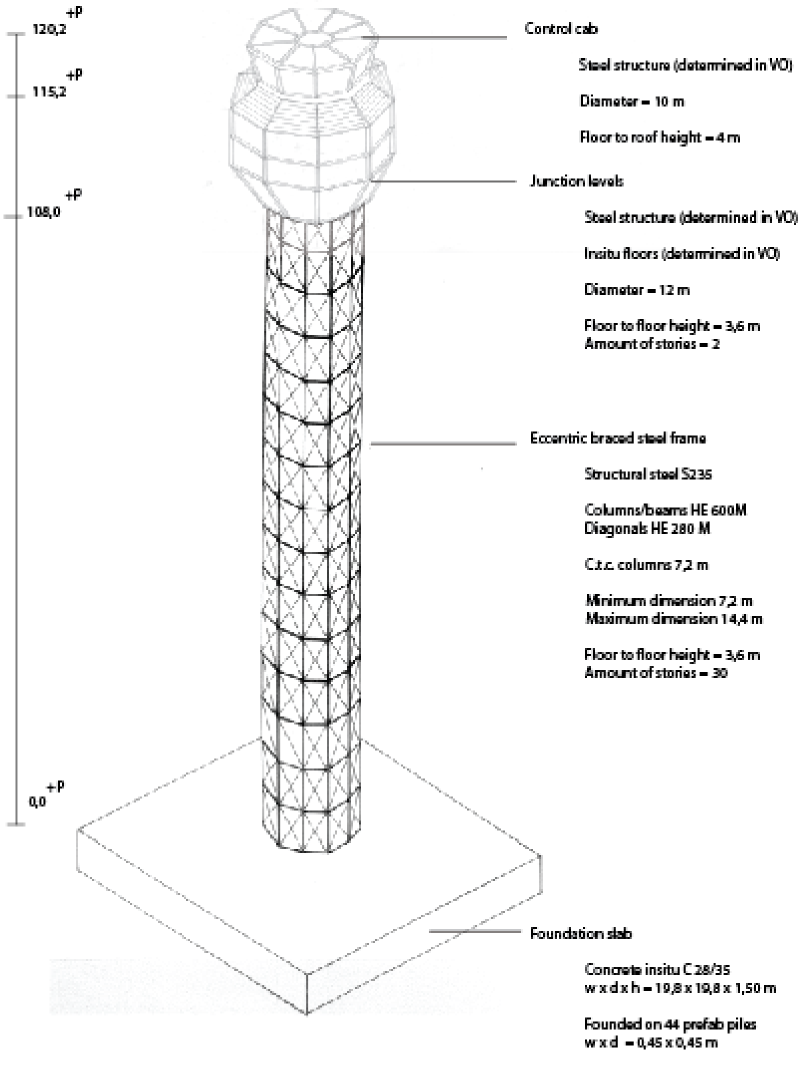


Figure 7.14: Concept design Jakarta airport, eccentric steel braced frame

7.7.3 Concrete core in-situ

The shaft diameter of the tower is determined on basis of deflection and strength requirements, making the tower shaft surface larger than functionally required. The inner length of the core is 12000 mm and an outer length of 13600 mm, whereby the wall thickness is 800 mm. The height of the concrete core is 111,6 meters which contains 31 stories, with a floor to floor height of 3,6 meter. In figure 7.15 an overview is given of the concentric core in-situ and in table 7.6 the most important key-figures are displayed of this design.

