Tall Buildings and Elevators
Historical Evolution of Vertical Communication Systems

João Miguel Serras Delgado Valente

Final Thesis for the Degree of Master in
Civil Engineering

Jury
President: Prof. Doutor José Manuel Matos Noronha da Câmara
Supervisor: Prof. Doutor João Carlos de Oliveira Fernandes de Almeida
Vowel: Prof. Doutor João Sérgio Nobre Duarte Cruz
Tall Buildings and Elevators

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Abstract

This paper addresses the evolution of tall buildings in their relation with structural systems and vertical communication systems. The main proposition is to take the historical development of structural solutions and elevator solutions to understand how both these aspects have shaped tall buildings that are being built today. Whenever deemed relevant these aspects are accompanied by brief description of social and economic context that could contribute to a broader notion of the motives and restraints towards building tall.

For the purposes of the above stated, there is an initial presentation on what a tall building is, how it can be defined and what aspects can contribute to that definition, afterwards a classification for the several systems will be presented. Then the history of tall buildings is broken down into several chapters that were found to carry significant relevance according to consulted bibliography; these chapters are defined in accordance with major changes in the paradigm for the conception of tall buildings. To further illustrate this distinction some short notes on relevant historical factors are given. Finally, conclusions are present regarding the parallels between structural development and technical evolution of vertical communication.

Keywords: Tall buildings, skyscrapers, elevators, vertical communication systems
Aknowledgement

I would first like to express my gratitude to Professor João Almeida for his support, guidance and encouragement through this long process.

I also thank Professor Dario Trabucco, of Università IUAV di Venezia, for his much appreciated advice and reading recommendations which have contributed extensively to the development of this document.

To Mr. Johannes Maasberg, of Japppen Ingenieure, and Professor Mona Domosh, of Dartmouth Colledge, I would like to express my appreciation of their availability and willingness to help.

Finally, I would like to thank my family,

and I would like to thank my friends,

and I would like to entertain the thought they know very well why.

à minha família,

obrigado.
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1 Introduction

1.1 The importance of tall buildings

Tall buildings have been one of mankind’s accomplishments for many years, taking the form of pyramids or cathedrals they have been a projection of man’s will and technique. Modern tall buildings have very little in common with the monuments of the past, though they still exert fascination upon people and many can be rightfully described as monuments, the modern tall buildings are built for practicality and everyday use.

Tall buildings as they are today came as a product of need, mostly the need to address rapid urban growth by supplying commercial and residential space. In their beginning in late 19th century commercial use buildings were the main trigger for construction development as businesses took great advantage of being close to each other and tended to concentrate in city centers, were consequently great pressure was put on land prices further enhancing the need to build higher [17].

Nowadays, demographics as well as economics still move construction of tall buildings as the densification of cities is evident worldwide. In China, more than 12 million people are expected to move into urban areas every year between now and 2030. In 2015, 3.9 billion (10^3) people worldwide will be living in cities and over 40% will be living in cities of more than 1 million people [27]. Tall buildings are solutions to these problems providing space where space is required.

Tall buildings are also a known presence, they mark the urban landscape, they are cities call cards making them recognizable and often symbolizing their power, but from a more technical point of view tall buildings have tended to be showcases for contemporary construction technology implementing the most advanced techniques and materials, and therefore embodying the very sense of vanguard of their time.

1.2 “How high is tall?”

Already several references have been made to tall buildings without clarifying what a tall building is. Most authors agree there is not a specific definition for tall buildings in fact the first tall buildings could hardly be called so by today’s standards Lynn S. Beedle, the founder of the Council for Tall Buildings and Urban Habitat (CTBUH) defined tall building as a building that exhibited some element of “tallness”. This element could have to do with its context, meaning its height relative to other buildings, its proportion, which refers to height to footprint ratio, and its employment of tall building technologies, this is the most interesting aspect.

Tall building technologies refer to special structural solutions, architecture, mechanical arrangements, elevator arrangements, etc. specialists of each of these areas will tend to qualify tall buildings in their own way. The consensus is that there is no specific definition for a tall building, though most specialists come to similar conclusions “The tallness of a building is a matter of a person’s or community’s circumstance and perception; therefore, a measurable definition of a tall building cannot be universally applied.” [17]. There should be however rules of thumb, simple criteria upon which a building should be considered tall,
CTBUH considers to be tall buildings those above 200m and super-tall the buildings above 300m, knowing that at these heights the “elements of tallness” such as wind resisting structural solutions, elevator solutions and other aspects become necessary for a building to stand and operate.

Having addressed this issue it must be referred the several names by which tall buildings can be addressed, such as skyscrapers, high-rise buildings, super-tall buildings, should be understood as synonyms in the context of this document. This is important to remark since these terms have specific meanings pending on the context.

1.3 The importance of vertical communication systems in tall buildings

Vertical communication systems refer to stairs and elevators, though for present purpose the term is to be understood as synonymous to elevators. These are fundamental requirements of tall buildings which have often been overlooked in spite of having an essential in a buildings performance and some significant consequences in building layout and overall economic performance for investor’s concern. This topic will be further addressed throughout this document emphasizing its role in the evolution of tall buildings towards their present form. Current elevator solutions will be analyzed and historical landmarks in elevator technology will be placed in context for other technological developments focusing also on building layout and structural implications.

1.4 How the thesis is structured

This research aims towards a better understanding of how innovation in structural design and elevator technology has shaped tall buildings in the past and present. For this purpose the following chapters will address structural systems, describing their basic functioning and classifying there several structural systems, and elevator systems, describing functions and configurations. The chapter that follows, which is basically the core of this research, considers tall buildings from an historical perspective attempting to consolidate several of the aspects affecting tall building at a given time period. Aspects such as economic and social conditions, architecture and the general paradigm shaping and motivating tall building development will be focused along with contemporary technical knowhow focusing mainly on structural systems and elevator systems. In the last chapter of the thesis summarizes and draws conclusions on the historical analysis focusing on tall building development and how structures and vertical communication systems between made a difference.
2 Structural Form

In spite of the many, aforementioned, interpretations and definitions for tall buildings and even considering some lack of consensus on a precise definition [26], structural attributes are ever present when characterizing high rise construction. It is therefore essential for the comprehension of high-rise construction to understand how the structure behaves and what are the main criteria influencing its conception. Thus the present chapter is devoted to the analysis of the structural design process, reviewing some of the main challenges of tall building structures and analyzing the most representative examples of such structures.

2.1 Structural design strategies

The evident implications of resisting lateral loading being one of the most dominant criteria in the adoption of the structural form are, however, just one of the many aspects the structural design team must account for. When designing such state of the art buildings questions rise that cannot be treated lightly as in regular buildings and therefore require the presence of specialists whose views are sometimes conflicting with those of the structural engineer, and can influence to great extent the structural form [22]. This chapter will address the design process only in the way it affects the structural form, thus leaving a more detailed and broadly focused analysis to a further chapter.

Early planning stages are of great importance for integrated and efficient design, thus demanding collaboration between all concerned parties, such as architect, structural engineer and services engineers [17]. Adding to traditional design teams building tall creates demand for other specialists uncommon to normal, low-rise buildings, such as:

- Façade engineers
- Wind specialists
- Geotechnical specialists
- Seismic specialists
- Fire consultants
- Elevator consultants
- Construction advisers

These specialists are to integrate the design team and have serious influence on structural design, it should therefore be acknowledged without any doubt that the full complement of parameters influencing the structural system is outside the structural engineers’ control [22]

2.1.1 Role of the structural engineer

Ideally, from a structural engineer’s perspective, determining the structural form would involve only the selection and arrangement of the major structural elements to resist most efficiently the various combinations of gravity and horizontal loading [17]. However, given the high degree of complexity characteristic of high-rise construction, the lack of margin for error and the need to optimize all
proceedings in order to guarantee the project’s viability, the role of the structural engineer must include not only the above stated aspects but also the consideration for the intended architectural layout and the accommodation of several other services determined by the respective specialists [44].

The role and impact of structure in a tall building is rather significant, not only for common support and safety purposes, but for functional, aesthetic and financial reasons [21]. Thus the structural engineer must present to the design team the fundamental characteristics and behavior of the structure, which other specialists are not expected to know, [45] dialog between specialists should provide further optimization of the structural system and the building itself leading to ever more environmentally efficient buildings.

There are some key aspects the structural engineer must be focused on in early design stages as guidance for dialog and project development [22], are aspects are now discriminated and will be properly addressed in a further chapter.

- Slenderness ratio
- Selecting the structural system
- Building services coordination, integration and Architecture
- Façade engineering and shape
- Planning the core
- The effect of building use
- Vertical transportation
- Fire requirements
- Buildability
- Damping
- Accidental damage

2.1.2 Explaining structural efficiency

A building’s efficiency can be subject to broad interpretation, it can be economically efficient and prove a good investment for its owners, it can be functionally efficient and meet all the occupants’ spatial and functional needs and, currently one of the main concerns, environmental sustainability.

Sustainability has been for some time a key issue in construction in general and high rise construction in particular, being associated with some of the major challenges that have faced the industry. To fully assort how sustainability impacted the whole paradigm of skyscraper design both in the past and present a more detailed analysis is to take place in chapters 4 and 5, concerning historical evolution and design strategies, respectively.

Coming back to efficient structures and efficient structural design in tall buildings two main issues must be addressed, the structural efficiency perspective and the environmental perspective. Both perspectives are at some points correlated but are quite different in meaning.

Structural efficiency concerns optimal use of structural elements, meaning the structure is making full use of all its components. As straightforward as this may seem it is a complex notion, that of structural
efficiency. Considering early super-tall buildings such as the Empire State Building, a braced frame structure, height was made possible by over dimensioning beams and columns [4] since a more detailed analysis of structural behavior was impossible. Comprehensively these massive structures used a lot more material than was actually necessary thus making the structure environmentally less sound.

Today due to modeling possibilities made possible by the increase of computer power more extensive behavioral studies can be provided, thus enabling comparisons between several structural systems leading to a better “tuned” and efficient structural form that requires less material resources. An unwanted result of these optimized structural systems is a reduction in the buildings’ structural redundancy, whereupon the elimination of seemingly unneeded structural elements must be attended with caution [10].

Considerations for the sustainable (meaning environmentally sound) design of structures concern not only the structure but the building as a whole, which means even though being structurally effective translates into being a step closer to being sustainable it alone is not enough as an environmentally effective structure should also enable optimal solutions for architecture, services and such other aspects.

The emphasis on efficiency and sustainability is a fundamental part of early stage design strategies to which all concerned parties should be receptive, from promoters to designers and constructors, as financial feasibility aspects are also connected through both construction materials, cost of required technology, maintenance costs, and so on.

Further development on the subject of sustainable design and financial issues of building tall will be provided in chapter 5.

2.1.3 Lateral loading
In the beginning of the 20th century structural members were assumed to carry primarily the gravity loads. However due to the advances in structural design and aided by the development of high-strength materials buildings are enabled to grow higher, weigh less and present greater slenderness. A result of this being the buildings’ increased vulnerability to lateral loads such as wind and earthquake [28].

Wind especially is of great importance for the conception of a tall building, hence the structural definition for tall relying on the determination of the structural system according to wind loading demands [18]. The “art” in tall building design is to balance structural strength, rigidity and dampening aiming towards the comfort of its occupants [39], naturally this does not mean other factors such as ultimate limit states are of lesser importance, just that tall buildings are generally not controlled by the strength of the lateral load resisting system but by limiting motion to acceptable limits [10].

Wind related dynamics can be broken down into three components: background static and background dynamic, which are a function of the surrounding environment and wind climate thus independent from building behavior, and resonant dynamic which proves to be the most relevant of the three [10].

Resonant dynamic forces induce vibration fundamentally in the two directions orthogonal to the building axis and torsion about the said axis which are associated with the fundamental vibration modes, however due this phenomenon’s high complexity other types of behavior may occur that cannot be described
through those basic movements [13]. Figure 1 presents a scheme of the several dynamic effects associated with the wind.

![Wind Dynamic effects diagram]

For tall building design the main concern will be Lock-in phenomenon associated with vortex-shedding, which is the actual shedding of vortexes in the downstream side of the building causing strong fluctuation forces in the cross-wind direction being the main distinctive feature between mid-rise and high-rise buildings [32].

Acknowledging such phenomena in an early stage of design is of great importance since it can be almost eliminated through the adoption of an aerodynamically more favorable shape [32], leading to lesser structural demand hence allowing for less material and a “lighter” more sustainable structure. As a final note to quantify the material requirements related with wind demands Figure 2 shows in accordance to building height what would be the material needs and to what purposes they would be applied, when considering buildings of similar structural type and intended purpose [17].

![Figure 2 - weight of steel in tall buildings Smith and Coull 1991, pp35]
As can be observed, and as previously stated, material requirements grow rapidly with height and mostly to wind demands, this approach of weight of material per unit of area is rather straightforward way of measuring structural efficiency of buildings with similar use, height and, of course, structural material [17].

2.2 Tall building structures

Tall building structures have come a long way since Le Baron Jenney’s days when steel frames were taking its first steps and the Chicago Home Insurance Building’s eight-stories set unprecedented height standards.

As stated earlier, structural form is one of the main characteristics of tall buildings due to very specific demands it must deal with, some of the more relevant have already been discussed. There is currently a wide array of solutions available to engineers when planning a building’s structural form.

As there are many buildings and building types, there are also structural types and such variety contributes to some division among specialists on how to classify said structures. In spite of it, since most proposed classifications consider as criteria the structure’s behavior under lateral loading most classification often come to similar conclusions as to what are the representative structural systems for tall buildings.

2.2.1 Structural materials

The most general way to approach the subject will be to consider there are 3 types of building according to their structure: concrete buildings, steel buildings and composite buildings [28]. This refers, of course, to the material used for the main structural elements such as columns, beams, bracing and shear-walls, other elements such as floor-slabs are not considered as structural elements, in spite of their contribution to structural behavior. Therefore a building with a concrete frame (beams and columns), bracing system or shear-wall will fall into the concrete building category, a building with steel frame, bracing and shear-wall is a steel building and if both materials are used in these elements it’s a composite building.

This approach is more relevant today than a few years ago when most skyscrapers depended almost exclusively on steel for structural support, benefitting from its high strength-to-weight ratio, ease of assembly and field installation, economy in transport to the site, availability of various strength levels, and wider selection of sections. Though having had a late entrance to tall building construction concrete has been evermore present due to its moldability characteristics, and natural fireproof property, architects and engineers utilize the reinforced concrete to shape the building, and its elements in different and elegant forms. Besides this, when compared to steel, reinforced concrete tall buildings have better damping ratios contributing to minimize motion perception and heavier concrete structures offer improved stability against wind loads. New innovations in construction technology, methods of design and means of construction, have all contributed to the ease of working with concrete in the construction of tall buildings [28]. Also, technological developments regarding high-strength concrete and pumping systems have enabled the use of concrete in the world’s tallest buildings such to the extent that at the beginning of 2011 the 1974 Willis Tower (442m) in Chicago was the only all-steel building featured in
the top ten tallest buildings in the world, the tenth tallest being the Trump International Hotel & Tower (423m) which has an all concrete structure, all other buildings in the top ten have a composite structure, as seen in Figure 3.

<table>
<thead>
<tr>
<th>#</th>
<th>building name</th>
<th>city</th>
<th>meters</th>
<th>feet</th>
<th>fl.</th>
<th>year</th>
<th>material</th>
<th>use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Burj Khalifa</td>
<td>Dubai (AE)</td>
<td>828</td>
<td>2,716</td>
<td>163</td>
<td>2010</td>
<td>steel-concrete</td>
<td>hotel/residential/office</td>
</tr>
<tr>
<td>2.</td>
<td>Taipei 101</td>
<td>Taipei (TW)</td>
<td>508</td>
<td>1,666</td>
<td>101</td>
<td>2004</td>
<td>composite</td>
<td>office</td>
</tr>
<tr>
<td>3.</td>
<td>Shanghai World Financial Center</td>
<td>Shanghai (CN)</td>
<td>492</td>
<td>1,614</td>
<td>106</td>
<td>2008</td>
<td>composite</td>
<td>office/hotel</td>
</tr>
<tr>
<td>4.</td>
<td>International Commerce Centre</td>
<td>Hong Kong (CN)</td>
<td>494</td>
<td>1,629</td>
<td>108</td>
<td>2010</td>
<td>composite</td>
<td>office/hotel</td>
</tr>
<tr>
<td>5.</td>
<td>Petronas Tower 1</td>
<td>Kuala Lumpur (MY)</td>
<td>452</td>
<td>1,482</td>
<td>85</td>
<td>1998</td>
<td>composite</td>
<td>office</td>
</tr>
<tr>
<td>6.</td>
<td>Petronas Tower 2</td>
<td>Kuala Lumpur (MY)</td>
<td>452</td>
<td>1,482</td>
<td>85</td>
<td>1998</td>
<td>composite</td>
<td>office</td>
</tr>
<tr>
<td>7.</td>
<td>Zifang Tower</td>
<td>Nanjing (CN)</td>
<td>450</td>
<td>1,476</td>
<td>86</td>
<td>2010</td>
<td>composite</td>
<td>office/hotel</td>
</tr>
<tr>
<td>8.</td>
<td>Wilke Tower</td>
<td>Chicago (US)</td>
<td>442</td>
<td>1,450</td>
<td>108</td>
<td>1974</td>
<td>steel</td>
<td>office</td>
</tr>
<tr>
<td>9.</td>
<td>Guangzhou International Finance Center</td>
<td>Guangzhou (CN)</td>
<td>439</td>
<td>1,439</td>
<td>103</td>
<td>2010</td>
<td>composite</td>
<td>office/hotel</td>
</tr>
<tr>
<td>10.</td>
<td>Trump International Hotel &amp; Tower</td>
<td>Chicago (US)</td>
<td>423</td>
<td>1,388</td>
<td>85</td>
<td>2009</td>
<td>concrete</td>
<td>hotel/residential</td>
</tr>
</tbody>
</table>

Figure 3 -Ten tallest buildings in the world adapted from CTBUH

Having discussed the basic structural elements special focus should now be drawn to the buildings service core. Structurally the service core consists of a group of shear-walls in most structural solutions the core will form the main backbone of the building thus carrying a large proportion vertical and lateral loading [22] as well as the buildings’ main functional. The fact that the service core generally houses most of the buildings vertical distribution elements, such as electricity, ventilation and of course the elevators, makes this the most important element during the design process requiring the combined attention of all specialists [22].

