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

Extended Abstract
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.

1. Introduction
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. Consequently a great deal of pressure was placed on land prices further enhancing the need to build higher [1].

The evident implications of resisting lateral loading, being one of the most decisive 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 some extent the structural form [3].

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 [1]. Adding to traditional design teams, building tall creates demand for other specialists uncommon to low-rise buildings.

These specialists are to integrate the design team and may influence, to a certain degree, the structural design. It should therefore be acknowledged without any doubt that the full complement of parameters influencing the structural system is not entirely in controlled by the structural engineer[4].

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 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 [5].

2. Tall buildings and elevators: a criteria for tallness

An elevator service approach towards building height classification differentiates between low, medium and high-rise buildings and mega-high-rise buildings [6] 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 [6], 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 that the building requires the use of one or more sky lobbies to guarantee proper occupant distribution, meaning more than 70 floors [7].

It is now important to also discuss the service core as it is central to the present work. Service core should be understood as a system built up of a number of individual components, each having a different function to perform, and highly technical in nature [8]. 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, among 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” [9].

Understanding what the service core is helps greatly to understand how important it is for the building and why designers place such importance in its planning for the earliest stages of the design process [4]. The service core is the buildings back bone for daily operations and many times for structural support. 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.

3. Sustainability and tall building development
Sustainability is one of the major issues considering tall buildings, they are perceived in public opinion, with some reason, as big energy consumers [6], though the problems relate to all buildings, which represent 30-40% of all primary use of energy worldwide [10]. 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.” [8]. 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, ventilation, elevators and illumination are here considered as running energy, opposed to the energy required to the building’s construction which is the embodied energy. Nevertheless, the main focus has been the running energy, mostly due to the rising cost of energy [9] and since it is representative of the greatest energy consumption associated with buildings. Embodied energy is also of extreme importance and should be analyzed in design stages to better assess the advantages of energy saving strategies.

4. Elevator arrangements 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 [11]. 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 following are some of the most commonly employed elevator arrangement solutions:

- Zoning
- Sky-lobby
- Double Decks
- Hall Call Destination
- Machine Room less
- Twin elevator arrangements

**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 a very large core thus making the building inefficient due to decrease on Net Rentable Area (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.

**Sky Lobby**

As buildings get higher, zoning becomes impractical and unfeasible as elevators start once again to take too much space [11], as stated early the limit is of about 4 zones. 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 that passengers will need to change elevators to get to their destination [6]. The great advantage of the sky lobby is the 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 [7]. 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.

**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 [6]. 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 1[6].

**Table 1 - Double deck advantages and disadvantages**

<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></td>
</tr>
<tr>
<td>9. Smaller lobbies</td>
<td>8. Lobby exits need to be larger</td>
</tr>
<tr>
<td>10. Fewer entrances</td>
<td>9. Special facilities for disabled access to “other” floor</td>
</tr>
<tr>
<td>11. Faster installation</td>
<td></td>
</tr>
<tr>
<td>12. Reduced maintenance costs</td>
<td></td>
</tr>
</tbody>
</table>
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 [6].

The three following technologies are probably the most relevant innovation in elevator technology in the last years in the 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”, 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, Table 2 shows the effect of call destination according to traffic intensity it includes one manufacturer’s specific algorithm.

<table>
<thead>
<tr>
<th>Traffic Intensity</th>
<th>Short Waiting Times</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>10</td>
</tr>
<tr>
<td>Normal</td>
<td>20</td>
</tr>
<tr>
<td>Heavy</td>
<td>30</td>
</tr>
<tr>
<td>Intense</td>
<td>40</td>
</tr>
</tbody>
</table>

![Table 2 - Hall call destination](image)

**Machine room less**

Machine Room Less (MRL) was enabled due to the introduction of the Permanent Magnet Synchronus 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 [32] therefore the machine room became expendable.
**Twin elevators**

Finally one very innovative solution that still has few applications is the TWIN elevator solution. Currently being developed by one of the major manufacturers, there have already been some successful applications of this system such as the Main Triangle building in Frankfurt. This system allows for two elevators to operate independently 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% [33],

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.

5. Historical evolution of tall buildings

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.

**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.

**Birth of the Skyscraper to New York zoning law of 1916**

This period considers the first “tall” buildings, which cannot be described as such by today’s standards but were groundbreaking in their day. It is particularly relevant for the technological innovation field, with achievements 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.” [15].

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 [10]. 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, much aided by the developments in computational capacity which allowed for more accurate calculations and modeling of structural behavior [15].

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 heat 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 [10].

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.

6. 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.
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 1, where the buildings that stood as the tallest are all depicted, the differences between the Home Insure Building and the Burj Khalifa are evident. Technological achievements allowed for this evolution.

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 analyzed 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. Elevators require space which is usually involved in core shear walls which means that the actual number of elevators 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. These issues affect the service core’s structural relevance and therefore should undergo careful consideration, as these will be some of the major direct constraints between elevators and structures. 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.

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 (though there are also steel shear trusses shear wall systems) taking full advantage of the material at the building’s rigidity level. 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 [9], 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 mainly 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 to 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. Tall buildings, to a further extent than regular buildings, 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.

7. Bibliography

4. FIB tg 16
5. CTBUH; Criteria for the Defining and Measuring of Tall Buildings
7. Fortune 1997
13. CIBSE Guide D