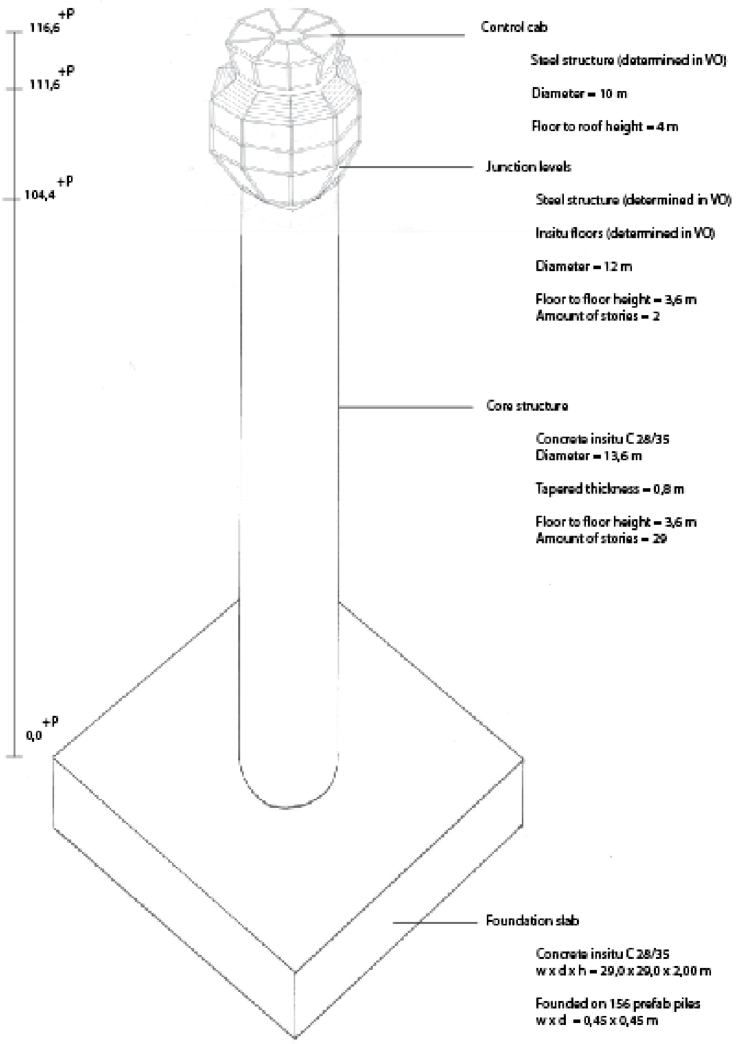


Figure 7.15: Concept design Jakarta airport, concrete core in-situ

7.7.4 Summary Jakarta concepts

Table 7.6: Design figures Jakarta airport

Aspect	Tapered concrete core in-situ	Eccentric steel braced frame	Concrete core in-situ	Value
Structural properties				
Inner length	13000 – 12000	14400	12000	mm
Wall thickness	300 - 800	-	800	mm
Beams / columns	-	HE 600M	-	-
Diagonals	-	HE 280M	-	-
Moment of inertia (80 %), average	3,79 E+14	4,7 E+12	5,29 E+14	mm^4
First Eigen-period	2,8	3,5	2,8	sec
Behaviour factor	5,4	6,0	5,4	-
Normative structural requirement	Stiffness, earthquake	Stiffness, wind	Stiffness, earthquake	
Material volumes				
Concrete core	2501	-	3590	m^3
Concrete foundation slab	1058	588	1682	m^3
Concrete total	3559	588	5272	m^3
Structural steel	-	-	798	tonne
Foundation piles (400 x 400)	96	48	156	-
Weight				
Upper structure	82643	30242	115293	kN
Foundation	31740	17642	50460	kN
Total	114383	47884	165753	kN
Relatively (total)	69	28	1000	%
Wind load				
Distributed wind load (80%)	13,22	22,74	13,22	kN/m
Moment wind between concepts	89713	146598	89713	kNm
Relatively (moment)	62	100	62	%
Earthquake load				
Base shear load	9435	2444	13163	kN
Moment earthquake	619778	305343	933940	kNm
Relatively (moment)	66	33	100	%
Relatively				
Moment wind	14	68	10	%
Moment earthquake	100	100	100	%
Functional				
Number of stories	31	31	31	-
Floor to floor height	3,6	3,6	3,6	m
Surface core	113	180	113	m^2
Surface elevator + stairs	10	10	10	m^2
Surface risers (remaining)	103	170	103	m^2

When comparing the tapered concrete concept design with the eccentric steel concept design, the main difference is the weight of the upper structure, which is expected. In this specific case the concrete upper structure is 2,3 times heavier.