2.2.2 Classification of Tall Building Structural Systems
As stated earlier, there is no generalized consensus on this subject and in the interest of this project only the most representative systems will be discussed with careful consideration for experts’ opinions and as much attention to subcategories as thought necessary.

The classification of structural systems became an issue only in the late 1960’s through the pioneering work of Fazlur Khan. Khan argued that the rigid frame had dominated tall building design for too long and, backed up by developments in mechanics of materials and member behavior, reasoned that the structure could be analyzed in three dimensions, supported by computer simulations, rather than as a series of planar systems in each principal direction [4]. Khan approach emphasized efficiency and as such presented his “Heights for Structural Systems” diagrams, shown in Figure 4 and Figure 5, which represent a hierarchy of structural systems according to relative effectiveness in resisting lateral loads. As can be observed Khan considered the influence of the structural materials, further it should be noticed that the classification does not concern a scenario where seismic load is the constraining criteria.
Key to understanding this hierarchy is Khan’s the notion of “premium for height”, a concept he developed when observing that as buildings grew higher demands on the structural system due to lateral loads increase dramatically thus the size of the structure increases in large proportion requiring more material and taking up more otherwise free rentable area [2]. This concept is illustrated in Figure 6.
Ali and Moon (Ali&Moon, 2007) propose a more updated classification that considers “premium for height”, the structure’s lateral load resisting capabilities and more importantly the most representative structural solutions today. The authors propose discrimination between interior and exterior structures according to the distribution of the components of the primary lateral load-resisting system over the building, hence a system will be considered an interior structure when the major part of the lateral load resisting system is located within the interior of the building and an exterior structure when the major part of the lateral load resisting system is located within the exterior of the building [4]. Other criteria accounted to further categorize the structures, Figure 7 and Figure 8 represent this classification and some of the solutions’ main characteristics, while Figure 9 and Figure 10 show the several structural forms according to viable height.

Figure 6 - Premium for Height
Figure 7 - Ali & Moon, 2007 Interior Structures

Figure 8 - Ali & Moon, 2007 Exterior Structures
<table>
<thead>
<tr>
<th>Category</th>
<th>Sub-Category</th>
<th>Material / Configuration</th>
<th>Efficient Height Limit</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Building Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid Frames</td>
<td></td>
<td>Steel</td>
<td>30</td>
<td>Provide flexibility in floor planning. Fast construction.</td>
<td>Expensive moment connections. Expensive fire proofing.</td>
<td>860 &amp; 880 Lake Shore Drive Apartments (Chicago, USA, 26 stories, 82 m), Business Men's Assurance Tower (Kansas City, USA, 19 stories), Seagram Building, 30th to the top floor (New York, USA, 28 stories, 187 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Concrete</td>
<td>20</td>
<td>Provide flexibility in floor planning. Easily moldable.</td>
<td>Expensive formwork. Slow construction.</td>
<td>Ingalls Building (Cincinnati, USA, 16 stories, 66 m)</td>
</tr>
<tr>
<td>Braced Hinged Frames</td>
<td></td>
<td>Steel Shear Trusses + Steel Hinged Frames</td>
<td>10</td>
<td>Efficiently resist lateral loads by axial forces in the shear truss members. Allows shallower beams compared with the rigid frames without diagonals.</td>
<td>Interior planning limitations due to diagonals in the shear trusses. Expensive diagonal connections.</td>
<td>Low-rise buildings</td>
</tr>
<tr>
<td>Shear Wall / Hinged Frames</td>
<td></td>
<td>Concrete Shear Wall + Steel Hinged Frame</td>
<td>35</td>
<td>Effectively resists lateral shear by concrete shear walls.</td>
<td>Interior planning limitations due to shear walls.</td>
<td>77 West Wacker Drive (Chicago, USA, 80 stories, 203.6 m), Casaden Place (Melbourne, Australia, 43 stories, 160 m)</td>
</tr>
<tr>
<td>Braced Rigid Frames</td>
<td></td>
<td>Steel Shear Trusses + Steel Rigid Frames</td>
<td>40</td>
<td>Effectively resists lateral loads by producing shear truss - frame interacting system.</td>
<td>Interior planning limitations due to shear trusses.</td>
<td>Empire State Building (New York, USA, 102 stories, 381 m), Seagram Building, 17th to 29th floor (New York, USA, 38 stories, 157 m)</td>
</tr>
<tr>
<td>Shear Wall (or Shear Truss) - Frame Interaction System</td>
<td>Shear Wall / Rigid Frames</td>
<td>Concrete Shear Wall + Steel Rigid Frame</td>
<td>60</td>
<td>Effectively resists lateral loads by producing shear wall - frame interacting system.</td>
<td>Interior planning limitations due to shear trusses.</td>
<td>Seagram Building, up to the 17th floor (New York, USA, 38 stories, 157 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Concrete Shear Wall + Concrete Frame</td>
<td>70</td>
<td>*</td>
<td>*</td>
<td>311 South Wacker Drive (Chicago, USA, 75 stories, 284 m), Cook County Administration Building, former Brunswick Building (Chicago, USA, 38 stories, 145 m)</td>
</tr>
<tr>
<td>Outrigger Structures</td>
<td></td>
<td>Shear Cores (Steel Trusses or Concrete Shear Walls) + Outriggers (Steel Trusses or Concrete Walls) + Steel or Concrete Composite (Super Columns)</td>
<td>150</td>
<td>Effectively resists bending by exterior columns connected to outriggers extended from the core.</td>
<td>Outrigger structure does not add shear resistance.</td>
<td>Taipei 101 (Taipei, Taiwan, 101 stories, 509 m), Jin Mao Building (Shanghai, China, 88 stories, 421 m)</td>
</tr>
</tbody>
</table>

Figure 9 - Interior Structures
<table>
<thead>
<tr>
<th>Category</th>
<th>Sub Category</th>
<th>Material / Configuration</th>
<th>Efficient Height Limit</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Building Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Framed Tube</td>
<td>Steel</td>
<td>80</td>
<td>Efficiently resists lateral loads by locating lateral systems at the building perimeter.</td>
<td>Shear lag hinders true tubular behavior. Narrow column spacing obstructs the view.</td>
<td></td>
<td>Aon Center (Chicago, USA, 83 stories, 346 m)</td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td>Water Tower Place (Chicago, USA, 74 stories, 262 m)</td>
</tr>
<tr>
<td>Braced Tube</td>
<td>Steel</td>
<td>100 (With Interior Columns) – 150 (Without Interior Columns)</td>
<td>Efficiently resists lateral shear by axial forces in the diagonal members. Wider column spacing possible compared with framed tubes. Reduced shear lag.</td>
<td>Bracings obstruct the view.</td>
<td></td>
<td>John Hancock Center (Chicago, USA, 100 stories, 344 m)</td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td>Omega Center (Chicago, IL, 59 stories, 174 m), 780 Third Avenue (New York, USA, 50 stories, 174 m)</td>
</tr>
<tr>
<td>Bunded Tube</td>
<td>Steel</td>
<td>110</td>
<td>Reduced shear lag.</td>
<td></td>
<td>Interior planning limitations due to the bunded tube configuration.</td>
<td>Sears Tower (Chicago, USA, 108 stories, 442 m)</td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td>110</td>
<td></td>
<td></td>
<td></td>
<td>Carnegie Hall Tower (New York, USA, 62 stories, 230.7 m)</td>
</tr>
<tr>
<td>Tube In Tube</td>
<td>Ext. Framed Tube (Steel or Concrete) + Int. Core Tube (Steel or Concrete)</td>
<td>80</td>
<td>Effectively resists lateral shear by producing interior shear core - exterior framed tube interacting system.</td>
<td>Interior planning limitations due to shear core.</td>
<td></td>
<td>181 Madison Street (Chicago, USA, 80 stories, 207 m)</td>
</tr>
<tr>
<td>Diagrid</td>
<td>Steel</td>
<td>100</td>
<td>Efficiently resists lateral shear by axial forces in the diagonal members.</td>
<td></td>
<td>Complicated joints.</td>
<td>Hearst Building (New York, USA, 43 stories, 182 m), 30 St Mary Axe, also known as Swiss Re Building (London, UK, 41 stories, 181 m)</td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td>60</td>
<td></td>
<td></td>
<td>Expensive formwork. Slow construction.</td>
<td>O-14 Building (Dubai)</td>
</tr>
<tr>
<td>Space Truss Structures</td>
<td>Steel</td>
<td>150</td>
<td>Efficiently resists lateral shear by axial forces in the space truss members.</td>
<td>Obstruct the view. May obstruct the view.</td>
<td></td>
<td>Bank of China (Hong Kong, China, 72 stories, 367 m)</td>
</tr>
<tr>
<td>Superframes</td>
<td>Steel</td>
<td>160</td>
<td>Could produce supertall buildings.</td>
<td></td>
<td>Building form depends to a great degree on the structural system.</td>
<td>Chicago World Trade Center (Chicago, USA, 168 stories, Unbuilt)</td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td>Parque Central Tower (Caracas, Venezuela, 56 stories, 221 m)</td>
</tr>
<tr>
<td>Exoskeleton</td>
<td>Steel</td>
<td>100</td>
<td>Interior floor is never obstructed by perimeter columns.</td>
<td></td>
<td>Thermal expansion / contraction. Systemic thermal bridges.</td>
<td>Palacio de Exposiciones (Barcelona, Spain, 43 stories, 137 m)</td>
</tr>
</tbody>
</table>

Figure 10 - Exterior Structures
Given this classification’s relative complexity, the authors stress it should be treated as a guideline and further state it is imperative that each system has a wide range of height applications depending upon other design and service criteria related to building shape, aspect ratio, architectural functions, load conditions, building stability and site constraints [4].

To the already very extensive classification presented by Ali and Moon, another very particular type of structure should be considered, the buttressed core system as it is supporting the tallest building in the world, the Burj Khalifa in Dubai.

2.2.3 Brief analysis of structural systems according to behavior

Having gone through some very sophisticated classification systems for tall building structures, a more synthetic approach will now be implemented as the aim is to address how the latter mentioned structures behave, regardless of structural material or feasibility.

For pure behavioral consideration structures can be categorized in: frame systems, braced or shear wall systems, outrigger systems and tube systems, however due to some behavioral characteristics worthy of reference other subcategories have been considered such as presented below [28].

1. Rigid frame systems
2. Braced frame and shear wall frame systems
   a. Braced frame systems
   b. Shear-walled frame systems
3. Outrigger systems
4. Tube systems
   a. Framed-tube systems
   b. Braced-tube systems
   c. Bundled-tube systems

This approach finds great similarities to the one proposed by FIB [22] for concrete framed buildings, therefore accentuating the adaptability to all structural materials. FIB considered further discrimination according to building height and feasibility as the more complex classification systems already discussed, the focus however is solely on concrete structures.

Rigid frame structures

This system is applied to both concrete and steel structures and has long been applied to structural design. Being known as moment-resisting frames (MRF), the system consist of a series of beams and columns rigidly connected in a planar grid form, resisting loads primarily through the flexural stiffness of the members [4]. The intended behavior is monolithic, column size being dictated mainly by gravity loads and beam size being determine in order to guarantee frame stiffness, for efficient frame action, columns should be spaced close together and beams must be deep [4]. Special attention must be paid to the joints, especially in seismic zones aiming towards the frames ductility and hysteretic dissipation properties.
Even though this structural form was historically groundbreaking and was widely used in steel construction, due to its intended monolithic behavior and with modern technology, it is more suitable to concrete building structures and so has been used with great success to heights up to 30 stories, (approximately 70 meters) in areas without earthquake risk, as above this height lateral stiffness demands overwhelm frame rigidity or otherwise require oversized columns and beams leading to an inefficient [28].

**Braced Frame structures**

This system is used in steel construction, it is both an efficient and economical way for improving the lateral stiffness and resistance of a rigid frame system. The bracing will almost eliminate the bending of columns and beams by resisting lateral loads primarily through axial stress, thus allowing for slenderer elements. The structure acts as a vertical cantilever truss, where columns act as cord members and braces act as web members. Bracing systems will be dependent of architecture and service needs as the bracing elements may act as a passage impediment, therefore bracing is commonly allocated to elevator and stairs areas where it can be enclosed within walls [4]. Figure 11 shows the main types of braces and a famous example of the application of bracing, the Empire State Building, with detail.

![Bracing Types](image1)

Figure 11 - Types of bracing and Empire State Building Structure
Shear-walled frame systems

Shear-walled frame systems are used for both concrete and composite construction, in the steel construction a shear-wall can be referred to as shear-trusses it is a matter of material as a shear-wall is made of concrete. Shear walls behave like vertical cantilever beams resisting wind and seismic loads transmitted by floor diaphragms or beams, thus creating a stiffer stronger structure [4], they are usually a part of the service core, accommodating multiple services, elevators and stairs.

The interaction between shear wall and frame bring great structural benefit due to the stiffness attained, as the frame acts to restrict shear-wall deflection towards the top while the shear wall restricts frame deflection at the bottom of the building, as shown in Figure 12[4]. Again, it was Khan who, alongside Sbarounis, presented the mechanics of the shear wall-frame interaction in a groundbreaking paper that led to the development of these innovative, cost-effective structural systems.

![Figure 12 - Frame shear-wall interaction](image)

This system can be applied to buildings up to 70 stories high though there are cases where this was exceeded, namely the Petronas Towers (88 stories, 452m) which is a composite structure. The Shear-walled frame system is depicted in Figure 13 alongside the Petronas Towers (Kuala Lumpur, Malaysia).

![Figure 13 - Shear-walled frame system + Petronas Towers](image)
Outrigger systems

Outrigger systems have been historically used by sailing ships to help resist the wind forces in their sails, making the tall and slender masts stable and strong. The core in a tall building is analogous to the mast of the ship, with outriggers acting as the spreaders and the exterior columns like the stays. [4]. In a way outrigger systems can be considered a modified form of braced frame and shear-walled frame systems, and are utilized in steel and composite constructions.

Outrigger system comprises a central core, including either braced frames or shear walls, with horizontal ‘‘outrigger’’ trusses or girders connecting the core to the external columns, which are in many cases connected between them by exterior belt trusses. Under lateral loading the core, which would otherwise act as pure cantilever, will experience a reduced overturning moment as the outriggers will transfer most of the stress to the outside columns, Figure 14 represents both behavior and stress distribution [4].

![Figure 14 - outrigger behavior and reduced moment on core](image)

Generally outriggers take the form of trusses when made of steel, and walls when made of concrete, as they are to transmit substantial loads along the building in order to mobilize a tension-compression couple in outer columns, outriggers are often position at several heights and tend to be at least two stories high, both to insure structural solidity and to minimize view obstruction from within the building [4]. In Figure 15 a scheme of an outrigger system is presented alongside the 101 story-high Taipei 101 Tower (508 m) which stood as the world’s tallest building until the Burj Khalifa’s overture in 2010.
Framed Tube system

Also a concept developed by Fazlur Kahn, the tube system is appropriate for steel, concrete and composite construction, it represents a logical evolution over the traditional frame structures. The paradigm of tube structures is that tall building structures when submit to lateral loading can be compared to a cantilever beam, as such the tube will mimic the beams behavior when submitted to a bending moment. Therefore the principle is to concentrate as much lateral load-resisting system components as possible on the perimeter of tall buildings to increase their structural depth, and, in turn, their resistance to lateral loads.

The framed tube system is the most basic form of tube structures, requires closely spaced columns (1,5m to 4,5m) and deep spandrel beams rigidly connected throughout the exterior frame, as a result aesthetics are deeply marked by the structure, an example of this structural form were the World Trade Center Towers.

An important factor associated with the framed tube system is shear lag, which is the non-linear stress distribution along both “flange” columns and “web” columns causing columns closest to the corners to be more stressed than those near the middle, as shown in Figure 16.
A target set when using tubular systems is to minimize the shear lag effect, both the bundled tube and braced tube systems come as possible solutions, as minimizing shear lag and balancing stress among the columns improves structural efficiency to smaller columns with larger spacing.

**Bundled Tube system**

The bundled tube system is an aggregation of several tube structures that as a result can be smaller and deal more efficiently with shear lag, thus allowing for more wider spacing between columns. An example of this structural system is the Willis Tower, depicted in Figure 17.
**Braced Tube system**

This system deals with shear lag through the introduction of diagonal bracing to stiffen the perimeter frames in their own planes while collecting gravity loads from floors and acting as inclined columns. Therefore, the columns can be more widely spaced and the sizes of spandrels and columns can be smaller than those needed for framed tubes, allowing for larger window openings [4]. An example of the braced tube system is the John Hancock Building in Chicago, as shown in Figure 18, the braces have deep impact on the façade.

![Figure 18 - John Hancock Building](image)

**Buttressed core system (Burj Kahlifa)**

Though not a common or diversely applied structural form, the buttressed core system is worth mentioning as it is currently the benchmark in tall building structures, reaching 828m.

As developed by William Baker of SOM, the structure consists of hexagonal reinforced concrete core walls that provide the torsional resistance of the structure similar to a closed tube or axle. The center hexagonal walls are buttressed by the wing walls and hammerhead walls, which behave as the webs and flanges of a beam to resist the wind shears and moments. Outriggers at the mechanical floors allow the columns to participate in the lateral load resistance of the structure; hence, all of the vertical concrete is utilized to support both gravity and lateral loads. [10]. The base floor plan is represented in Figure 19.
Figure 19 - shear lag in tubular structures

Being superlative in all ways, the Burj Khalifa is yet another proof of ingenuity and overcoming ability, it sets new standards and raises expectations for what is to come, its project and construction is yet another step forward in meeting the technological challenges of future construction.
3 Vertical Communication Systems

Vertical communication systems are key requirements to buildings both tall and low, having major influence on a building’s daily operation as well as the buildings plan. In tall buildings vertical communication becomes more relevant and implies the integration of elevator specialists to fully assess what are the building’s needs and thus coming up with an optimal solution. As is the case of the structural system the elevator system is also a distinct characteristic of tall buildings thus being a differentiating factor between medium and high rise buildings.

Though further references mostly address elevators this does not mean other relevant forms of vertical communication, such as staircases and escalators, have been forgotten, though the relative importance of elevators for building planning and service surpasses to some extent the former.

This chapter addresses the relevance of elevators in tall buildings from a performance, financial and environmental perspectives, offering a perspective of what are the currently available elevator solutions for high-rise buildings, leaving historical perspectives and solution evaluation to chapters 4 and 5 respectively.

3.1 Building height criteria and elevator systems

An elevator service approach towards building height classification differentiates between low, medium and high rise buildings and mega high rise buildings [11] according to specific elevator needs.

To this purpose a low-rise building will be one where “someone able does not need the elevator to reach their floor but if it is available they will invariably use it”, meaning 3-5 floors, mid-rise building means the elevator becomes essential for occupants to use the building, which means about 8-10 floors and high-rise building means there may be the possibility, meaning feasible alternative, of the building’s elevators being divided into two zones, which could mean 15-16 floors [11], this describes the majority of buildings.

Tall buildings are differentiated from the previously mentioned regular buildings, and are addressed as either tall buildings or skyscrapers if the building requires more than one zone of elevators – in practice this means a building up to 60 floors - and very tall buildings or mega-high-rise buildings which would mean the building requires the use of one or more sky lobbies to guarantee proper occupant distribution, meaning more than 70 floors [23].

This classification was not applied, as has been noted, in the present document and therefore some of the above terms are used as synonyms of tall buildings.

3.2 How elevators affect tall buildings

First elevators and the safety issue

When elevators were introduced the key word was safety, not performance or sustainability, as buildings height was constrained by access to the top floors people required a safe and confortable way to make this
journey. Elisha Otis’ 1851 unveiling of the safety brake system met that people finally had a safe way of getting to a building's top floors, thus enabling architects and engineers to start the height race [10]. The historical importance of this breakthrough and the fact that it took place in Chicago can only be fully understood if addressed from a broad perspective, thus leaving the subject to be further analyzed in chapter 4, however since it important for present understanding of elevators’ importance a few key issues will be considered.

Firstly regarding mid-1800’s structural solutions, which were mostly dependent on load bearing masonry walls, there was already viability to build rather efficiently up to 7 or 8 story buildings, however since a building's top floors could only be reached by stairs there would have been an unwillingness to stay in top floors due to accessibility issues, thus buildings would tend to go no further than 3 or 4 stories high. Elevators, of course, allowed for ease of access to higher floors thus making them more attractive to occupants and in turn making them more valuable [43].

Also due to the rapid industrial development cities were experiencing high demographic growth and there was great demand for space, therefore building higher was both a need and a financially solid bet, this situation not only contributed to technological evolution of elevators but also took great advantage of it.

**Elevator arrangements and financial implications**

As safety was no longer a key issue concerning elevators performance started to draw more attention as buildings started to get higher and higher and increasing the number of elevators was proving to be insufficient. This situation still proves to be a constraint today as regardless of how tall the building is, all floors need to be easily accessible. A super tall office tower could have tens of thousands of daytime occupants and if it’s well designed, none of them should wait longer than 20 to 25 seconds to begin their elevator journey. The more people and the more floors, the greater the number of high-speed elevators required [24] this of course has tremendous impact on the buildings plan as elevators affect the size of the service core thus taking up otherwise rentable area which can be extremely damaging to the return on investment [33]. A study performed on an office building with 50 floors came to the conclusion that to achieve good quality of service the required elevator system would take almost 5% of the gross floor area (GFA), this value does not consider staircases or service shafts, which gives a perspective of how substantial the elevator impact is on built area [33].

**Efficiency**

As is the case with all aspects related with construction, the sustainability of the elevator service is also taken seriously from both a planning and technological perspective, benefits of careful planning are evident in a building’s operational costs as an efficient elevator system will decrease vertical transportation energy consumption, and although this is not the only aspect of sustainability is also of great importance for a building’s image and for return on investment [33].

As explained above elevators carry significant importance in tall buildings whether by enabling their use or by introducing financial and environmental constraints, and therefore the conception of the elevator system should be carefully planned by specialists from as early a stage of building conception as possible. The implications on return of investment concern both initial and long-term maintenance costs, as
Elevators account for 6-12% of a building's construction cost [21] and can account for up to 8% of a building's total energy consumption instead of about 2% if the proper system is applied [33].

Elevators can therefore be said to greatly influence buildings in general and tall buildings in particular, their influence can be asserted as structural, for they will affect core size, functional as they must effectively transport occupants to their destination, environmental as they account for a significant part of a building’s energy consumption, and financial which can be considered in a direct way, elevator construction and operation costs, and indirectly as elevators will occupy some otherwise rentable space.

3.3 Discussing the service core

The service core of a building of any height is a key aspect of the building’s design and as happens with other already addressed aspects, its relevance in overall building quality increases with height, “thus the more time spent on core design, the more efficient and sustainable the building can be” [5]. To further consider how the service core carries such importance in a project's outcome a definition for what is the service core must be provided.

What is the service core

The service core should be understood as a systems built up of a number of individual components, each having a different function to perform and highly technical in nature [14], these components are the facilities and services needed for buildings very existence. These components are services such as HVAC installations, elevator systems, stairs, storage rooms, and toilets and so on, with the necessary sub-services that are required for their proper functioning, ducts, pipes and others. Many times these services and sub-services are enclosed by shear-walls or trusses which constitute the building’s core in a structural sense, this however is not always the case. From addressing these characteristics the service core can be defined as “An element that gathers the space necessary to provide visual, physical and functional vertical connections that work effectively to distribute services through the building” [49].

The importance of the service core

Understanding what the service core is helps greatly to understanding how important it is for the building and why designers place such importance in its planning for the earliest stages of the design process [22]. The service core is the building's backbone for daily operations and many times for structural support too. Apart from its functional and structural importance, the service core should also be addressed from a financial perspective and from the evermore important sustainability perspective.

Financial aspects regarding the service core

This aspect has already been slightly addressed when tackling the financial aspects of elevator planning in the building's rentable area, the issue is very similar only for the fact that the service core encompasses other services apart from the elevators and therefore has an even more significant impact on return on investment.

From a return on investment approach the service core area is all the area that is not rentable which is to say:
Where SC is the service core area, GFA is the gross floor area and NRA is the net rentable area [49]. The net rentable area represents the actual purpose for which the building was made and can therefore be held as an indicator of a building’s efficiency. For the purpose of the current analysis focus should be placed on a NRA/GFA ratio analysis as proposed by Trabucco (2008) for a clearer perspective of the impact the service core can have on financial outcome and some considerations for stakeholder concerning the service core and building height.

As is the case with the structural system the service core also experiences the effect of premium for height as was described in chapter 2, however this has a minor effect, for the purpose of service core analysis, when compared with inefficient use of floor area which translates to low NRA/GFA ratios. It is a fact that as buildings grow higher, so does the needed service core area, hence the need to carefully address the subject [49]. Table 1 and figure xx below show the results of a study of several buildings considering the average NRA/GFA ratio according to building height, observing the notes made by the authors the influence of elevators for efficient use of the building.

**Table 1 - Net rentable area - NRA and Gross floor area - GFA**

<table>
<thead>
<tr>
<th>Number of stories of the building</th>
<th>Average share of area available as NRA on the GFA of the building</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>19–29</td>
<td>0.85</td>
<td>Sudden drop of the efficiency; shorter buildings require only one bank of lifts while taller ones, around 25 storeys, need two banks, lowering the efficiency</td>
</tr>
<tr>
<td>30–39</td>
<td>0.78</td>
<td>‘Standard’ buildings: efficiency decreases as height increases. No strategies (such as sky lobby) are economically sustainable or functional.</td>
</tr>
<tr>
<td>40–49</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>50–59</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>60–69</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td>70–79</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>80–89</td>
<td>0.75</td>
<td>Theoretical efficiency decreases; however, real-building efficiency improves if compared with lower buildings as a consequence of tapered shapes and the use of sky lobby and double-decker lifts.</td>
</tr>
<tr>
<td>90–99</td>
<td>No data available</td>
<td></td>
</tr>
<tr>
<td>100–110</td>
<td>0.80</td>
<td></td>
</tr>
</tbody>
</table>
This evidence backs up many other authors’ statements on the importance of elevator strategy for tall building economics enhancing the fact that space usage can be financially as important an issue as the actual cost of the elevators [53]. The issue of energy consumption associated with the service core though of great relevance to any financial analysis was integrated along with the other sustainability issues just ahead, as there are other aspects associated with the energy efficiency of a tall building of great relevance that should be addressed separately.

**Sustainability: Embodied energy and Running energy**

Sustainability is one of the major issues considering tall buildings, they are perceived in public opinion, with some reason, as big energy consumers [21], though the problems relate to all buildings, which represent 30-40% of all primary use of energy worldwide [40]. Experts such as Powell and Yeang (2007) have drawn similar conclusions claiming that “the tall building typology is the most unecological built form (...) when compared with other built typologies it uses three times more energy resources and material to build, to operate and to demolish. In reality, the tall building cannot be made completely green and having realized this, architects should try to mitigate its negative impacts on the environment.” [14]. The service core is central in the sustainability debate as it encompasses most of the services that account for a significant part of the building’s operational energy consumption. The energy consumption associated with services such as heating, ventilating, elevators and illumination are here considered as running energy, opposed to the energy required to build the building with materials and such which is the embodied energy. Though main the focus has been on the running energy mostly due to the rising cost of energy [48], and since it is representative of the greatest energy consumption associated with buildings as can be seen in Figure 21 - Relative energy consumption, embodied energy is also of extreme importance and should be analyzed in design stages to better assess the advantages of energy saving strategies.
Some interesting approaches involving service core design have been attempted with good results by displacing the service core from the building center to a peripheral area for the building to benefit from the core’s shading [48]. There are some disadvantages from this procedure, as depicted in Table 2, which imply careful study of the buildings specific conditions.

**Table 2 - Side effects of unconventional core design.**

<table>
<thead>
<tr>
<th>Negative factors not assessed by existent studies</th>
<th>Positive factors, some of them not mentioned by existent studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decreased floor plan efficiency due to longer corridors (NRA/GFA)</td>
<td>Shading effect, thus reducing energy requirements for cooling</td>
</tr>
<tr>
<td>Increased requirements to HVAC due to longer ducts and increased volume</td>
<td>Heavy and opaque materials service core delay heat transfer</td>
</tr>
<tr>
<td>Need for autonomous/additional structural systems for external service core</td>
<td>Natural ventilation of external service cores, thus reducing HVAC-controlled volume</td>
</tr>
<tr>
<td>Increased heat-absorbing/dissipating surface</td>
<td>Easier dissipation of internal gains generated by services (lifts, lighting, etc.)</td>
</tr>
<tr>
<td>Increased costs for building/cleaning/maintenance and refurbishment</td>
<td></td>
</tr>
</tbody>
</table>

A comparative study conducted by Jankassim (2006) between two buildings in very similar conditions apart from the referred core design shown there are actual benefits on acclimatization energy consumption from applying this strategy, however this study did not take into account some of the referred drawbacks associated with this procedure and therefore the results cannot definitely state this to be an evident improvement in core design [48].

Turning once again to a comparison between running and embodied energy an important aspect regarding the general awareness of the former in detriment of the latter arises from the difference in the energy cost for big consumers and standard consumers, meaning the embodied energy associated with building construction and materials comes at a lower price to the promoter than the running energy to the building occupant, thus creating a distortion of the actual energy consumption [48].

The service core will again be considered in the following chapters but the general scope for its relevance was given here, it should be considered of the most important elements in building design with great impact on building functionality, economics and sustainability and is therefore one of the key elements in early stage building design.
3.4 Regulatory and safety aspects of elevators

Regulations on elevators are extensive and therefore will be briefly addressed. For European Union countries legislation can be found both in EU law and national law. EU law on elevators can be found in the following documents: Regulations 95/16/EC and 89/392/EC of the European Parliament, CE Identification regulation 93/68/EWG, EN 81, Safety rules for the construction and installation of elevators; EN 81-1 Electric elevator and EN 81-72 firefighter elevators. In Portugal the latter codes are adopted and harmonized with national regulations are set in several legal publications: DL320/2002, DL298/98, DL513/70, DL220/2008, DL103/2008, DL176/2008 and DL1532/2008. The national regulations found in the referred publications are as follows:

- EN81-1:2000 Norma Portuguesa
  Regras de segurança para o fabrico e instalação de ascensores
  Parte 1: Ascensores eléctricos

- EN81-1:2000/A2:2007 Norma Portuguesa
  Regras de segurança para o fabrico e instalação de elevadores
  Parte 1: Ascensores eléctricos
  A2: Locais de máquinas e de rodas

- EN81-2:2000 Norma Portuguesa
  Regras de segurança para o fabrico e instalação de ascensores
  Parte 1: Ascensores hidráulicos

  Regras de segurança para o fabrico e instalação de elevadores
  Parte 1: Ascensores hidráulicos
  A2: Locais de máquinas e de rodas

- EN115:1995 Norma Europeia
  Versão Portuguesa
  Regras de segurança para o fabrico e instalação de escadas mecânicas e tapetes rolantes

These regulations establish minimums for proper performance and operational conditions, since high rise construction is uncommon in Portugal there are fewer regulations or standards and codes of practice for tall building elevator systems.

Firefighter elevators

Special attention is now paid to firefighter elevators as they are required by law and are a major issue in tall building evacuation. These elevators mandatory in buildings exceeding a certain height which varies according to country, it is important to refer that for buildings considered in this document which fit into the several descriptions of tallness provided, firefighter elevators are always obligatory.
Firefighter elevators are there to help firefighters to get to the fire and to permit people evacuation, these elevators can be used in normal conditions to transport passengers, and special provisions must be made for these elevators concerning both the elevators and the buildings. Starting with building requirements, national law determines the maximum distance between workstations and firefighter elevators which must be located in a separate fireproof shaft that in the elevator landing must be wide enough for a gurney to be brought out of the elevator, meaning minimum 5m². Figure 22 - Elevator Shaft depicts a regulation approved elevator and firefighting shaft [15].

Moving to elevator requirements several issues are tackled and set in EN 81-72, starting with dimensions and load capacity these elevators must be at least 1.10m wide by 1.40m deep with the door entry at least 800mm wide, minimum loading capacity is regulated at 630kg. Other requirements include a separate electricity supply to guarantee the elevator will remain active at least 90 minutes during a fire, there should also be a redundant electricity supply. All materials used in for the elevator must be non-combustible; the elevator should have a top escape hatch and a ladder to access it; a ladder must be kept on the roof of the elevator to enable firefighters to reach the upper exit and leave the elevator shaft; and the elevator must be fast enough to guarantee that all floor are available from the entry level in less than 60 seconds.

Concerns on building evacuation and firefighter elevators since the World Trade Centre attack have led to extensive research on building evacuation and fire safety, this is a crucial safety area where there still is a lot to be done.

3.5 Elevator systems - current trends.

Though many technological advances have occurred since Elisha Otis first demonstrated his safety break, the basic elevator components still remain similar: machine, gearing and sheave, suspension, guide shoes and rails, safety gear, car and counterweight. Not to dismiss the importance of the technological evolution associated with each of these components, some of the biggest and more noticeable changes in elevator
systems have to do with performance particularly drive control, traffic control and signaling, monitoring and management systems, and in engineering and traffic design techniques [15].

It is also important to note that the basic techniques used to assess a building’s optimal elevator system are common to both high and low rise buildings, the main difference is related to the greater number of solutions available for the former, which means studies will be more extensive and more scenarios will have to be compared, the analysis of the several possible elevator system solutions as performed by consultants is commonly called elevatoring.

3.5.1 Basic elevator elements

For present purposes hydraulic elevators will not be addressed since they are not used except for low rise buildings and are less common today, they will be referred in the historical analysis in chapter 4. Concerns are directed towards electric elevators and their basic mechanical functioning and components: machine, lift car, counterweight, guide rails, entrances, safety gear and governor, buffers ropes and fixtures (buttons switches and so on) [15]. In Figure 23 - electric elevator the stated elements are depicted with further detail other elevator components.

![Figure 23 - Electric Elevator](image-url)
Since the technical analysis of elevator functioning is well documented and outside this document’s scope only a few observations are to be made concerning the mechanical operation of current elevators. These observations concern the drive mechanism are important to illustrate some recent technological advances concerning elevator mechanics particularly in the drive mechanism. The drive mechanism is what enables elevator movement, and therefore “drive” the elevator, these mechanisms were in their initial stages powered by steam or water, currently almost all drive mechanisms are electric, the most common system being the Ward-Leonard drive.

The Ward-Leonard drive system employs a DC motor and DC generator which is connected to an asynchronous three-phase generator that provides power. This system allows for good control but have high energy consumption since the transformer practically runs continuously without shutting off, also the system produces a lot of heat due to the braking system and the machine room must let this heat out. For a better understanding Figure 24 - drive mechanism depicts a normal drive mechanism [15].

![Figure 24 - drive mechanism](image)

Other aspects related with elevator mechanics and their evolution will be addressed in chapter 4, though only from a general perspective as to understand how the technological evolution of elevators enabled or contributed to tall building development. The fact that only the elevator drive mechanism was considered in this chapter has to do, as referred, with recent technological innovations related with the drive system and elevator energy consumption, this does not intend to diminish in any way other mechanical aspects of elevator operation and their relative contribution to elevator development.