Comparing both concrete structures, the tapered concept design contains approximately 30 % less concrete, resulting in 30 % less weight and a reduction of 35 % of the earthquake moment. This additional increase is caused by the movement of the centre of gravity of the entire tower downwards, reducing the arm and therefore bending moment.

7.7.5 Country comparisons

Table 7.7: Concrete core in-situ comparisons

Concrete core in-situ	**Japan**	**China**	**Turkey**	**Unit**
Earthquake hazard	9,8	1,6	4,8	m/s^2
Height	81	93	77	m
Structural properties				
Inner length	11000	6000	7500	mm
Diameter determination by	Structural requirements	Functional requirements	Structural requirements	-
Wall thickness	650	650	650	mm
Moment of inertia	3,24 E+14	6,06 E+13	1,11 E+14	mm^4
First Eigen-period	1,533	3,9	2,01	sec
Normative structural requirement	Strength, earthquake	Stiffness earthquake	Stiffness earthquake	-
Material volumes				
Concrete core	1927	1262	1258	m^3
Concrete foundation slab	1922	286	663	m^3
Concrete total	3849	1548	1921	m^3
Relatively	100	40	50	%
Foundation piles (400 x 400)	132	48	64	-
Weight				
Upper structure	**64738**	**45161**	**43452**	kN
Relatively between concepts	100	70	68	-
Foundation	57660	8570	19874	kN
Relatively between concepts	100	15	35	-
Total	122398	53731	63326	kN
Relatively	100	44	52	-
Earthquake load				
Base shear load	18108	2062	5953	kN
Moment earthquake	**955286**	**129800**	**292158**	kNm
Relatively	100	14	31	%
Base isolation	Yes	No	No	-

This section is made in order to give an idea how dominant the earthquake hazard is for concrete structures and other structures in general. For the comparisons the Japanese, Turkish and Chinese towers are used. This is allowed because the towers do have almost the same height and in this specific case the wind load can be disregarded, due to the normative earthquake requirements.

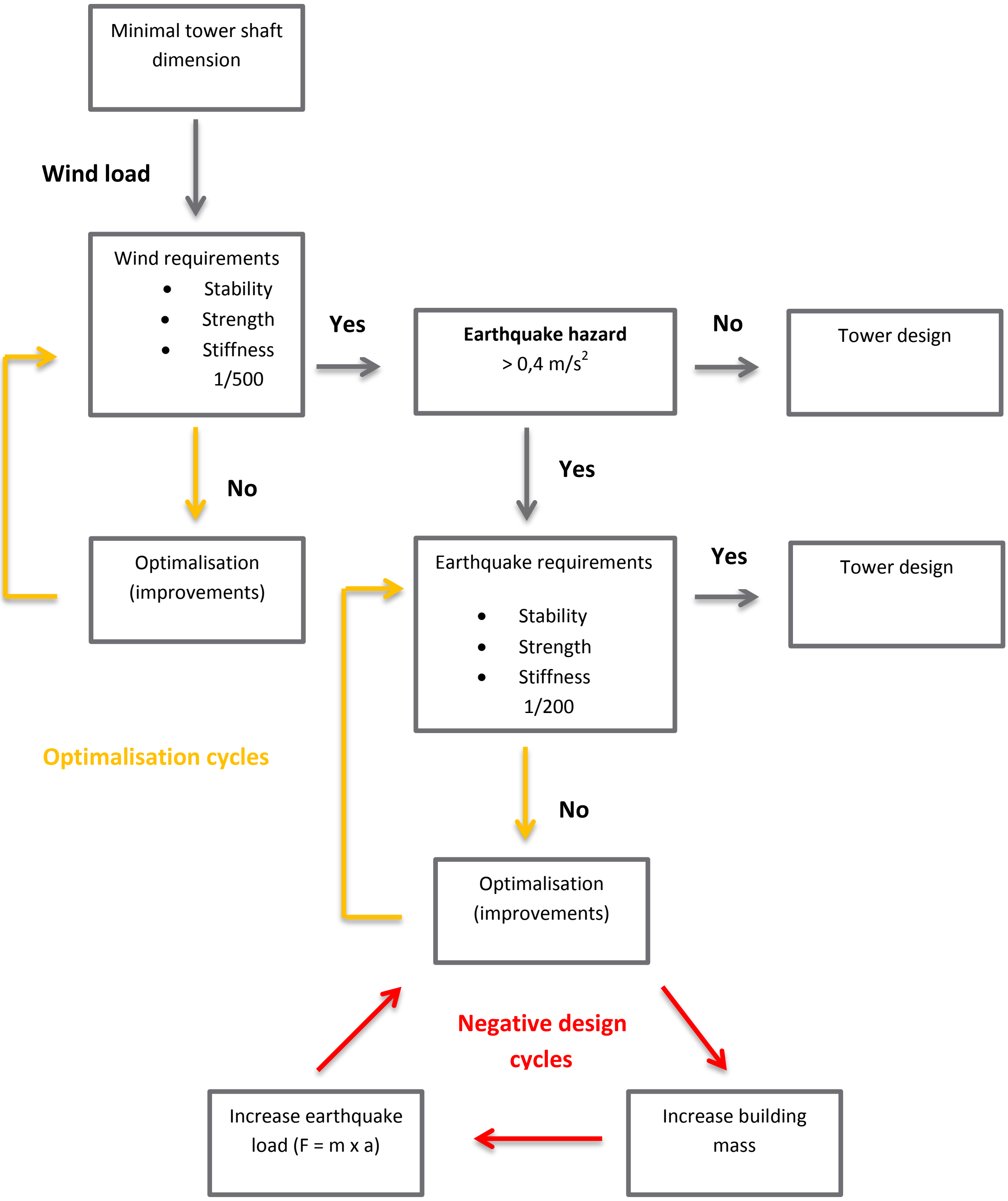
It can be seen that the Japanese tower is almost twice as large in diameter as the Chinese tower, in order to produce enough strength and stiffness. As a result the first Eigen-period decreases, which makes its more sensitive for earthquakes (design spectrum). More important is the relation of both masses and the applied hazard. The masses of the upper structures are respectively 64738 kN to 45161 kN, a difference of 30 %, however when looking at the earthquake moment it is respectively 955286 kN to 129800, of difference of 86 %. This is a very large increase, which can be dedicated purely to the increase of the earthquake hazard and this explains automatically the large differences in the foundation comparisons. The same appearance is seen while comparing the Chinese tower with the Turkish tower. The upper structures have nearly the same weight, a difference of 4 %, while the bending moment for Turkey significantly increases due to an increased earthquake hazard; a difference of 56 %.

7.8 Conclusions

The key-question *"How do these local boundary conditions relate with the structural design characteristics?"* is elaborated in this chapter and is answered by the following conclusions.

Based on the simulations of the previous concept designs, the conclusion can be made that the best structural methodology to design ATC towers is as displayed below.

Table 7.8: Structural design methodology



The earthquake load is an internal reaction force, which is directly related to the earthquake hazard and building mass. Improving the structure, results (in general) an increase of building mass which subsequently results in a higher earthquake load, forming an unavoidable negative (vicious) circle. The higher the earthquake load, the larger the related earthquake bending moments and larger the structure.

The wind load requirements are always normative for countries with an earthquake hazard lower than 0,4 m/s^2. In those countries the emphasis must be placed on the reduction of the wind load, whereby round structures are the most preferable shapes.

For round concrete core structures, in countries with an earthquake hazard higher than 0,4 m/s^2, the earthquake load requirements are normative. In those countries the emphasis must be placed on reducing the building mass by using tapered structures or using light weight structures.

Tapered structures (reduction of wall thickness along the height) are efficient solutions to reduce material volume; however the initial stresses increases and the stiffness of the tower decreases. The decrease of stiffness does not affect the maximum earthquake deflection, because due to the reduction of mass along the height, the related shear forces and total bending moments also directly increases. However it affects the maximum wind deflection.