### 3.5.2 Elevator arrangements for tall buildings

Having discussed some basic aspects of elevator systems it is appropriate to discuss the elevator systems available for tall buildings. As buildings become taller more focus is put on decreasing the number of elevators as regular elevator solutions begin losing their effectiveness and cannot cope with the required service levels [19]. The several solutions presented are proven solutions for elevator systems developed to
allow good operational performance in a cost effective way, though optimum solutions vary according to building and owner demands, some solutions are more appropriate than others according to building height, use and intended level of service. The reasoning behind the selection of the optimum elevator system and performance analysis will be addressed in chapter 5, leaving for this chapter only the basic characteristics of each system.

The following solutions are featured in no particular order though the first three, zoning, sky lobby and double decks are arrangements that admit increasing taller buildings, the last three solutions have more to do with technological developments that when applied permit better service conditions and can contribute significantly to lessen the number of elevators.

**Zoning**

In low-rise buildings it is possible for all elevators to stop at all floors without compromising performance, or by keeping performance to acceptable levels, however for buildings higher than 15 stories in order to maintain appropriate service levels the number of elevators required would imply very a very large core thus making the building inefficient due to decrease on NRA. One way that has proven to be very effective in tackling this issue is the adoption of elevator zones to serve different floors, thus limiting the total number of stops, therefore the name zoning. Though zoning can be applied in ways, for example elevators stop only in odd or even numbered floors, the usual arrangement involves zoning according to height, as depicted in Figure 25 - zoning according to height.

This allows for the discontinuation of the lower-rising elevator shafts thus improving on the NRA of the top floors, which is a further improvement as the reduction in elevator stops related to zoning had already accounted for an upgrade when compared to normal elevator arrangements. Though there are several other criteria involved in defining an optimal solution, in general terms and just considering the number of stories experts consider this arrangement to be sufficient for up to 60 stories with single deck elevators and 80 stories with double deck elevators, this limit being 4 zones of up to 6 elevator cars each, each zone should not exceed 15 to 20 stops as it damages service [15], [11], [23], [19].
Sky Lobby

As buildings get higher zoning becomes impractical and unfeasible as elevators start once again to take too much space [19], as stated early the limit is of about 4 zones as shown in Figure 25 - zoning according to height. Once buildings reach over 80 stories, sometimes less according to building use and desired service, the sky lobby becomes a necessity and the elevator problem becomes that of two buildings stacked one upon the other. Now there is no longer the possibility of accessing all floors from the main entrance lobby, as some floors are to be only accessible through the sky lobby, via an express or shuttle elevator, and then on distribution can once again be made by zoning. Shuttle elevators tend to be fast and to provide good service though this arrangement implies passengers will need to change elevators to get to their destination [11]. The great advantage of the sky lobby is core optimization since all elevators do not have to serve the entry level the upper local zones are stacked on top of one another, so the elevator shafts, generally, occupy the same "footprint" as the local zones below [23]. Sky lobby arrangements can vary both in terms of elevator type, single or double deck, but also they can be top-up or top-down, meaning local elevators can be dispatched up or down, respectively, from the sky lobby as shown in Figure 26 - Sky Lobby arrangements

![Sky Lobby arrangements](image)

The use of sky lobbies associated with local zoning can serve buildings up to 120 stories, if single deck elevators are used or 160 floor if double deck elevators are employed, the Burj Khalifa which is currently the tallest building in the world has such an arrangement to provide for its 163floors. This is thought to be
very close to technical limitation of this arrangement since further height would imply stacking a third building on top, and this would require shuttles to travel a total span of 130 or more stories. De Jong (2008) states that “With these travels, building sway, suspension rope resonances and suspension rope weights, energy consumption per unit, become serious problems. The present rope elevator can go up to 200 floors, but rope weight increases rather exponentially with height. When one sees rope weights of 50-70 tons to move just 21 passengers, one can hardly see the long-term financials and ecological values of these systems work. Before new revolutionary technology hits the market, elevator technology might be an obstacle for further increase of building heights.”

**Double decks**

Double deck elevators were referred in the previous elevator arrangements, they consist of two passenger cars one above the other connected to the same drive system. The upper and down decks can serve two adjacent floors simultaneously and permit doubling an elevators capacity while maintaining the same footprint [11]. Double decks imply careful planning of the lobby arrangement as they can bring many advantages but also some inconveniences as pointed out by Fortune (1996) and shown in Table 3 [11].

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Fewer lifts</td>
<td>1. One significant supplier</td>
</tr>
<tr>
<td>2. Smaller car sizes</td>
<td>2. Passenger misuse</td>
</tr>
<tr>
<td>3. Lower rated speeds</td>
<td>3. Zone populations must be large</td>
</tr>
<tr>
<td>4. Fewer stops</td>
<td>4. Balanced demand from even and odd floors</td>
</tr>
<tr>
<td>5. Increased zone size</td>
<td>5. Interfloor distance must be regular</td>
</tr>
<tr>
<td>6. Quicker passenger transit times</td>
<td>6. Slightly larger hoistways</td>
</tr>
<tr>
<td>7. 30% less core space</td>
<td>7. Increased pit and machine room loadings</td>
</tr>
<tr>
<td>8. Taller buildings on same footprint</td>
<td>8. Lobby exits need to be larger</td>
</tr>
<tr>
<td>9. Smaller lobbies</td>
<td>9. Special facilities for disabled access to “other” floor</td>
</tr>
<tr>
<td>10. Fewer entrances</td>
<td></td>
</tr>
<tr>
<td>11. Faster installation</td>
<td></td>
</tr>
<tr>
<td>12. Reduced maintenance costs</td>
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The effective use of these elevators implies the use of sophisticated traffic control systems to better manage elevator travels according to passenger demand and thus cutting on unnecessary stops, improving performance and energy consumption [11]. Figure 27 show a scheme of a double deck elevator and a picture of Double-deck elevators at Midland Square, Nagoya, Japan.
The three following technologies are probably the most relevant innovation in elevator technology in the last years in specialists perspective, they are both directed towards traffic performance and mechanical optimization and have opened new possibilities.

**Call destination**

Call destination or Hall Call Destination Dispatching is one of the most relevant technological innovations addressing elevator control systems creating substantial benefits in the reduction of elevator stops and thus optimizing elevator use. Conventional systems allow passengers to choose whether they want to go up or down and only after entering the elevator cabinet choose the specific floor, this results in heavily loaded cars where usually the number of floor buttons pushed is only slightly less than the number of passengers (Jong, 2008). Call destination allows for passengers to enter their intended destination in a “Destination Operation Panel”, shown in Figure 28, before entering the elevator pod, the requests are then processed using complex algorithms and elevator travels are optimized towards gathering passengers who are going to the same floor, Figure 28 shows the effect of call destination according to traffic intensity it includes one manufacturer’s specific algorithm.
Further illustrating call destination benefits and taking as an example an ordinary office building with 4800 people and 52 floors, the building is arranged in three zones, low, mid and high-rise, each with 8 elevators for a total of 24 elevators, with the introduction of call destination the building would be in need of just 6 elevator per zone which means a decrease in 20-25% in the number of elevators which translates into a smaller core area need for their accommodation. If further improvements are made towards implementing double deck elevators in the same situation estimates indicate similar service levels could be provided with just 2 zones of 7 and 6 double deck elevators, which translate into only 13 elevator shafts comparing to the initial 24, though the increase in investment would be of about 10 to 30% compared with the basic single deck system and it is about 30-50% higher than single deck with Hall Call Destination Dispatching but the gains in rentable area may compensate the difference [19].

**Machine room less**

Machine Room Less (MRL) was enabled due to the introduction of the Permanent Magnet Synchronous Motor (PMSM) combined with variable voltage, variable frequency (VVVF) drive. The change reduced the size, weight, heat output and energy consumption of traditional Ward-Leonard traction systems by up to one-half therefore the machine room became expendable. Figure 29 shows an MRL engine opposite a common system with machine room and summarises the system’s advantages.
Finally one very innovative solution that still has few applications is the TWIN elevator solution. Currently being developed by one of the major manufacturer there have already been some successful applications of this system such as the Main Triangle building in Frankfurt. This systems allows for two elevators to operated independently of each other in the same shaft, this requires a sophisticated monitoring system and call destination system to work effectively, but results are satisfying. According to manufacturer projections the implementation of Twin can help decrease the number of elevator shafts needed by up to 30% [47], Figure 29 provides an example.

This system can prove of extreme utility in case of modernizations in buildings where current system does not comply with performance standards, as it allows for gains in service while utilizing the same shaft areas, Figure 31 shows the panoramic TWIN in Main Triangle, Frankfurt.
Figure 31 - Twin elevators in Frankfurt Main Triangle Building
4 Historical perspective

This chapter focuses on a historical approach to skyscrapers, it is an attempt to discuss some of the key aspects that influenced tall buildings as they are known today. Since high rise construction has been subject to many influences, ranging from technical aspects to financial and social issues, which are complex in nature and therefore require careful and extensive explaining which is mostly outside the scope of the present research. As of this, the historical analysis proposed will address these issues in as brief a manner as possible to provide sufficient background to understand the skyscraper paradigm, and will draw focus on the vertical communication systems and high-rise structures. The goal being to show how present day high-rise buildings came to be and how vertical communication systems played a part in that development.

This chapter draws some of the most technical aspects from the preceding chapters thus some aspects related with structural behavior and elevator operation will be addressed but left undeveloped when found redundant.

4.1 Relevant periods, how the chapter is structured

To organize this chapter several factors were considered since tall buildings are tremendously affected by social, financial, legal and technological context at the time of their development. Thus to get a full perspective of what drove skyscraper development several periods were chosen according to building typology and paradigm, within these periods when thought relevant some sub-periods were also considered. The technological innovations in each period will be analyzed and parallel aspects related with the industry will be addressed to the extent permitted.

Choosing this form of organization may seem to privilege factors other than technical and related with engineering innovations, however due the nature of tall buildings non-technical aspects have long been major drivers. Engineering and mechanics in general have acted as enablers for tall building development and even though they have sometimes been constraints to tall building development they have seldom been motivators or drivers for the will to build taller. The periods chosen which are strongly correlated with the architectural paradigm reflect major world events that go far beyond the construction industry, these events and their consequences have had serious impact on public perception in general and in tall building construction in particular. This should not be understood as depreciative towards the importance of engineering and technology in tall building development, only that building higher is the product of a need and will that have themselves stimulated innovation in the construction sector.

Will and need to build higher are mostly related with financial outcome, “Form follows finance” [53] is a very telling statement when tall buildings are concerned, though solely financial aspects cannot account for the hole of skyscrapers development they have been one of the main influences as can be seen in the following analysis.
Considered periods
Five periods were considered according to the previously stated criteria.

- Birth of the Skyscraper to New York zoning law of 1916
- 1916 to Second World War (WWII)
- Post WWII to 1970’s Energy Crisis
- After the Energy Crisis
- Rise of an Environmental Consciousness (1997) to present day.

This form burrows heavily from a historical analysis based on tall building energy consumption [40], and was adopted due to its general characterization of the buildings which allows for the full understanding of contemporary high-rise construction paradigm. Other authors consider periods that are very similar to these when employing similar criteria [5] for based on architectural characteristics, which are very closely correlated with energetic performance.

Birth of the Skyscraper to New York zoning law of 1916
This period consider the first “tall” buildings, which cannot be described as such by today’s standards but were ground breaking in their day. This period is particularly relevant for the technological innovation such as the elevator and the steel frame, issues related with the symbolic nature of tall buildings will also be addressed. This period is considered until the New York zoning law of 1916 since it was key to a change in conception which would eventually spread to Chicago. This chapter focuses on the cities of New York and Chicago.

1916 to Second World War (WWII)
This period, could be considered only until early 1930’s since the financial collapse of 1929 severely hampered high-rise development, however new developments came only after WWII and therefore this period was considered until then. Apart from the implications related with the zoning laws there was little structural innovation during this time which consisted mostly of taking contemporary steel framing technology to its limit epitomized by the Chrysler Building and the Empire State Building, the latter holding the title of world’s tallest building for over 30 years, though “Their enormous heights at that time were accomplished not through notable technological evolution, but through excessive use of structural materials. Due to the absence of advanced structural analysis techniques, they were quite over-designed.” [4].

Post WWII to 1970’s Energy Crisis
This period is deeply connected with the International Style in architecture, technically it is marked by the development of the glazed curtain wall. During this period buildings energy consumption increased dramatically due to illumination and also acclimatization, the concept was to create a building form that would be reproduced regardless of the buildings location which eventually led to poor performing buildings that relied exclusively on mechanical means for temperature control and illumination [40]. This energy dependence became an obvious problem in the 1970’s with the petroleum crisis. This was also an important period for structural advances which saw the introduction of new concepts such as tubular
structures that opened new possibilities for tall buildings, this was much aided by the developments in computers which allowed for better calculations and modeling of structural behavior [10].

After the Energy Crisis
Though this period saw the introduction of some new technologies that improved the glazed curtain wall system it is mainly important to illustrate a change in building paradigm which means building conception and operation. The mass use of personal computers in offices started in this period bringing new challenges both due to the computers energy consumption but also due the heats gains associated with computer use. Authors consider this period as ongoing till today as many characteristics of these buildings still prevail in today’s construction [40].

Rise of an Environmental Consciousness (1997) to present day
Though many buildings constructed today do not fall in this category it is very relevant for the purposes of design orientation and sustainability which translates into new approaches that try to surpass regulation demands in order to achieve more efficient buildings. This implies more creative and out of the box design placing great concern on purpose, function, running and embodied energy, building energy generation, all these aspects carry about further implications to all other building characteristics such as structure and the elevator systems and are therefore worth analyzing.

The incident of September 11th 2001 will also be approached in this part as there will be some considerations on its impact in high-rise construction.

4.2 Birth of the Skyscraper to New York zoning law of 1916
Discussing the origins of modern skyscrapers implies discussing two American cities, New York and Chicago, which saw the early days of high-rise construction each in its own way. It is very important to underline some of the social-economic conditions that favored the development of high-rise construction.

4.2.1 Social and economic context
Demographics
Due to the industrial revolution in the second half of the 19th century cities became the destination of both companies and workers. Companies were in need of office space and workers needed a place to stay, there was, therefore, demand for built space, offer would come shortly as investors became increasingly aware of the benefits related with vertical development associated with the new technical possibilities. Chicago’s location and connection to Canada by both rail and barge made it one of the fastest growing cities in the world at the time. In addition to these demographic aspects further reference should be made to the devastating fire Chicago had suffered in 1871, leading to an urgent need to rebuild the city, in fact many tall buildings rose on the same plot as buildings that were completely destroyed in the fire [49].

City zoning
Both Chicago and New York developed different tall building typologies, mostly due to differences in the cities’ historic grid, municipal regulations and zoning [53]. In spite of these key differences the drive remained similar, economics in the form of real estate. Like most prominent American cities Chicago and
New York were ordained in a geometric pattern of blocks, Chicago blocks were of about 100 x 100 meters which made large lots possible, New York’s buildings were laid out on smaller, slimmer blocks of approximately 20 to 30 meters (street front) by 60 to 70 meters in depth, which made for considerably different building types [49]. Due to the extremely function, and financial orientations of contemporary architecture buildings took great advantage of whatever possibilities city ordinance gave them, which were more restrictive in the case of Chicago, partly due to the post fire prudence, than in the more laissez faire New York where eventually lawmakers were forced to intervene.

Further consideration of zoning in building development during this period will be addressed along with the architectural characteristics of buildings, the main influence being evident when comparing buildings before and after the 1916 New York zoning law.

4.2.2 Relevant technology

The Elevator

Though other factors such as the “steel” frame structure and the flat arch system for floor fire proofing are deeply connected with the first tall buildings it was the elevator that made the difference. Building structures were by then about load bearing masonry walls which were feasible solutions for buildings up to eight stories high the problem being the ability to get people to the top floor safely and without much effort. Elisha Otis’ dramatic display of the elevator safety brake in the 1854 Crystal Park Exposition in New York where he hoisted himself up in a platform and cut the hoisting rope for a gasped crowd to see the brakes stopping the platforms descent, proved to be a valuable publicity stunt as it drew investor attention towards the elevator, Figure 32 depicts the Otis’ presentation and his sketches for the patent.
Apart from investors, public acceptance came only in 1857 with the installation of the first passenger elevator in the store of E. V. Haughwout & Company in New York, depicted below in Figure 33, this elevator served five floors at a speed of 0.20 mps (meters per second) [43].

The technical development of the elevator was aided by the availability of improved wire rope and also the developments in steam power for hoisting, however and in spite of these advances the elevator remained a slow alternative to stairs and the demand for downtown space was outpacing technical innovation and thus demanding an alternative. The hydraulic elevator presented itself as the alternative being capable of speed up to 3.5mps and rises up to 30 stories, though these buildings did not become a reality until after 1900, the hydraulic elevator served practically all the 10 to 12 story buildings of the 1880 to 1900 era becoming the spur that made upper floors of buildings more valuable through ease of access and egress [43]. Figure 34 depicts a hydraulic elevator with a regular rising tube or plunger and with telescopic rising tubes to avoid unnecessary soil perforation.
It was also in the late 1800’s that many of the aspects currently associated with elevators were introduced, such as the complete enclosure of the hoist way and the introduction of doors. The electric elevator was taking its first steps first simply replacing the steam engine, 1889 at the Demarest Building in New York, and in 1894 when Otis installed the first automatic electric or push-button elevator.

Other issues regarding elevators started to arise by early 1900’s as the steel frame was allowing buildings to get ever higher, elevator number, size, arrangement and location became the problem to solve. A usual mindset in those days was to consider that if a building was running well with two elevators a building twice as big would run just as well with two elevator with twice the size or capacity, which was a wrong logical approach as became quickly evident through passenger complaints [43]. Answering these new met the development of a new design specialty dubbed elevatoring, which is “the technique of applying the available elevator technology to satisfy the traffic demands of multiple and single-purpose multifloor buildings.” [43].