For steel structures, in countries with an earthquake hazard higher than 0,4 m/s^2, the earthquake load requirements are not always normative.

The aim is to find a design whereby the maximum earthquake / wind moment is the smallest, offering the most optimal solution structural wise, but this does not always mean that these concepts are also optimal in an economical optimal perspective.

The first Eigen-period of ATC towers is in general high, which is very favourable for earthquake engineering. Therefore base-isolation and eccentric braced detailing are no straightforward solutions to improve the design spectrum of the tower in order to reduce the earthquake load and optimize the structure. For tower designs whereby the Eigen-period is larger than 2 seconds, these solutions have no effect. Per specific design these solutions must be reviewed and applied.

In general the cross-sectional area of the tower shaft is determined on basis of structural requirements, resulting in larger tower shafts than functionally required. Steel structures require a larger cross-sectional area in comparison with concrete structures, making steel structures in functional prospect less optimal.

Prefabrication reduces the stiffness of the tower, resulting in more construction material or higher required concrete classes.

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Phase III

“Closure thesis research report”

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8. Discussion

This thesis research started first by conducting a comprehensive international investigation (appendix I) in order to select a small amount of representative countries that will cover the globe. These selected countries are ranging from rich to poor, having large differences in both geographical and climatological conditions and having all their own specific construction industry characteristics, e.g. technical knowledge, material preferences and labour costs.

On basis of these countries a large variety of possible ATC tower designs and related characteristics were investigated making this thesis research applicable to use for all the countries around the globe. Conditions of non-investigated countries can be related with the identifiable conditions (conducted in this report) and from which the ATC design methodology (elaborated in the conclusions) can be followed in order to achieve an optimal design.

This thesis research is representative for use in designing new air traffic control towers located anywhere around the globe. First, the fundamental international aviation requirements set up by the FAA and ICAO are followed and applied with care in this research. Next, all the presented concept designs are examined with care to the dedicated building codes. However, during this thesis research also several design criteria were disregarded and assumptions were made.

The most important disregarded aspect would be the role of the architect. The role of the architect is disregarded during this thesis research, in order to reduce the design complexity. In reality each tower design is developed by its own architect based on his conception, resulting in different starting points and desires each time. As a result the role of the architect can have a major influence on the structural design of the tower and could subsequently results in other design solutions. For example, the tower designs in the middle-east are more extraordinary (higher, extravagant and bigger) than the ATC towers seen here in Europe.
In order to limit the influence of the architect, the author made this thesis research on basis of the fundamental functional requirements set by the FAA and ICAO, resulting in ordinary straightforward slender buildings. This type of design corresponds with the majority of ATC towers build around the globe, making this research also highly suitable to design ordinary ATC towers around the globe.

Other criteria which are disregarded in this research are durability, sustainability and maintenance aspects. Around the globe the importance and conception of these criteria are expected to be very diverse, which could result in different solutions. Whereas in the third world countries the maintenance aspects are assumed to be more important, compared with durability and sustainability, which are hot topics at this moment in the developed countries.

During this thesis research, most of the assumptions and starting points are based on extensive literature studies and interviews. The literature studies can be seen as very reliable, whereas the interviews can be seen as reliable but subjective. The assumptions based on the interviews are obtained by conducting questionnaires and interviews with experts from Royal HaskoningDHV and the air traffic control industry. These can unfortunately not be seen as scientific sources.

Therefore in order to increase the reliability and reduce the subjectivity, more interviews concerning the same topics were taken during the research process, with both professionals in the Netherlands as professionals in the selected countries. A few assumptions are formulated by the author itself, but these are made in line with the logical train of thought.

Along this thesis research several comprehensive calculations (wind calculations, earthquake calculations and structural design calculations) were performed by the author. These calculations are conducted on basis of reference examples and consulting colleagues of Royal HaskoningDHV. At the end these were checked by colleagues of Royal HaskoningDHV on correctness, making the outcomes of the calculations reliable. However, during this thesis research several assumptions regarding these calculations are made.