Elevatoring is considerably about understanding and predicting people flow through the building thus aiming towards an optimal elevator solution that will guarantee efficient flow, without great time delays, while procuring to minimize space occupation [43]. The taller buildings get the wider the number of available solutions and the more complex and needed the planning of the elevator system, such the perception in the beginning of the 19th century.
Another major innovation that took place during this period was the introduction of the Gearless traction electric elevator in 1903, possible thanks to the wide spread of electrical distribution. This system which is still used today allowed the surpassing of several limitations of elevator systems until then which were either drum-type elevator machines or hydraulic-type elevators. These limitations were the drum size required as the higher the hoist the more rope was needed and consequently the bigger the drum had to be and for the hydraulic type high implicated ever bigger cylinders, the traction elevator had none of the rise disadvantages of those other systems and therefore constituted the better alternative to equip the new steel framed buildings that were starting to reach above 150 meters and were starting to be held back by the elevators performance. The Gearless traction machine being electric allowed for better standards of elevator operation and control so that elevators trips could be treated through time related factors as speed was no longer dependent on steam or water pressure. This type of elevator system is depicted in Figure 35 and was mentioned in chapter 3 as it is the more primitive version of the Ward-Leonard Drive system of electric motor speed which allowed for the smoothness and of acceleration and deceleration common in today’s elevators [43].

To sum up the relevance of the elevators in this early stage of high-rise construction and to emphasize the change in paradigm they implicated some early references referred to the new building typology as “elevator-buildings” or “elevator architecture” [49].
Steel frame
As already mentioned buildings of the mid and also late 1800’s were mostly dependent on masonry load bearing wall structures, these exterior walls would carry vertical loads and thus grew thicker as the building grew taller thus starting to take too much space and making the building unfeasible. The iron frame skeleton construction as which would be quickly replaced by rolled steel (thanks to the development of the Bessemer process) [5]. The concept was first implemented by William Le Baron Jenny in the Home Insurance Building in Chicago which is considered to be the first modern skyscraper, though many seem to disagree [49] as though the building features the first iron cast frame it still relied partially on load bearing walls to sustain its 10 floors, still the building managed to weight about one third of what a similar building with traditional load bearing brick walls would weight. Further development of steel framing revolutionized and marked high-rise construction for the following decades overshadowing concrete as a structural material, especially since steel benefited from developments in other industries such as the railroads but also the car industry air both through the development of the material itself but also through the development of project management techniques that were beginning to be implemented in these industries, early 1900’s approach to building tall successfully married the ancient craft of building with the contemporary engineering methodology, the techniques of mass production and consequently to continuous technological improvement [4].

Contemporary statements (1891) on these advances in building technology referred that with the elevator, the flat arch system for fire proof floors and skeleton construction there was simply no limit to the height a building could be safely erected [49]. This is of course an overstatement but given the time when it was made, 1891, when the tallest building in the world was the 106 meter 20 story tall New York World Building, commissioned by Joseph Pulitzer, and acknowledging that little improvement took place between then and the completion of the 443 meter, 102 story high Empire State Building in 1930, it could be said to have been a reasonable assumption.

4.2.3 Building typology and Architecture
Still continuing to focus on both New York and Chicago and having emphasized some differences between both cities, mainly zoning, a more detailed analysis is now provided concerning some other aspects of influence in tall building conception and construction of the time.

Function and finances
Arguably the main driver for high rise construction is real estate finance, it is still true today and it was even more so for the first tall buildings, there are other significant aspects less direct to account that were also of importance in this period such as prestige, but this was also correlate with a premium for the office space, thus being also a financial motive. As put by Donald Trump, in an interview to National Geographic Magazine in 1989; “Ego is a very important part of the building of skyscrapers. . . . It’s probably a combination of ego and desire for financial gain. I mean, once you have enough money so that you can eat and live, then ego enters into it. It’s involved with the building not only of skyscrapers but all great buildings whether they are tall or not.” [6]. Current buildings though still having to make economic sense [44], face sustainability issues that pose as great a concern to developers as other purely economic aspects, even though once again sustainability and economics can be correlated as the more sustainable
and energy efficient a building is the smaller will be its running energy requirements and thus the cheaper it will be to run. This argument is obviously simplistic and does not carry the whole sustainability perspective but never the less is a valid approach.

Coming back to early tall building types and influences, function was one of the key concerns it those days the corollary being “Form follows function” as put by Louis Sullivan an architect who influenced to a great extent early skyscraper design redefining these buildings as “proud and soaring things” [5]. Sullivan’s approach was most hostile towards the social and economic forces that fostered office building conception deeming them incompatible with the art of architecture, this view of the tall building as an art form was obviously contested by those connect with real estate stating that “every cubic foot that is used for purely ornamental purposes beyond that needed to express its use and to make it harmonize with others of its class, is a waste – is (...) perverting some one’s money” [53]. Sullivan’s view and corollary are therefore replaced by “form follows finance”, as Barr Ferree, an editor of engineering magazine observed in 1893 “Current American architecture is not a matter of art but of business. A building must pay or otherwise there will be no investor ready with the money to meet its cost. That is at once the curse and glory of American architecture.” [53].

Social perception, the symbolism of early skyscrapers
As previously stated ego is a big part in tall building development and this was evident in the early height race that took place in early 20th century, pushed mostly by newspapers and insurance companies, such as the already referred News of the World Building and Metropolitan Life Building both depicted in Figure 36.

![News of the world Building and Metropolitan life Building](image)

Figure 36 - News of the world Building and Metropolitan life Building

Newspaper industry was one that was dominated by a few magnates with strong personalities who reflected their competitiveness and their journals in their companies’ headquarters, which served as a
promotional vehicle for their product. Life insurance companies took over the newspapers spot as leaders in business construction, much like the newspaper industry, life insurance companies saw a period of extreme growth in late 19th century due to immigration and again companies desiring to gain prominence developed their headquarters as promotional symbols, a testimony to their solidity, therefore stimulating public confidence in their products [21].

Connecting ego, public perception and real estate finance is the unclear but relevant aspect of being the world’s tallest. To further illustrate both the relevance and perception of the rent premium this aspect implied the example of the Woolworth Building is to be considered. “In 1909, the Singer Building was exceeded by the Metropolitan Life Building. In 1913, the Woolworth Building was completed, displacing the Metropolitan Life Building at the top of the list of the world’s tallest buildings. In private conversations with builder Louis Horowitz, Frank W. Woolworth made it clear that an accounting that related the costs of the building to its leasing revenues failed to capture the great value that accrued to being tallest: Woolworth told Horowitz that he had something up his sleeve: the intangible profits in publicity and brand-name recognition that his firm would receive for erecting the world’s tallest building far out- weighed any real losses he might suffer from the venture. Woolworth realized that all successful entrants in the biggest or highest of something, from the time when pharaoh vied with pharaoh and matched tomb against tomb, were essentially in the same race and reaped the same benefits. The day after the world’s tallest building opened in 1913, Woolworth knew, practically every newspaper would cover the story. The building would be pointed out to every tourist visiting the city, it would be written up in every guidebook to the city, and entered in every almanac and encyclopedia. Whatever the medium, the corporate name would be forever attached to the building.” [29].

Put simply, Woolworth assigned value to being tallest that was independent of the narrow value of the skyscraper as a piece of real estate. As will be seen below, this situation is one that has repeated itself several times, with builders assigning value to being biggest and so topping each other with structures of undeniable symbolic significance but doubtful economy [29].

**Building layout**

Though having similar driving forces buildings in New York and Chicago developed quite differently due mostly to the grid display that has already been referred. Having large blocks Chicago’s tall buildings developed in quarter-block lots that made for large “bulky” buildings with approximately 50x50 meter footprint while New York buildings were set on smaller blocks which architects developed in different ways.

New York buildings either occupied almost square shaped parcels that led to U-shaped buildings with a top elevator bank, near which were also stairs and other facilities, or buildings could take up the entire depth of a block and thus the elevators and stairs would be distributed in the center of the building along its greatest depth [49], these configurations are depicted in Figure 37.
The central positioning of the vertical communication at the center was not a rule as vertical communication systems could be organized to occupy one of the buildings sides if there were perspectives for future adjoining buildings, other practical use spaces such as restrooms, electrical closets and vertical ducts, were placed according to each building though they tended to take peripheral areas for ventilating purposes and generally areas that might be found less lucrative [49]. As of early 1900’s assembling lots for development became more common and allowed profitability from a compact core plan since the additional elevators demanded by higher buildings could occupy the otherwise unrentable building centers, though this was starting to become a standard practice sophisticated elevator arrangements were only achieved near 1910s [53].

Chicago’s buildings were of much larger footprint dimensions due to city zoning and also since there were legal limits to building height as of the 1893 land ordinance act, maximum height being of 45 to 90 meters, promoters encouraged architects to develop layouts that were more suitable to their purposes of financial gain. The result was massive structures some of which almost cubical in form, the “quarter blocks” that allowed for an optimal use of built space. These buildings were shaped like square donuts, with a middle well that allowed for illumination of the interior offices, this deprived the center of a building of its usual distribution function meaning elevators and stairs were usually aligned down a single row, attached to one of the buildings sides which led to some offices being located rather far from the elevators, this was dealt with by putting stairs on the inside corners of the building to facilitate inter-floor traffic by dividing people circulation between elevators and stairs [49]. Figure 38 shows Chicago’s Strauss Building, an example of the “quarter block” building typology.
Some of these buildings are still functioning today and represent landmarks in several ways, their design though lacking in some aspects was the product of great attention and careful planning according to contemporary technical possibilities and available technology. One of the greatest concerns when designing these buildings was the need to guarantee natural illumination as incandescent light bulbs remained weak and inefficient until the development of the fluorescent bulbs in the 1940s [53]. Though there was no legal demand placed on lighting requirements developers and designer were sensitive to the issue and procured office layouts that provided optimal lighting, though a changing criteria a survey carried in 1916 recommended about 80 to 90 lux for adequate lighting, a result of this survey is depicted in Figure 39[53].

Other technological aspects of buildings were also still undeveloped, such as climate control, therefore buildings required on natural ventilation and other solutions that did not rely on mechanical means. Office

1lux is the SI unit of illuminance and luminous emittance measuring luminous power per area, it equals one lumen per square meter. An average sunny day (not direct sun) is between 10.000 and 25.000 lux
windows occupied about 20% to 40% of the façade, allowing for maximum light penetration, but still buildings had reasonable thermal inertia since they were quite compact [49].

Service cores during this period had little structural relevance, as horizontal and vertical forces were conveniently dealt with by the steel framing and the building’s massive dimensions. These buildings had relatively unsophisticated structures which were what current structural analysis permitted and since the potential of the steel skeleton was still far from topped there was little need to investigate other alternatives while increased height could still simply be attained by stacking up floors. As many of the buildings that proceeded them these early pre-zoning law tall buildings were carefully planned highly return on investment oriented buildings where quality was privileged over size as put by architect Harvey Wiley “it is better to build less and have well lit offices than to have more building with deep poorly lit offices. In other words it is better to have less space thus less investment that is rented at prime values instead of low priced rentals” [41]. Promoters such as Chicago’s Owen Aldi also shared in the same opinion “Second-class space costs as much to build as first-class space. Therefore build no second-class space” [53].

4.3 1916 to Second World War (WWII)

Though technologically there is not much interest in separating this period from the one before it the effect of the zoning law was considerable when considering building characteristics as well as adding other factors to promoters plans other than purely technical or financial. This does not in the least imply a change in the mentality behind tall building development what it means is that further aspects started acting as constraints to project and real estate development, with rather interesting consequences to traditional building design.

4.3.1 Social and economic context

The financial downturn of 1929 and later the war period caused for comprehensive stagnation in tall building development, however until then and mainly in New York the race to be the tallest continued and was punctuated with some of the most emblematic examples of high rise construction. Until the market crash economic and social context remained as it was, there being limited changes to what had been witnessed until then, incentives for building high continued as the city’s trade center was so concentrated and such was the demand for down town space that land prices were tremendous and building high was financially mandatory [53].

Another relevant event occurring in this period was the First World War (WWI) which hampered investment in construction leading to a disruption in market equilibrium towards the side of property demand. This was very noticeable in Chicago which had until the war seen sustained economic development which carried for growth and demand for built space. Since there had been little investment during the war period in the early 1920s office space demand had widely surpassed supply which translated into a tremendous increase in rent values, up to 100% between 1919 and 1924 [53]. This was one of the main causes for Chicago’s 1923 zoning law which replaced the 1893 legislation thus removing then imposed height limitations and vastly contributing to further investment in high rise construction.
In both New York and Chicago during the 1920s there were great incentives to building development, credit rates were low, as real estate bonds were sold as stocks meaning ordinary public could be financially involved in the developments which was a source for more funding, “shoestring” financing made it possible to proceeding with a project with little initial capital allowing for total mortgage financing based on future rent income. These conditions that may seem unwise considering the events that followed but in a pre-crises perspective were extremely lucrative investments as office space was quick to rent and attained good renting values [53].

**City zoning**

Before the passage of the 1916 zoning law a building could, in theory, be built straight from the lot lines as high as the promoter wanted or money allowed [53]. This “laissez faire” attitude that to some extent epitomized New York eventually led to excesses thus requiring the implementation of city policies towards building development. As commonly referred in historical papers the culmination of these excesses is the Equitable Building in New York cited as the “final cause of the zoning law”, shown in Figure 40.

![Equitable Building, New York](image)

**Figure 40 - Equitable Building**

The Equitable building unlike many tall buildings of the day was not a company’s headquarter but a speculative project designed to obtain maximum profitability for the investors, when drawing comparisons with the Woolworth Building which at the time stood as the world’s tallest, the Equitable building provided more office space, 110,000m² compared to 92.00m2 of the Woolworth Building, which emphasizes the building’s massiveness when built it was the worlds largest building. The Equitable Building was built according to economic height principles and therefore unlike engineering height principles that determined a maximum number of stories that were structurally feasible, economic height referred to the number of stories that produced the maximum rate of the money invested. Developers
opted to go with a shorter a bulkier building in spite of lot size, which was similar to that of the Woolworth’s hence allowed for a taller building, since the construction was less expensive.

Also since being one of the major aspects of this document it is important to refer that the economic height of the Equitable Building was defined not according to structural costs but with the requirements of efficient vertical circulation, since not only were elevators expensive to build their major cost is the large amount of space consume by shafts. The Equitable Building’s elevator system was a special concern of promoters who prided in having the best elevator service in the world and for which they hired an elevator consultant, Charles Knox, since faulty elevator service was by then affecting the reputation, and therefore rent premium of both the Singer Building and the Woolworth Building. This was one of the first times such an approach was taken, the calculation which aimed towards a rush hour transport capacity of 300 people per car per 15 minutes, thus providing first class elevator service a daily population of 50,000, came to the conclusion the building was to require 48 elevators, in order to offer prime service to for a 36 story building, thus limiting the promoters early wishes of a 42 story-Figure 41 shows the ground floor of the Equitable Building with enough detail to see the elevator shafts.

![Figure 41 - Equitable Building ground floor detail of elevator](image)

The building’s H-shape was conceived to allow the maximum light penetration, since the building’s height was incompatible with a center well like those of Chicago buildings, this shape permitted long rows of offices on the inner sides. The buildings careful planning made for it to feature a 5% return on investment which was considerably more than the Woolworth that allowed for only 2% to 3% of return [53]. This attitude is, of course extremely damaging for the surrounding buildings which made the Equitable a very unamiable neighbor, as it left most of the surrounding buildings in its shade and thus created a change in attitude in real estate businessmen who once opposed legal restrictions to building height development and then saw how their investments could be jeopardized when a new building either surpassed theirs in height or literally overshadowed it [49].

The 1916 zoning law, which was then replicated in other forms across the United States, reshaped New York’s tall buildings affecting how promoters and designers were to approach tall buildings since it
imposed constraints to projects that up to then had only known technical or financial limitations. The main lines of the zoning law applied the zoning envelope to all commercial highrises (this excluded apartment houses until a revision in 1929) according to five formulas based on street width and setback angle. For example in a “1 ½ times district” with a 30m wide street, the building could rise up to 45m before the first setback and above that level the condition was for the mass to step back in a 1:3 proportion, meaning 1m back for every 3m of additional height. Other formulas were of similar standards, varying height to street with ration and setback ratio, this led to a very characteristic look as tall building became shorter with height in to what was dubbed a “wedding cake” massing [53]. In Figure 42 the several districts are represented with numbers showing height regulation and letters showing use regulation, also depicted profiles of three height districts.

Usual practice during this period was for developers to privilege smaller more compact buildings that while offering reasonable return on investment did not carry the risk associated with the development of towers [53]. However in prime properties, since the law permitted unlimited heights in 25% of the lot, towers were a standard, and so the height race not only continued but was encouraged by the zoning law as developers needed to stack up evermore floors to attain enough rentable area to produce a satisfactory return. This produced yet another problem since as buildings got higher the number of elevators needed also increased thus reducing the Net Rentable Area to Gross Floor Area ratio – NRA/GFA, which meant greater attention to and complexity towards assessing the maximum economic height of the building. This equilibrium between economy and functionality of the building regarding in great part the elevators, was one of the major constraints of maximum building height up until the 1960s [49].

In 1923 Chicago also saw the review of its land ordinance mainly to remove height limitations that had been set in the 1893 land ordinance act, and had until then been changed several times to cope with real estate cycles a vacancy rates. The Chicago zoning law aimed towards enabling the construction of taller buildings which led to slight changes on the Chicago skyline. Consequences of this zoning change in
Chicago were less dramatic than in New York as developers while trying to fully exploit their new possibilities took more conservative approaches than their New York counterparts.

4.3.2 Relevant Technology

From a technological standpoint as far as elevators and structures are concerned this was a rather uninteresting period which saw but a few novelties related with elevator control systems and the topping of steel frame and braced frame technologies for building structures [4]. Some of the innovations of this period are mostly related to new approaches to the problems posed by the implications of the zoning law, some of these innovation were to do with building layout, elevator arrangements and service core concept.