First, measures for progressive collapse are not taken into account. From interviews obtained with experts of the ATC industry it is determined that these towers are not designed to resist airplane impact and measures are mainly taken to avoid accidental actions near ground level. Therefore the influence of progressive collapse on the structural design was thought to be small and allowable to disregard.

For the earthquake calculation a hand calculated linear analysis is used to examine the structural reaction on earthquake action. This is a conservative method which is suitable because of the simplicity of the tower. However, this method is only taking into account the first Eigen-period of the structure, whereas in reality a structure has multiple Eigen-periods resulting in a slightly different behaviour.

In general, the Eigen-periods of the calculated ATC towers are high (> 2 seconds). These figures are determined by the NEN 6702, making these results reliable. However the foundation characteristics are not taken into account, therefore in reality (slightly) other Eigen-periods are expected.

The towers developed in chapter 7 are designed on basis of the two main construction materials; concrete and steel. However, during this thesis research only concrete or steel structures were developed, whereas composite concrete/steel structures were disregarded. Therefore the total range of structural possibilities is in reality even larger than elaborated in this thesis research.

Next the validity of the thesis research is discussed by validating the thesis objective. The overall objective was to perform an international investigation regarding the main local influences in order to provide an economical optimal structural design methodology for air traffic control towers. After a comprehensive research of 10 months, whereby 6 different countries were analysed, four important local influences were found which influence structural design of an ATC tower significantly. Next, on basis of these influences a methodology was developed to achieve targeted optimal design solutions, which subsequently results in the most likely economical optimal design.

At last the reliability is discussed, in order words, would another person obtain the same conclusions? In mainline, the author thinks that the main-, key-, and sub-questions along this report would be answered with the same conclusions. Whereas several recommendations are given in chapter 10 in order to improve the reliability.

9. Conclusions

Along the report all the sub-questions, key-questions and their conclusions can be summarized into the answers of the following main research question:

"What are the local influences on the structural design of an air traffic control tower and How do they relate with an economical optimal structural design?"

The answer on the "What" part of the main research question is that the following local boundary conditions are the most important local influences on the structural design of an air traffic control tower:

- Current and projected future air activity of the airport
- Wind climate
- Earthquake hazard
- Construction industry
  - Labour cost
  - Material cost
  - Technical construction standard

The answer on the 'How" part of the main research question cannot be answered by an unequivocal solution. First, per location the four boundary conditions (can) have different characteristics. Next, every single characteristic relates differently towards an economical optimal structural design, resulting in a large variety of possible solutions.
As a result, no economical optimal design for an ATC tower can be given from the drawing board at first sight. The local boundary conditions, as mentioned above, compete with each other in importance for every individual tower to provide the most economical solution. To clarify this statement, for normative wind loading other solutions are found than for normative earthquake loading.

In the methodology of chapter 6 and the comparative calculations of chapter 7 it has been proven that choices have to be made for each country on its own specific national bases. This results in the fact that in each country one or more optimal solutions can exist, whereby the final solution can be selected using optimization cycles along the conceptual design phase.

Nevertheless, the designer can follow a methodology conducted for an ATC tower design as displayed figure 9.1, in order to have a good design direction towards an economical optimal structure as elaborated in this thesis research.

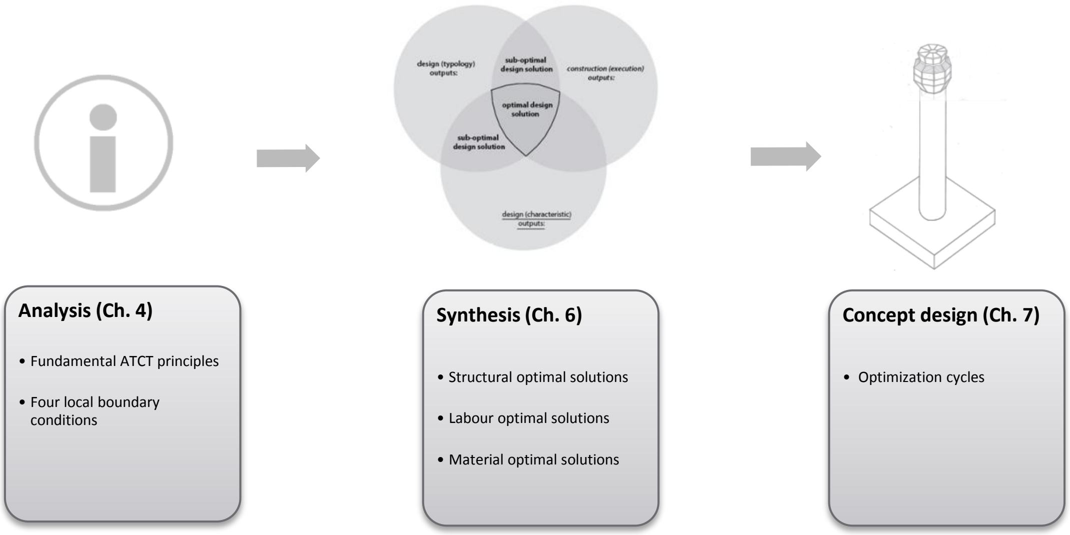

Figure 9.1: Design methodology optimal ATC tower design

Below examples are given of the six investigated countries in this thesis research, clarifying that the local boundary conditions results in different economical optimal ATC designs:

- The base of the Netherlands is the high labour costs (2x > World Average (WA)), confronted with very low earthquake hazard (0,4 m/s^2).
  The preferred solution is expected to be a prefab concrete core structure.

- In Nigeria the high material prices (2x > WA), the low technical construction standard, the low labour cost (4x < WA) and the heavy wind load (3,61 kN/m^2) are the most decisive factors.
  The preferred solution is expected to be a tapered concrete core in-situ structure.

- The bases for designing ATC towers in Japan are; high labour cost (2x > WA), high wind speeds (3,42 kN/m^2) and very high earthquake hazard (9,8 m/s^2). The preferred solution is expected to be an eccentric steel braced frame structure.

- In China the low labour cost, (3x < WA), the low earthquake hazard (1,6 m/s^2) and the cheap concrete (2x times < WA) are the most normative factors.
  The preferred solution is expected to be a tapered concrete core in-situ structure.

- The bases of Turkey are the high earthquake load (4,8 m/s^2), intermediate labour cost and the mediate technical construction standard. The preferred solutions are expected to be a concrete core in-situ or concentric steel braced structure.

- As last, in Indonesia the low labour cost (2x < WA) and the intermediate earthquake load (4,0 m/s^2) are the most decisive factors. The preferred solutions are expected to be a tapered concrete core in-situ or eccentric steel braced structure.

It is not possible to compare the abovementioned towers in cost, because these costs are depending onto many variables. However, these towers are expressed in the required construction materials; concrete or steel. An identical tower design (concrete core in-situ) requires in China 60 % and in Turkey 50 % less material compared with a tower in Japan. These differences can be entirely dedicated to the large difference in the local earthquake hazard.

10. Recommendations

The aim of this thesis research is to investigate the local influences on the structural design of an air traffic control tower around the globe. During this thesis research unfortunately not every aspect has been analysed (in detail), due to the defined duration of this research and the comprehensive international research field. As a result a few assumptions have been made or some issues have been disregarded.

In this chapter the recommendations are divided in two types. First, recommendations are given which can or should be further investigated leading to further improvements. Secondly, recommendations are given how to use the optimisation methodology to design an ATC tower in a randomly selected country and how to implement this methodology into a guidebook.

By clearly defining these recommendations, this thesis research retains its value and motivates structural engineers of Royal HaskoningDHV to use this report for their international work operations or my fellow students to continue further research regarding this international research topic.

Recommendations leading to improvements for future research

1) Progressive collapse of the structure is unacceptable, because these towers are very important buildings. To limit progressive collapse, the identification of accidental actions and taking specific measures has been chosen as the most efficient strategy. However these measures are not taken into account in the structural designs. Therefore research is required to identify the accidental actions to see how they relate and influence the structural design.