The elevator

During this period though there was little technological improvement regarding elevator mechanics a refinement in buildings design brought on by the zoning law as well as the growing importance of elevator service quality for a buildings reputation and rent demand, contributed to new elevator arrangement solutions and to a general formal conception of service core. Meantime elevator companies were focusing on ways to automate the elevator which required car operators.

By early 1920s the adoption of zoning for elevators had already become a practice, promoted by the constraints of the zoning law that put extra pressure on efficient space occupancy, a different and very relevant novelty was however first implemented in Chicago in the Strauss Building (now Metropolitan Building) in the form of a sky lobby. Not being particularly tall the Strauss Building much like the Equitable Building in New York was developed with great care for elevator service, such was the speculative importance of a high quality image, it was the first time in Chicago a building adopted such a sophisticated elevator arrangement as it took advantage of elevator zoning to satisfy service demands while diminishing the total number of elevators needed, freeing up space for rental purposes further and as referred it also introduced the first modern example of a Sky lobby as the 9 story tower that emerged from the 21 story main façade had its own elevator that could only be accessed through the 21st floor [48].

The sky lobby, was also implemented in tall buildings in New York, the Empire State Building being the most relevant example as the solution accounted for considerable space savings as the elevators of the higher group did not have to cross the whole building. The elevator system was also significant in choice of height and implicated careful considerations as specialists posed limitation to the intended number of floor, 88 stating, the maximum economic height was of 75 stories any more would require an additional bank of elevators. Despite this considerations developers considered the advertising value in being the world’s tallest would provide a favorable trade-off when considering the extra elevator space [53]. The final elevator solution implied a total of 67 elevators, with low risers located on the sides of the service core so that as the building stepped back these could be discontinued while the more central elevators would carry on to the top, Figure 43 shows the floor layouts towards the building’s top.
Other significant innovations in elevator technology are related with automation with the introduction of the automatic car door and gate closer, patented in 1929 by Haughton, previously in 1924 Otis Elevator company had already installed the first automatic "Signal Control" in New York City allowing elevator cars to dispense attendants. This period also the implementation and revision of New York’s “elevator rules”, the original document, published in 1918, comprised 16 pages and while establishing rules for good service it also limited elevator speed to 3.6m/s (700fpm), this particular subject was changed in 1931 to a new limit of 5m/s (1,000fpm).

**Braced frame Structure**

Though not a major innovation bracing was in fact a stabilizing solution for the taller steel frame structures applied in both the Chrysler Building and the Empire State Building. Since bracing can hamper in-floor circulation the system tended to be placed near the central service core where it could remain unseen, from this perspective these were the first steps towards the development of the service core’s structural role, as concrete construction in tall buildings remained uncommon. Figure 44 represents the Empire State Building’s structure, bracings located in the center of the building [17].
More sophisticated methods of structural analysis were unavailable until after the war which meant structures remained oversized and highly redundant, construction continued favoring steel over concrete as bolting up beams and columns not only provided good structural support it also allowed for great construction speed. Bringing forward once again the example of the Empire State Building as referred in a 1930 issue of Fortune magazine the building was constrained by site, capital, land ordinance, the laws of physics and May 1, 1931 – which was when all business space leases were signed – this meant the building was to be complete 1 year and 6 months after the beginning of the sketches [53].

4.3.3 Building typology and architecture

As has been referred the building typology was severely influenced by the zoning law, however despite what might be apprehended the constraints brought on by the zoning law were triggers to further development and optimization of the tall building form. As contemporary remarks pointed out “New York’s ordinance was the most interesting single phenomenon in American architecture today (…) the zoning law taught practicality and suggested design as well.” Proving the advantages of the new design was the adoption of similar forms in cities with no such land ordinance as that of New York [53]. In some cases the adoption of a similar form was mostly due to cultural statements as the buildings in New York
set new standards in modernity and as pointed out sometimes form follows fashion, but to the extent that it fits comfortably within the budget [53].

**Building layout**

As has already been stated the zoning law introduced a shape constraint commonly known as building envelope which implicated restrictions to building height according to city zone and street width as explained when discussing the zoning law. This had evident consequences in both building appearance but also in floor layout with special concern with the positioning of the service core.

Starting with the general building typology of the post zoning period, the wedding cake format was a consequence of the new regulation towards guaranteeing that buildings would not be overshadowed by their neighbors as illumination and office fenestration still mattered considerably to determining rent value. The new buildings were allowed to grow without limit in 25% of the lot leading to huge slender towers emerging seldom from the center of the building. Figure 45 depicts the some of the differences between pre-zoning typologies and post-zoning typologies.

![Figure 45 - Effects of the Zoning law](image)

These new buildings were consequently less bulky than their predecessors which has a severe impact from a sustainability point of view since studies show that in a climate with severe winters as New York’s a buildings energy requirements for heating are proportional to a buildings surface area to volume ration,
the higher the ratio the higher the heating requirements, since larger surfaces increase heat loss [40]. Figure 46 compares pre and post-zoning buildings’ surface to volume ratio.

A positive aspect regarding energy consumption would have been the smaller floor areas in upper levels requiring less illumination that before in bigger, deeper floors, however the illumination requirements were also growing so this potential benefit did not transit to actual results. This particular generation also witnessed the introduction of office acclimatization which meant more energy consumption, this procedure remained uncommon until late 1950s after the invention of mechanical air conditioning by Willis Carrier in 1939 [5], still buildings of this period and as a consequence of the zoning law showed a higher energy consumption than their predecessors [40].

The zoning law’s implications on building typology, the constant concern with optimal use of space and to some extent improvements in electrical illumination and electrical companies aggressive sales strategies, contributed to a more defined approach towards buildings services and consequently the service core. By the late 1930’s a 50 year long evolution in tall building’s service core culminated in what could be defined as “An element that gathers together the spaces necessary to provide visual, physical and functional vertical connections that work effectively to distribute services through the building” [48]. Efficiency drove cores to the center of the building and to an ever more compact form.

The 1929 market crash and subsequent recession and eventually the war meant projects such as the Chrysler Building and the Empire State Building were no longer feasible, the latter remaining the tallest building in the world for over 40 years, some relevant projects such as the Rockefeller Center were developed during the 1930s but were an exception rather than a rule. Further developments in tall building history were to occur after the war and accounted for yet another very significant change in the high rise construction paradigm, as will be discussed next.
4.4 Post WWII to 1970s energy crisis

The 1950s and 1960s were very interesting years for high rise construction, great advances in technology allowed for new approaches and changed building design almost completely. Structural systems were completely revolutionized during this period thanks to the integration of recently developed computer technology that allowed for more complex simulations, leading to structural optimization and consequently to the adoption of new structural forms. Fluorescent lighting, air conditioning and the glazed curtain wall façade technology liberated the tall office building from its relation with nature and site [40] permitting better space usage and therefore increasing usable floor area that had until then been limited, to some extent, by natural illumination.

However despite all the technological innovation buildings of this period also show extremely negative attributes relating sustainability, as a consequence of the new paradigm buildings’ energy consumption underwent a tremendous increase to which the 1970s energy crisis put an abrupt end.

4.4.1 Social and economic situation

Through the 1930s and until the end of the war there was considerable and comprehensible stagnation in high rise space development, demand for space was little, which cities such as Chicago reflected by imposing limitations to building height and volume in 1942, such was the building vacancy rate. Figure 47 shows office space occupancy in the central business area of New York between 1925 and 1934, where a great decline in office space demand is evident.

![Figure 47 - New York City Building occupancy](image-url)
However with the end of the war came great economic recovery that was accompanied by demand for office space, new projects were quick to arise and with them a new concept of modernity. In the tale of the two American cities it was New York the first to see its built space increase as the referred restrictions imposed by land ordinance law in Chicago were said to have inhibited investor from high rise construction. An evidence is the fact that between the end of the war and 1959 New York had seen the development of 5.4 million square meters of office space while Chicago only had 240 thousand square meters of new office space, this meant according to Schultz and Simmons [53] that corporations were made to choose New York over Chicago when looking to build their income producing headquarters.

**New zoning regulations**

Several years had passed since the 1916 zoning law in New York and all social, economic, and technological aspects had witnessed dramatic changes which were to be reflected in tall buildings as well. Though the 1916 zoning law had suffered several amendments the 1961 zoning law introduced a new concept of ordinance in New York, similar to that already applied in Chicago by that time, and which addressed building density not by means of an envelope but by limiting construction according to lot size. These legal mechanisms replaced the imposed setback with a *floor area ratio* (FAR) land density formula, the definition as is found in the *City of New York’s Zoning Maps and Resolution* made effective of November 15th 1961, is as follows

FAR land density formulas: “Floor area ratio is the total floor area on a zoning lot, divided by the lot area of that zoning lot. (For example, a building containing 20.000 square feet of floor area on a zoning lot of 10.000 square feet has a floor area ratio of 2.0)” (City of New York zoning maps and resolution effective of December 15th 1961 [16].

This new zoning law made indirectly for a limitation in building height, and was meant as a way of controlling urban density by regulating building size [53] the FAR regulation made some special remarks towards benefiting developers who included public spaces or plazas on a portion of the lot, this could mean a maximum 20% density bonus [40], meaning an FAR rise from 15 to 18 which is a considerable amount of office space.

<table>
<thead>
<tr>
<th>Maximum Floor Area Ratio</th>
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<th>C7</th>
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<tbody>
<tr>
<td>6.00</td>
<td>C8</td>
<td>C8-1</td>
</tr>
<tr>
<td>1.00</td>
<td>C4-1</td>
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<td>C4-3</td>
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<td>10.00</td>
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**Figure 48 - Maximum floor area ratio**
As shown in Figure 48 above, land ordinance now imposed a maximum floor area ratio as opposed to the previous ordinance that stipulated an exterior envelope without imposing height limits to buildings. Though such an imposition could have been historically regarded as detrimental to investors and therefore would have been ill received, reality was that many of the stipulations imposed by the new zoning law had already been applied for quite some time as the Seagram Building and Lever House, both shown in Figure 49, testify.

Figure 49 - Seagram Building (left) and Lever House (right)

The reason being the new floor layout made possible by the referred technological innovations in illumination and acclimatization allowed for better space usage, which combined with the new ordinance meant buildings were no longer forced to fill the entire surface of a lot in order to obtain the maximum gain in terms of built areas [49]. Further discussion of building layout will be pursued after discussing the relevant technology.

4.4.2 Relevant technology

As referred this was a period of intense technical innovation, new or improved technology of this period such as fluorescent lighting and air conditioning were as important for these tall buildings as the elevator and steel-cage construction was to the first skyscrapers of late 1800s [53]. Other marking features of the time were the glazed curtain wall and the new approach towards structure which in many ways invigorated the service core’s structural role [49].

Illumination, HVAC and the Glazed curtain wall

Other than the structural revolution that took place simultaneously, illumination, HVAC and the Glazed Curtain Wall can be said to have been the most significant influences towards the new concept of high rise construction, and, ironically, also the reason for its downfall.

Starting with illumination, as has been previously stated, the introduction of fluorescent lighting from the late 1930s onwards, replacing the ineffective incandescent bulbs, allowed for office layout to be
independent of natural light and therefore window proximity. Adding to the dependency of interior space illumination was an increase of the advised luminance levels, from the 269 lux recommended in the 1930s to 1076-1615 lux of the 1960 Recommended Practice for Office Lighting, this carried for significant increase in the building’s energy consumption [40].

HVAC systems had already been applied since the invention of mechanical air conditioning by Willis Carrier in 1939, however it was only during this period that they saw widespread use as the new paradigm made them essential for building operation [5]. Also it meant yet another substantial increase in the building’s energy consumption, emphasized by the low thermal inertia of the glazed curtain wall [40].

The Glazed Curtain Wall can be described as visually the most characteristic aspect of Modernism in tall buildings, the vision of the glass tower meant “modern” which translated to “fashionable” thus carrying for great public recognition. As Schultz and Simmons noted the glass wall had “no financial purpose, except as advertising” [53], which was backed up by Lever president Tom Carol, who claimed that the 7 million dollar Lever House had generate the equivalent of 4 million dollar returns on publicity. This technology was pioneered by architect Mies van der Rohe and Skidmore Owings Merrill (SOM) and made for fully glazed, fully sealed buildings, as windows were inoperable, thus making for total reliance on the mechanical ventilation and the aforementioned dependency on HVAC systems [5]. This system, of which a detail is presented in Figure 50, made for total glazed surfaces of 50% to 70% of total building surface, a significant jump from pre-war building values of 20% to 40% [40].

![Figure 50 - detail of Lever house glazed façade](image)

The problems associated with the glass curtain wall were noticeably its poor thermal performance, as it makes for great heat losses in the summer, and unwanted solar gains in the summer, which since the building is hermetically sealed, must be compensated by artificial acclimatization, thus more energy consumption. A fact that was aggravated with the widespread of black skyscrapers with dark colored
glazing which decreased lighting gains and made for even more pronounced solar absorption in summer months [40].

The aforementioned technologies in spite of representing great advances in terms of building comfort did so at the cost of high energy consumption, an aspect that probably was of no great concern since energy was still a cheap asset, and considered to be limitless, a perspective the 1970s events were quick to discard.

**Elevators**

This period saw some interesting developments both in terms of elevator operation, meaning further advances towards an automatic system, and in terms of elevator arrangements specially due to the new possibilities in terms of floor layout, which called for ever more optimized elevator solutions, and also partly due to the second height race of early 1970s and the high rise possibilities of the new structural systems.

Automatization of the elevator systems had already been attempted but not until 1949, when Otis Elevator Company introduced a fully automatic elevator system, was it possible to replace elevator attendants. The key concerns were mostly on automated doors’ safety as to keep doors from striking moving passenger or to quickly reverse door motion if a person or object was encountered when closing, this was achieved through electric or photoelectric devices that altered closing time if light beam was interrupted [43]. From this point on elevator operation could have new approaches though the most significant would only come in later years.

As for elevator arrangements, during this period they saw intense development especially in the form of the skylobby which saw a careful, efficient spread in its use, most notably through the John Hancock Center, the Sears Tower and the New York World Trade Center [48]. The development of this new more efficient skylobby, as opposed to that which had already been developed for the Empire State Building was triggered by the increased potential of inner office areas for rental. Service cores were becoming more compact in search of an optimal compromise between service conditions and space usage, and elevators continued to take up most of the service core, innovation was once again set to take place.

Considering the John Hancock Center’s elevator system, shown in Figure 51, though employing a skylobby, it is a less extreme situation that the World Trade Center, since the John Hancock Center is a multiuse building, one of the very first to take advantage of this configuration [18], with slightly more residential area, 39.5% that office area, 33% it made lower demands of the elevator system.
The World Trade Center, however, was groundbreaking in its elevator system, and stood for years as the largest vertical communication system with a combined 208 elevators and 49 escalators (both towers), the building required 2 skylobbies on the 44th and 78th floors to provide transportation for an estimated daily population of 250,000 people [24]. The feasibility of the project relied heavily on this arrangement as otherwise elevators would take up just too much space, since as an office building service requirements were more demanding than those of the John Hancock Center, which adding to floor area explains the difference in the total number of elevators when the buildings’ floor difference is of only 10 stories. Figure 52 depicts the elevator arrangement of the World Trade Center Towers next to a depiction of the floor layout.
Figure 52 - World Trade Centre elevator arrangements

Further steps in elevator innovation were to come in the form of control systems, but not until computing power could be widely spread, meaning the 1980s, this period however saw the application of elevator arrangements to their contemporary limit, projects as demanding as the World Trade Center have never again been undertaken as multiuse configurations have become a more common practice and a good practice regarding elevator requirements in tall buildings.

Structural system

Not only was this a key period for structural design and conception much aided by the technological advances in computing calculations, but it is also a very relevant period when concerning the service core’s structural role. Desire to maximize views, enabled by the glazed curtain wall, was an incentive to bring structural bracing systems to the inside of buildings, this meant service cores were now becoming the buildings main structural element [49]. The development of tubular structures would deprive the service core of much of its newly attained structural functions.
It is not possible to refer to this period without referring to Fazlur Kahn, who stood behind many of the developments here referred, as was already mentioned in chapter 2 of this text. His expertise and approach allowed for unprecedented innovations in structural design and tall building conception with great structural and architectural concern as is reported by many of his peers [12]. This bond between Engineering and Architecture had implications not only in building layout but many times in the buildings visual expression as structure was presented in all “honesty” thus becoming the architectural form[12].

Initial developments were related with shear-wall structures as addressed in the, already referred, 1964 Kahn-Sbarounis paper which proved through a direct mathematical solution for the interaction forces, using a forced convergence solution developed by Kahn for early versions of computers, the benefits of frame/shear-wall interaction for tall structure stiffness. This meant a more efficient use of the structural form which allowed for better behavior while employing less material, both improving on embodied energy and cost-efficiency [12].

Simultaneously even more relevant to structural innovation, and particularly to the use of concrete in tall buildings, was the development of the first tube structure for the DeWitt-Chestnut Apartment Building in Chicago, Figure 53.

![Figure 53 - DeWitt-Chestnut apartments](image)

This building relied upon its closely spaced exterior columns (1,7m apart) to give the building its primary resistance structure to lateral forces, this implied persuading both architects and promoters as the structure was then to have noticeable impact on the building’s façade. Also the implications of a tubular structure in terms on behavior meant 3 dimensional analysis when only 2 dimensional analysis were available, Kahn addressed this problem through approximations from a two dimension model [12].

Some very significant aspects of the framed tube system are the following
1. Significant increase in building’s lateral stiffness, by concentrating lateral resisting elements in the building’s periphery, this is achieved without increasing costs.
2. The flat plate is protected from high lateral load effects
3. Windows are set between columns of the framed tube, significantly reducing costs for the exterior window wall

Further enhancing the cost benefits of this new approach was Bruce Graham, architect at SOM who collaborated with Kahn in the DeWitt-Chestnut project, refers using the framed tube system allowed for the construction of the 43 story building for the same cost as a 28 story building with traditional structure [12].

A further innovation which also benefitted structural cost efficiency was the application of frame/shear-wall interaction to tubular structures which was the tube in tube structure first applied in the Brunswick Building, Figure 54.

![Brunswick building, one shell plaza and structure of one shell plaza](image1)

**Figure 54 – Left to right Brunswick building, one shell plaza and structure of one shell plaza**

This building also employed very interesting solutions to solve the differential thermal induced variations between outside and inner tubes, and thus was an incentive to further investigation on the effects of column exposure in tall concrete buildings, it also employed a 7.3m high transfer wall beam to direct loads from the closely spaced upper columns to the widely spaced columns of the atrium, a detail of which is shown in Figure 55. Later the concrete structure of the One Shell Plaza would require what was to be the first sophisticated creep analysis of a tall building structure, this was therefore a very important period for concrete usage in tall buildings [12].

![Brunswick building, detail of transfer beam](image2)

**Figure 55 - Brunswick building, detail of transfer beam**
A problem with tubular structures was the effect of shear lag, as already stated, and the consequent overloading of columns nearer to the corners, a way devised to solve this problem was the bundled tube system, which consisted of several tubes acting as a whole to increase resistance and stiffness, the other solutions being diagonal bracing, applied in both steel and concrete, Figure 56. The application of these solutions made not only for greater structural efficiency, but it also meant columns could be spaced further apart, the downside, if such considered, was the aesthetical value of the bracing system.

![Figure 56 - John Hancock Building (left) and 780 3rd Avenue (right)](image)

These new structural systems not only allowed for greater heights and better structural behavior, they also allowed for this achievement in a cost effective structurally efficient way, that taking full advantage of materials. This meant a building like the 50 story One Shell Plaza could be constructed with a building cost of 205 to 215 $/m², an impressive figure at the time, and the 100 story John Hancock Center used 145 kg of steel per m², while it was current for 50 story buildings at the time to use between 195 and 245 kg of steel per m² [12].

### 4.4.3 Building Typology and Architecture

Lighting and air conditioning allowed for interior spaces to become rentable as only the naturally illuminated peripheral areas had been until then. This meant new possibilities for office space design which aided by company needs contributed to the development of the new office spaces. During this period of time that went from the end of WWII to the energy crisis of the 1970s, though severely marked by the miesian architecture features distinct buildings especially when structural arrangements are concerned. These different types of buildings though very similar in terms of interior layout and technology employed are mostly addressed in terms of their scale. As some of the first buildings of this period, until mid-1960s, were not particularly tall, the buildings of late 1960s and early 1970s were of distinct proportions much aided by the structural innovations already described. The aim is to describe inner floor layout in both buildings according to what technology made possible, while addressing some of the differences induced by the new structural systems.
Building layout and architecture
From 1940 to 1960 employment of white color workers doubled and so did the area of the average office. In 1965 the average tenant occupied about 240m$^2$, double the area of 1952. Many companies preferred to consolidate operations on large, full floors and utilized space far from windows for clerical staff, meeting rooms, and office machines. From an investor’s perspective, as put by Lee Thompson Smith, president of the Real Estate Board of New York, these new buildings’ concept in spite of its technological attributes was inadaptable to older buildings since the former “provide large blocks of space on one floor, with great glass areas, better lighting, fewer courts, less waste space, and new automatic elevator arrangements with fewer cars and faster service.” Once again the importance of the elevator arrangement is pointed out. All these innovations made for an NRA/GFA ratio of about 80% in these new buildings whereas older buildings only managed about 60% [53]. Further consequences of the technological development related with illumination were a decrease in floor height, as high ceilings were no longer needed to guarantee light penetration, this meant that inside the same envelope more floors could be fitted meaning an even greater office density. This disposition in line with what has been previously stated is a further evidence of the importance of the FAR rule in the effort to control the city’s population density. Figure 57 shows an office in 1960 and the plan for the Sears Tower office building.

![Figure 57 - Sears Tower floor](image-link)

The International Style
Construction during this period reflected some characteristics that had already begun to manifest before the war, and reflected the architect’s holistic view of the project, the paradigm as had been laid by Le Corbusier and Walter Groupius urged “utility, straight lines and technology” [6].

This interpreted through Mies van der Rohe’s “less is more” doctrine meant buildings were mostly striped of any non-functional ornamentation [6], the glazed curtain wall was the visual expression of this paradigm. The international Style statement included 3 principles [30]

1. Volume – space enclosed by thin planes or surfaces as opposed to the suggestion of mass and solidity
2. Regularity – instead of pure radial symmetry as main guide for ordering design
3. Resistance to any frivolous or arbitrarily applied decoration
Other characteristics taken from the tall buildings of this period suggest other interpretations, some of which already mentioned and at sometimes contradictory. These buildings were conceived with great care for both its occupants and those who passed them by on a daily basis, thus the ground floors often featured “public amenities”, the plazas, commercial spaces, metro entrances, etc.; though this was later an “imposition” of the zoning law, many buildings preceded the law in presenting these features. Lever House once again is a good example of a building giving back to the city through its plaza which has been stage for many public exhibitions since its completion Figure 58

This, however, is in stark contrast with the concept of building without constraint of site or nature that to some extent epitomized these buildings, after all, the glazed curtain wall fully isolated the building from the exterior and buildings tended to stand on columns as if to emphasize their independence from site. Both these perspectives are to some extent accurate, but more importantly than the motivation for the adoption of such forms are its consequences to building functioning. As mentioned earlier buildings of this period completely dependent on HVAC systems, the consequently raising the building’s energy consumption, as already referred, aggravated by the miesian aesthetics in the form of black sky scrapers, such as the Seagram Building, 860 and 880 Lake Shore Drive, and later the John Hancock Center and the Willis Tower, all shown in Figure 59.
Both the John Hancock Building and the Willis Tower are not the typical International Style building but are shown above to emphasize the wide acceptance of the black skyscraper, both these buildings fall into the category of buildings which is to be described next.

The decision to consider another category for the description of buildings in this period comes from the predominance structure was to take following mid-1960s. These buildings that epitomize the International Style in tall building, such as Lever House, the Seagram Building, 860 and 880 Lake Shore Drive, were not particularly tall buildings compared to those that had already been built, the Seagram Building is the tallest of these and has “just” 38 floors, not much by the day’s standards. These buildings though aesthetically very different from those before them, still relied on the typical steel frame structure for support. Structural innovation tough maintaining many of the functional aspects of the International Style, demanded a different approach to the building’s façade, instead of a light surface covering the building the exterior structures demanded a dense array of load bearing columns.

**Structural innovation – continuing the height race**

The new structural systems had tremendous visual impact on the buildings though in some it was more evident, tubular structures brought great benefits to the construction of tall buildings, and contributed to some changes in the industry, such as a promotion for the use of concrete in tall building structure.

Though these buildings still suffered from many of the ailments as those of typical miesian architecture, the fact that the exterior tube or bracings were used as façade made for a smaller glazed surface, therefore, a small improvement in thermal performance, this was more evident in earlier tubular structures where columns still could not be very far apart. Apart from this all other aspects remained similar, great need for artificial illumination and mechanical ventilation. Also since buildings were getting higher more elevators were required and therefore this also added to the ever increasing running energy consumption.

These new structural forms were soon to be taken advantage and a new height race started in late 1960s first with the World Trade Center which reigned as the world’s tallest from its inauguration in 1972 until the Sears Tower (now Willis) was finished in 1974.
Until then the Empire State Building had remained the world’s tallest building, meaning more than 40 years, the new structural systems made these buildings possible and economically feasible. Though from an environmental perspective these buildings had major faults, they were otherwise carefully planned and built attending on function and structure. From a technical perspective they represented great improvement over buildings built before the war.

4.5 After the energy Crisis

The years of 1973 and 1979 saw a severe economic downturn in the form of the energy crisis, the growth in oil production that had enabled low energy costs was suddenly halted with a consequent shortage felt worldwide. The price of energy soared at a time building’s primary energy requirements averaged about 820 W.h/m²/year, more than doubling the value averaged for buildings built 15 years before, as shown in Figure 60 [40].

![Figure 60 - Primary energy consumption (1 btu/sqft/year = 3.1546 Wh/m²/year)](image)

This evolution in energy consumption, as has already been discussed, had mostly to do with hermetically sealing tall buildings and consequently making them absolutely reliant on artificial acclimatization and illumination, while providing them with thermally ineffective façades [40].

It is important to say that unlike the periods described until now that have had a beginning and an end, the aspects associated with post energy crisis buildings are still found in buildings being built nowadays, so these aspects are not just to be considered as a passing vogue as they are very current, though regulations differ from those of the 1970s, most buildings today still manage just to comply with regulation instead of attempting to improve on its requirements [40].

4.5.1 Social and economic context

In the mid-1980s economic conditions in the US were improving. A recession had passed rates of interest were falling, inflation had been tamed and demand was up for everything. This was indeed greatly contrasting with the conditions of the previous decade when the Oil Shock, the New York Fiscal Crisis, and a glut of office space inherited from the early 1960s, had conspired to depress land values and curtail
real estate development [34]. This economic improvement was then steadied by the 1987-91 recession in US economy [34], another very relevant issue concerning the trend in tall buildings in late 1970s and early 1980s was their development outside the US mainly in Asia. The Pacific Rim countries such as Hong Kong, Malaysia, Singapore, Vietnam, and South Korea experienced significant economic growth during the 1980s and 1990s. With the region’s leading economy, Japan, in recession and stagnation for much of the 1990s, the “Asian Tigers” were considered miracle economies because they were strong and durable despite being small and vulnerable [46]. These emerging economic powers tended to concentrate urban development in key locations in each country, thus creating a great demand for space which saw the creation of many tall buildings, both offices and residential, mostly ranging from 12-20 stories, or 30 to 60 stories in the case of Hong Kong.

The Petronas Towers were completed in Kuala Lumpur, Malaysia in 1997 setting a new record for the world’s tallest building at 452m beating the old record by 10m (the two towers were only 88 stories high compared with the 110 story giants built in the early 1970s). [46].

In the legal context the post crisis years saw many developed countries adopt regulations for energetic performance of buildings and reviewing past recommendations such as the 1982 revision of the American National Standard Practice for Office Lighting which proposed a reduction of 20-25% in office luminance [40].

4.5.2 Relevant Technology

Though as stated earlier this is to some extent a current period only the technologies here described are those that concern directly the aftermath of the 1970s energy crisis, since more recent technological advances are mostly connected with sustainability and are therefore more suited to be discussed in the following chapter.

The 1980’s saw the mass spread of personal computers for office use, this implied not only an increase of building energy consumption but it also meant internal heat gains from the computers, this implies more HVAC related energy consumption in the summer months to cope with the excess heat produced.

The energy crisis prompted several measures that contributed to technological evolution mainly in the glazing system. As energy consumption had become a major issue all systems that represent some form of waste were put under intense pressure and criticism, the glazed curtain wall was an obvious target as even the common windows was being considered an energy leak [40]. This pressure manifested itself directly in the glass production industry which introduced improved double glazing technology to answer the stated concerns.

Double Glazing

The glazed curtain wall that had been applied until then relied on single glazing technology which meant extremely poor thermal performance to which the fashion of dark tinted glass added a reduction in natural light penetration thus promoting further energy consumption for artificial illumination. Double glazing technology making use of better glass and utilizing argon-filled cavities made for an overall better performance of glazed curtain walls thus reducing thermal losses and consequently temperature related
energy consumption. Aiding to these advances were also the low-emittance (Low-e) coatings which basically consists of microscopically thin, virtually invisible, metal or metallic oxide layers deposited on a window surface primarily to reduce the U-factor\(^2\) by suppressing radiative heat flow. Figure 61 represents the U-factor reduction associated with the several glazing improvements.

![Figure 61 - heat loss reduction due to double glazing and scheme of double glazing](http://www.upvcwindowsthailand.com/double-glazing/)

For further illustration of the importance of the tainted glazed surfaces or the black skyscrapers Figure 62 shows the rupture in the trend due to the energy crisis, their negative consequences having been already described.

![Figure 62 - Construction of "black" skyscrapers](http://www.upvcwindowsthailand.com/double-glazing/)

\(^2\) The U-factor measures how well a product prevents heat from escaping, the metric unit is W/m\(^2\) K.
Elevators

Elevators did not suffer much of an alteration regarded to what had been previous practice. Elevators systems though experiencing some operational improvements and some performance enhancements regarding speed, did not experience any industry changing innovations until mid-1990s when computer development allowed for the improvement of elevator operation most notably in the form of destination control and the already referred PMSM technology. Elevator operation though a relevant element in running energy consumption was difficult to minimize with the available technology without compromising service, though elevators remained the biggest service core space consumers their impact on running energy was less than HVAC and more difficult to reduce.

Structures

The greatest impact of the energy crisis was immediately felt on the buildings running energy, structural form relates to this through new approaches towards building design that began to take place even in mid 1980s. Most early proposals of passive climate control devices for buildings, were mostly related with façade technology, many times applying sunshades, and did not have any serious impact on structural design, however some designers and promoters were more ambitious in their approach, and started taking advantage of structural elements to provide said shade [5]. It is important to associate this need for improvement with the referred emerging countries, as tall buildings are regarded, countries such as Malaysia and the UAE had very challenging environmental conditions and thus required more ambitious approaches for minimizing dependency on air conditioning.

A good example is the National Commercial Bank of Jeddah building, designed in 1982 just after the energy crisis, which placed its service core on the outside of the building thus providing additional shade for the office building while the buildings structural system consists of external concrete walls and interior columns. The building’s windows face the interior as the external walls not only support the building but also provided a thermal shield, this solution allied with an interior disposition of floor that promotes air circulation, is said to reduce the external temperature at the glass façade by as much as 10 degrees which means a substantial energy saving [5]. The National Commercial Bank of Jeddah is shown in Figure 63 alongside its plan and floor scheme.

![Figure 63 - National Commercial Bank in Jeddah](image-url)
Though not a particularly tall building, at 27 stories high, the National Commercial Bank of Jeddah building is a good example of a building being adjusted to its surroundings and making the best of its design for sustainability purposes. The external service core for shading purposes is a design alternative which has been subjected to much research and particularly developed by Ken Yeang, there are some negative consequences resulting from the unconventional positioning of the service core thus the solution requires careful planning [49].

Structural development also reflected the increased computational power that was made available allowing for better structural solutions and the further development of 3 dimensional analysis which would allow for structures such as the National Bank of China Tower. This building was the first application of a 3 dimensional truss to support almost the entire weight of the building while making use of that same system to resist the lateral thrusts of the typhoon winds this is ever more important since space-truss is achieved without the need to resort to the complexities and the cost that have been associated with cross-braced structures of the past [36]. Figure 64 shows the National Bank of China Tower with its evident structural form.

Figure 64 - National Bank of China Building

Though computational power brought many benefits to architectural and structural design the fact that computers could now allow an engineer to make a building stand without a rational structural system lead to a detriment in building’s structural efficiency [10]. This problem however concerned more mid-rise buildings that high-rise buildings whose structure and development required more careful planning.

The role of concrete in tall building construction continued to assert itself as an alternative, as Fazlur Kahn had predicted years earlier [46], designer started adopting evermore concrete and composite solutions for structural support, which may have been to some extent aided by the new economies now leading tall building development, since construction is linked to local economies.
The most relevant aspects relating to the period here described relate to the implementation of measures to limit energy consumption in tall buildings, further developments would deepen the environmental perspective of tall building development. Many of the buildings constructed today comply with the characteristics described for this post-crisis period, architecture and building layout did not undergo significant transformation except for the buildings where an exterior service core was implemented. These were, however, punctual situations.

4.6 Rise of an Environmental consciousness (1997) to the present day

Given the attention already given to environmental issues what makes the year of 1997 special and what exactly is the environmental consciousness and why does it imply a change in tall buildings design and construction?

Firstly to address the issue of the date, 1997 can be said to mark the rise of the environmental consciousness as it was the Frankfurt Commerzbank building was finished marking the first time environmentally conscious principles were applied to tall buildings [40]. This means not only complying with regulatory standards but actually bettering them significantly in an environmental perspective. The Commerzbank building started a trend in tall buildings and tall building technology which was quickly adopted in many tall building developments leading to a new public perception and integration of the tall building in the urban landscape. Buildings running energy, which had been the main concern of the past period, started giving way to a more holistic approach towards building’s energy consumption giving evermore importance to embodied energy.

A quick reference is to be made to the events of September 11th 2001 and some of its consequences for tall building development worldwide.

4.6.1 Social and economic situation

The global economic situation of late is of great turbulence, however in spite of this these economic difficulties in recent times there have been some amazing developments in tall building construction. Picking up in 1997 in the countries that had been spotlights for tall building development the decade before saw financial and economic problems induced by the beginning of the extreme drop in Malaysia’s stock market, rapid depreciation of its currency, and widespread social unrest, spread to economies throughout the region, a phenomenon known as the “Asian Contagion” [46].

Other countries were quick to take the spotlight, this time in the Middle East and China as promoters for tall building construction. Both Dubai and Shanghai have been among the major developers of the past few years much in accordance to the booming economic development the respective countries were experiencing. In their context building tall is to assert the countries position and dominance, giving the countries an *ex libris* to match economic status much as the tall buildings of earlier generations. As motivation still remains similar some constraints of earlier buildings particularly those located in already developed cities such as New York and Chicago were not to be encountered, this means both technological constraints and site constraints. This does not mean development was unregulated, quite on the contrary, since modern buildings benefit from a more extensive learning curve and can look to avoid
mistakes of the past, but while obeying regulations the historical heritage that in the urban context is less expressive than that of American cities is less of a burden to building format and thus makes for buildings that are very different that those found elsewhere in the world, the box shaped skyscraper gives way to more organic forms.