2) Several important design aspects and criteria are disregarded in this research as mentioned before in the discussion. These aspects and criteria are the influence of the architect, durability, sustainability and maintenance aspects. Further investigation is required. Subsequently, the criteria can be implemented in the same converge process presented in chapter 6. The criteria can be classified as stand-alone input variables and can be placed within one of the three main aspects, depending on its background. They have their own "passage" and will result in their own output, subsequently they can compete with each other regarding the most likely optimal structural design.

3) The information about the six international construction industries is gathered by conducting interviews with experts from Royal HaskoningDHV in both the Netherlands as abroad. More information is required in order to verify the used subjective assumptions in order to improve the reliability. This can be done by analysing local literature or conducting more interviews with other local design, construction companies or universities.

4) The steel and concrete concepts elaborated in chapter 7 are compared regarding their weight of the upper structure. Unfortunately the total construction cost of both designs cannot be compared, because the final cost of one m^3 concrete and one tonne of steel are unknown. In a further investigation it is interesting to investigate how the cost of one tonne assembled steel is related to one m^3 poured concrete. If this ratio is known, which is depending onto a variety of variables, these concepts can be compared on price. On basis of these prices the most optimal ATC tower design for the certain airport can be determined.

5) Only steel and concrete concept variants are elaborated in this thesis research. Composite concrete/steel variants are very interesting structures to explore in more detail, especially for earthquake regions, whereas the steel reduces the mass and the concrete combined with steel provides the stability.

6) A hand calculated linear analysis is used to examine the structural reaction on earthquake action, which is acceptable due to the simplicity of the tower. However, the results should be checked with a finite element program for correctness and adjustments must be taken when necessary.

7) Base isolation is proven to be an effective method to reduce the earthquake load on a building. In this thesis the assumption is made that the response spectrum of the tower is moved to the lowest part of the design spectrum (> 2 sec). However, how effective is base-isolation in reality and does it also relate with the height of the earthquake hazard and upper building characteristics? More research is required to determine the effect of base-isolation on these towers.

Recommendations to use this research and implementation for a future guidebook

8) In the conclusions, a design methodology for optimal ATC design is given which is displayed in figure 9.1. A designer can use this method as guideline.

   First the designer should gain knowledge about the fundamental aspects of ATC tower design which is elaborated in chapter 4. Very comprehensive background information could be found in the FAA and ICAO documents [FAA, 2004] and [ICAO, 1984].

   Next, the four most important local boundary conditions should be determined for the new air traffic control tower, examples are given in chapter 5.

   These boundary conditions are forming the inputs variables for the synthesis process (chapter 6) and should be implemented in the converge process. The “passages” which should be used are displayed in appendix VIII. More inputs or variable could be supplemented when necessary. The outputs are forming one or more optimal solutions which require further investigation.

   At last, the structural design approach prescribed in chapter 7 can be used to simulate the concepts in order to determine which concepts would be the structural optimal. Next, these structural solutions can be worked out in more detail which can form the conceptual basis for the multidisciplinary design teams of RHDHV.

   In this thesis research the Eurocode is taken as the normative building code. In reality the local code is decisive and must be used. However, if the local code is almost equal to the Eurocode, no big differences are expected and the Eurocode is adequate to use on conceptual design level.

9) One of the first intentions of this thesis research was to provide a guidebook in order to design optimal ATC towers around the globe. Unfortunately due to the lack of time no separate guidebook is written. However the author achieved to developed the most important part (ingredient), the optimal ATC design methodology.

Below several recommendations are given for the next students/colleagues to set up this ATC design guidebook.

- In general the set-up of this master thesis research can be used as framework for the guidebook in which the next items need to be elaborated in more detail.
- Improving the reliability of the ATC design methodology by applying recommendation numbers 1 to 7
- Provide checklists that guide the designer by every step, which allows the designer to validate his progress
- Step-by-step instructions that makes information easy of understand and it helps to avoid mistakes
- Providing design examples to clarify instructions, the design of chapter 7 can be used
- For further inquiries or assistance in writing this guidebook the author can always be counselled

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