As cities focusing economic development in fast rising countries tend towards higher population densities the skyscrapers as current a need as they ever were. City development is an undeniable need as according to the UN reports about 50% of the world’s population is living in cities with a prospective rise of this figure to about 70% in 2050 [50]. Associating this growth with the already impressive notion that cities are currently responsible for 75% of the carbon emissions worldwide [27], the need to minimize energy consumption in buildings comes as no surprise.

Public perception of the tall building has once again been of great importance in two distinct ways, one being the perception of skyscrapers as environmentally unfriendly buildings due to their high energy consumption and second due to the events of September 11th 2001 which made people question the safety aspects of building tall. The first matter is easier to address since there have been serious improvements towards more energy efficient buildings value both for building user since there are considerable long term economic benefits associated with adopting energy efficient methodologies in building development, also the “green” label means good publicity for both promoters and developers. Recent years have also seen the development of institutions such as the United States Green Building Council which has strived to develop a holistic approach towards building certification, the result being the Leadership in Energy and Environmental Design (LEED) Green Building rating systems [51].

As for the safety issue matters are more complicated as though structural resistance can be increased to meet the impact of certain kinds of terrorist attacks there is no absolutely reliable way to design a building for the impact of a large scale commercial airliner.

4.6.2 Relevant technology
Technological development of recent is associated mostly with energetic efficiency, computer monitoring of buildings and computer assisted design for buildings, along other more creative approaches to power generation. Some very important changes in the design process and building layout, benefitting from advanced computer simulations related with both structural behavior and energy consumption, have also contributed significantly to sustainability and though these aspects are related with new technological possibilities they will be addressed further when architecture and building layout is considered.

Building Management systems
Computer technology and automated systems have been increasingly relied upon for bettering the sustainable functioning of tall buildings. The Building Management System (BMS) is a centralized control system to manage the operation of the various building systems such as fire protection, security, communication networks, elevators, HVAC systems, etc., with incorporated data collection functions and also the possibility to control other more passive building features such as window opening and shading devices [3]. The component of BMS that deals with energy-related services is controlled by the Building Energy Management System (BEMS) also known as the Energy Management and Control System
(EMCS), which may function autonomously and may be located elsewhere outside the building, making for great versatility.

**Facade technology**

Other than the improvement of glazing, façades have been developed towards allowing natural ventilation where climate conditions allow. A strategy that has been implemented with some success is the double skin façade which, combined with suitable building layout allows for natural ventilation. The GSW Headquarters in Berlin is a good example of this practice, its airflow system is depicted in Figure 65 and makes natural ventilation in the building possible in 70% of the year which significantly reduces air conditioning needs [40].

![Figure 65 - GSW Headquarters](image)

These solutions imply suitable building layouts consequently affecting structural disposition and affecting service core design both in its location but also in its size since service core area affected to ventilation may be reduced.

**Elevators**

In recent years technologies such as Hall Call Destination Control, PSMS and twin elevator systems have brought new possibilities of enhancing service without increasing the number of elevators and minimizing energy consumption. Most of these advantages come once again from the use of computer based control systems that have allowed for more rational elevator control aiming towards more efficient travelling patterns that consequently minimize energy consumption. Other benefits of these improvements are that in some cases mean fewer elevators and therefore smaller service cores, the possibilities of these technological achievements have already been addressed in chapter 3, subchapter 3.5 Elevator systems – Current trends, and will therefore not be further dwelled upon. The concern being to acknowledge that current possibilities for elevator systems are still very recent and still have much to offer, another important fact is the importance of September 11th for the purposes of elevator and core security in fire scenarios.

**Structures**

Structural design had already come a long way from masonry load bearing walls, but recent trends have seen evermore impressive structural arrangements as buildings reach higher than before while debating
cost efficiency and sustainability. Environmental issues associated with embodied energy have led to a more careful choice of materials from which concrete has benefited over steel confirming a tendency started in the 1960s.

New structural arrangements such as the diagrid has been a differentiating trend in recent years with good material saving results even when compared with braced-tube structures which are among the most efficient structures for tall buildings [3]. Successful examples of the application of this structural type are the Swiss RE Tower, the Hearst Building and the Guangzhou International Finance Center which standing at approximately 438 meters tall with 103 floors above ground is currently the 9th tallest building in the world, all these buildings are shown in Figure 66.

![Figure 66 - Left to right, Swiss RE, Hearst building, NY Guangzhou International Finance Center](image)

September 11th which must be addressed in this part came as a remainder of some of the perils of tall buildings raising public awareness on how safe tall buildings actually were. In a recent interview Leslie Robertson, who was the structural engineer responsible for the World Trade Center, stated his take on tall buildings, as a structural engineer, remain the same, “(…) tall buildings are safe. They were safe before 9/11 as they are safe today.” Though considering that the tragic events directed much attention towards improving building safety he considered to be unrealistic, from a structural point of view, to think much could be done against large airplanes flying into buildings. This perspective is shared by other structural engineers however the will to build higher was shaken as according to William Baker of SOM, the events caused a change in the plans of Trump Organization’s new Trump Tower for Chicago, which initially had proposed to become the tallest building in the world but saw its intended height be cut considerably as if emphasizing the disappearance of the former glory and fascination skyscrapers exerted.

Of course today tall building construction has once again resumed with the Burj Khalifa, coincidentally designed in collaboration with William Baker of SOM, stands at an unprecedented 828 meters with plans underway for the construction of even higher buildings, skyscrapers are here to stay.
4.6.3 Building layout and architecture

When approaching building design focusing on passive ways to reduce energy consumption, such as inner atria and natural ventilation, much in the way as the Commerzbank was developed, there result carries deep changes into what in conventional building design. Starting with floor configuration and the resource to inner atria much as was evidenced in Yeang’s National Commercial Bank in Jeddah, and to which the Commerzbank shows evident similarities, Figure 67, what had been a tradition of deep office floors with central service cores cannot be applied.

![Figure 67 - National commercial Bank in Jeddah (left) and the Commerzbank in Frankfurt (right)](image)

These features, which greatly help to improve ventilation and natural illumination, require careful planning as far as services and structure are considered, the main difference between the two buildings being the positioning of services and the outside façade transparency, which are products of local climate.

The inner arrangement leading to effective ventilation, as shown above, included unmatched floor where winter gardens are included. The positioning of the winter gardens rotates in height around the façade of the building which as the garden floor are higher than normal floors creates for increased light penetration [25].
For the structural arrangement the Commerzbank building relies on a tubular, steel frame construction where at each corner stand the cores which provide the vertical support for the building, spanning between these cores are 8-floor deep Verendeel trusses which allow for support along the span of the winter gardens, the whole of these elements allows the structure to behave like a tube [25]. Figure 68 depicts the structure of the Commerzbank in Frankfurt.

Another noteworthy project also by Foster and Partners, is the Swiss RE building in London which makes use of a diagrid structure to support a unique spiral form that not only minimizes dynamic wind effects but also enables natural ventilation. According to developers the building is expected to require around 215kWh/m2/year for its operation, about 40% less than buildings of the 1970s, which is considerable assuming buildings energy consumption associated with electronic equipment has risen significantly [48].

Still evolution continues as far as tall buildings are concerned with new ambitions projects still arriving, current buildings come in many sizes and shapes but all share careful planning and execution. Ingenuity has currently driven buildings above 800 meters and some projects already top the 1,000 meter mark, modern approaches towards tall building design and conception borrow heavily from past experiences and strive to perfect form and function in skyscrapers. That present process that leads from an idea or will to a finished building is as complex as it ever was, with new paradigm emphasizing the importance of collaboration between all specialists in early design stages for the best possible end result. Buildings of today are more than ever conceived with sustainability in mind, and tough buildings have always followed finance modern buildings attempt to also follow the environment.
5 Conclusions

Having presented a very concise history of skyscrapers focusing on motivation for construction, paradigm and technological knowhow in the core areas of structural and elevator systems, this chapter proposes to draw some conclusion on elevators and structures in their role towards the design and construction of better tall buildings. For this purpose the information of the past chapter will be presented summarized so that trends can be asserted for validating some conclusions, these summaries will be mostly based on the analysis of graphics and tables for better reading.

5.1 Tall building development and the economy

One fairly stressed aspect of tall building development is its relationship with finance, tall buildings are assets to their owners and should therefore provide adequate revenue. Profit is historically one of the main drivers for height in buildings, with revenue perspectives favoring the development of skyscrapers for office use, further reflecting the relationship with the economy as the more business a city has the more demand there will be for office space and consequently more pressure on land value, increasing the benefits of constructing in height. When addressing building height, researchers have noticed it does not increase year on year as the factors relating to optimal height relate to global, national and city economies and their respective regulations. These factors have been extensively studied to better explain the development of tall buildings [52].

Andrew Lawrence established a correlation between tall building development and economic cycles dubbed the Skyscraper Index which correlates the development of the world’s tallest buildings with global financial turmoil. Figure 69 shows a chronologic record of the world’s tallest buildings and the major economic downturns.
Explaining this correlation are Cantillon effects, which describe the economic effects that follow low interest rates and the consequent stimulation of money supply. The primary Cantillon is that money supplied for investment, whether from government or private sources, promotes further investment, raising prices where economic activities become more concentrated which surges interest in more highly capital-intensive projects such as tall buildings. Land prices in areas with concentration of value-adding activities, such as central business districts, will tend to increase more than in areas where less valuable activities take place, this increase in land prices makes for an increase in number of floors – building height, consequently needed to meet return on investment needs [52].

The current global economic crisis also coincided with not only one of the greatest years for tall building development, 2008, but with the development and completion of Burj Khalifa which increased the tallest building mark by almost 60%, there is yet another entry favorable to the skyscraper index [52]. The current economic situation has put numerous projects on hold as could be expected and it further supports how connected tall buildings are with the economy.

5.2 Tall Building trends

Skyscrapers have come a long way since the late 19th century experiencing an evolution that makes early examples of tall buildings seem small and unworthy. When observing Figure 70, where the buildings that stood as the tallest are all depicted, the differences between the Home Insure Building and the Burj Khalifa are too evident. Will aided by technological achievements allowed for this evolution.
Of course tall building development is more than just about the tallest buildings in the world, and probably more important than noticing the increase in height of the tallest is the actual increase in the number of tall buildings which can be seen in Figure 71 that considers all the buildings of 200 m and higher.
5.2.1 From North America to Asia

Another interesting fact which can be taken from the previous figure is that until recently the tallest buildings were all located in North America, mostly in New York, a trend that stopped with the construction of the Petronas Towers in Kuala Lumpur. Tall building development has been of recent mostly focused in Asia and the Middle-East, with many new developments that focus other than the more media covered world tallest contenders. In fact in 1930 99 of the tallest 100 buildings were located in North America, with 51 of these in New York. In 2010 these value were significantly diminished to 30 and 5, respectively [18]. Figure 72 shows this trend.
5.2.2 Building Use
Statistics also show a move away from a predominantly office use building towards mixed-use functions and residential, indicating both uses have registered an increase from 12% to 38% in the top 100 tallest buildings in the world in the last decade alone [18], as can be seen in Figure 73.

![Function of the 100 tallest buildings, per decade](image)

The rapid urbanization of developing countries partially explains why many of these buildings are now residential in nature rather than commercial—to accommodate the growing populace in the city. There are other reasons for this shift however, especially towards mixed-use, not least the commercial incentive to “edge bets” on fluctuating demand for office–residential–hotel functions by including them all in the building program. It also makes sense that, if great height is the main objective of the project, then it is easier to achieve this with a residential rather than an office function. Residential floor plates tend to be much smaller in area than office ones meaning there is an allowance for more vertical structural elements columns and walls—increasing rigidity and redundancy an advantage when subjecting materials to wind and other pressures almost a kilometer in the sky—and also require less floor-area-consuming elevators and other vertical services to support the function [18].

5.2.3 Structural Material
The subject of structural material was referred in the previous chapter where much credit was given to the contributions of Fazlur Khan to the structural development of tall buildings and the consequent integration of concrete in tall building construction. For a better understanding of what this trend actually represents and of its importance in the evolution that led to the modern tall building, Figure 74 lists the structural material of the tallest 100 buildings in the world in each decade, a significant decrease can be
seen as the all-steel buildings have dropped from 90% as recently as 1970, to 23% now (September 2011) in favor of concrete or composite structure.

![Material of the 100 tallest buildings by decade](image)

The reasons for the trend towards concrete/composite structure in the world’s tallest buildings are multilayered. It is partly a product of the developing countries where these projects are located—which are much more likely to have sufficient concrete technological expertise, over steel. Cost is also a significant factor, with concrete believed to be cheaper than steel. The aforementioned change towards residential and mixed-use functions is also influential, since the fire, acoustic and cellular requirements of “living” lend themselves better to concrete construction rather than open-plan-enabling steel [18].

### 5.3 Elevators and Structures

Tall buildings could not have become what they are today without elevators and their support structures, this is a fact that needs little explanation. From the documents gathered in this thesis it can be stated that both structure and elevator developments have both influenced and inspired tall building development, and hold tremendous importance on tall building design. However between elevators and structure there are not many mutual constraints. Elevators require space which is usually involved in core shear walls which means the actual number of elevator will affect the size of the core and does, therefore, have implications in the actual load bearing potential of the service core. Same can be said of the elevator bank’s positioning which may not take full advantage of the service core’s structural potential. Apart from these issues which can affect the service core’s structural relevance and therefore should undergo careful consideration, elevators and structures will not necessarily pose direct constraints to one another. What has occurred however are indirect interactions between both elevator and structural developments
for tall buildings, and currently great efforts towards integrating elevators and structures, as well as all other features, for more rational, sustainable buildings.

As was described in this document, elevators were the great invention of the 19th century that allowed for buildings to grow taller. Construction technology already permitted buildings to rise to reasonable heights, the elevator however made the higher floor easily accessible.

Elevators provide a vital function for buildings – accessibility. If floors cannot be reached with ease there will be no demand for upper floors. As most technological achievements the elevator removed a constraint to a certain purpose, in this case, building height, in mid-19th century that was the main issue concerning building height. Once accessibility was tackled time was to pursue other aspects such as structural form. Elevators hereby influenced structural innovation as developments in one area triggered developments in the other, this was certainly valid for early skyscrapers, which does not mean the structural skeleton would not have been developed if not for the elevator. It means the development of the elevator further stimulated the will and benefit of building higher and therefore put pressure on the development of new ways to build taller buildings.

Further constraints imposed by both elevators and structures were many times associated with financial aspects that were considerably addressed in the previous chapter. As elevator service is something a building cannot be constructed without, the service requirements in tall buildings can be overwhelming as a large number of elevators takes up a lot of otherwise rentable area. Until the full development of the skylobby in the 1960s, elevator area requirements had been one of the main constraints to tall building development. Technology today allows for minimizing elevator space requirements by maximizing elevator service with sophisticated operation control mechanisms.

The 1960s were the great period for structural innovation as tall buildings were no longer exclusively dependent on the steel frame or braced steel frame for support and were given a wider array of more efficient alternatives both in layout and material. For service core load bearing properties the new structural alternatives had different effects: for buildings with shear-wall structures, frame-shear wall combinations and eventually tube in tube structures the service core would be structurally relevant providing significant rigidity and carrying both vertical and horizontal loads. These types of structures are predominantly concrete structures (tough there are also steel shear trusses shear wall systems) taking full advantage of the material for building rigidity. However contradicting the structural importance of the service core were the now called exterior structures, since as buildings became taller there is great advantage in placing elements for lateral resistance in a peripheral position, therefore the inner structural core will tend to carry primarily vertical loads, while an outer structural system will provide the building with its lateral resistance and stiffness. As a result the service core will be less stressed which allows it to be smaller, or at least permits a design not as constrained by structural behavior. Considering relevant buildings of the period the Willis Tower’s service core has no structural function and the service Core of the John Hancock Building only carries vertical loads [49], both buildings have steel tubular structures. Though this may suggest concrete structures were more prone to take advantage of the service core as a structural element the correlation is somewhat more complex, as the combination of structural systems
and material would be determined according to the intended building height which together with intended building use would also condition the number of required elevators thus conditioning the size of the service core. According to the required size of the service core including elevator and all other services, shear wall and inner tube solutions could be calculated to analyze the actual possibilities of the service core for structural purposes which could then influence the structural format to be adopted. In a situation such as the one described the structural solution would be designed around the service core and therefore to some extent service core size and potential load bearing properties should influence the overall structural solution. This situation would apply to “moderately” tall buildings as according to the classification systems presented in chapter 2, concrete shear-wall structures tend to be feasible for buildings up to 60 stories high.

Recent trends in tall buildings such as opting for mixed use instead of manly office use makes for less demanding elevator service needs, which helps to make the service core size less dependent of the elevators. Other trends such as procuring solutions for better natural ventilation and illumination have driven the service core from the interior to the buildings periphery, these solutions not only introduce new variables or tall building floor layouts but also contributed to further development of structural forms, the Commerzbank fits as an example for the previously stated.

Current tall buildings dispose of vast technological options which allow for finely tuned buildings where all features are rationally developed to obtain optimal performance. Each aspect related with tall buildings, being architecture, structure, elevators, façade and all other mechanical aspects, are of high complexity and specific of each building. The more technology allows, the more careful the design can and must be in order to take full advantage of its possibilities as more than regular buildings tall buildings cannot require greater efficiency and careful planning deriving from their complexity and cost. As buildings cannot do without elevators they should be developed to take full advantage of service core needs for structural purposes, whether by relocating the service core or by allowing for the service core to minimize other structural needs.

Tall buildings are a need and will so continue to be as global population becomes ever more urban. Demography, economy and will are to keep driving buildings higher and engineers and architects will keep striving to make ambitions and dreams into feasible, sustainable realities.
6 Bibliography

18. CTBUH; Criteria for the Defining and Measuring of Tall Buildings.
22. FIB tg 16
25. Foster, N. Foster, Norman and Partners.”Commerzbank.”
50. United Nations, Department of Economic and Social Affairs (http://esa.un.org/unpd/wup/index.htm)