Universidade do Minho
Escola de Engenharia

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# Tall Buildings Shaping Factors: Technical Evolutions, Macroeconomic Drivers and Future Perspectives

novembro de 2013

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# Tall Buildings Shaping Factors: Technical Evolutions, Macroeconomic Drivers and Future Perspectives

Tese de Mestrado
Ciclo de Estudos Integrados Conducentes ao
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# RESUMO

Os edifícios altos são uma das maiores conquistas tecnológicas do século XX. O Burj-Khalifa ou o Shanghai World Financial Center colocam as cidades onde são construídos no imaginário do cidadão comum.

Esta dissertação pretende fornecer uma compreensão básica dos modelos estruturais aplicados nestes edifícios e que lhes têm permitido ir cada vez mais alto. Também são analisados alguns padrões macroeconómicos que são identificáveis aquando da construção de um edifício mais alto do mundo, de modo a estabelecer uma ligação entre edifícios altos e a macroeconomia. É ainda elaborada uma linha de raciocínio e de acontecimentos que ajudam a explicar a evolução nos edifícios altos, no que concerne à sua localização, função e altura. Finalmente, no contexto de desenvolvimentos recentes no contexto da construção rápida de edifícios altos, explora-se o conhecimento actual sobre métodos inovadores de construção de edifícios altos focando a pré-fabricação e a modularização.

A metodologia adotada nesta pesquisa é baseada principalmente em investigação bibliográfica e recolha de dados e análise de bases de dados relacionadas com a construção de edifícios altos. Os dados recolhidos foram analisados em termos de relações entre estímulos económicos e políticos na construção de edifícios altos. Adicionalmente, foram analisados e enquadrados no contexto de vários factores identificados como fortemente relacionados com as características de arranha-céus alguns exemplos de projectos de arranha-céus paradigmáticos, tanto em fase de construção como já construídos.

Os resultados sugerem que a evolução nestes edifícios é intima do ambiente económico e estratégico em que eles se encontram. A construção dos edifícios mais altos do mundo é o clímax de um clima económico artificialmente criado. A evolução nos edifícios altos é, em parte, devida a performances económicas e de desenvolvimento tecnológico, mas também a motivações ego centristas e de simbolismo. A inovação necessária na construção de edifícios altos, para os tornar mais sustentáveis e a mais acessíveis é um caminho que ainda está a ser percorrido. A pré-fabricação e a modularização parecem ter potencial de criar um novo paradigma na construção de edifícios altos, apesar de alguns desafios que são colocados.

*Palavras Chave: Edifícios altos, Estímulos Económicos, Evolução, Modularização, Pré-fabricação*

# ABSTRACT

Tall buildings are one of the major technological achievements in the 20th century. Burj Khalifa or Shanghai World Financial Center put the cities in which they are built in the imaginary of the common citizen.

The following dissertation will focus on provide a basic understanding of the different structural methodologies applied in tall buildings that allows them to go higher. It also address some macro economical patterns that are present when there is the construction of a world's tallest building, in order to connect tall buildings with macroeconomic environment. To provide a thinking line about which happenings and factors led to the evolution of tall buildings, especially regarding their location, function and high. Finally, to release some of the knowledge and challenges that innovative ways to construct tall buildings enclosure, focusing on prefabrication and modular tall buildings.

The methodology adopted in this research was mostly based on bibliographic investigation and data collection and analysis from databases related with the construction of tall buildings. The data collected was especially analyzed in terms of the relationship between relevant economical and political drivers and the construction of tall buildings. Additionally, recent examples of paradigmatic tall building projects, either still in the project stage or already constructed, were analyzed and framed in the context of the several factors identified as strongly related with tall buildings features.

The obtained results suggest that tall buildings evolution is closely related with economical and strategic environment of where they are built. The construction of the world's tallest building holders is the climax of an artificial economic environment around societies. Moreover tall buildings' evolution is shown to partly result from economic performances and technical development but also from ego and symbolic motivations. The innovation in tall buildings construction necessary to make them more sustainable and affordable still has a long way to travel. Prefabrication and modularization seem to have real chances to provide a new paradigm in tall buildings construction, in spite of some challenges that are still faced.

*Key words: Tall Buildings, Economic Drivers, Evolution, Modularization, Prefabrication*

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# 1. INTRODUCTION

## 1.1. General Overview

Reaching the skies is present in human aspirations since Egyptians and Mayan temples. The symbolism of the Great Pyramids, for example, is the greatest relic we have from those civilizations and attest how important it is for humans to be near the sky.

In the 20th century this quest for height reached another level: technological barriers were overcomed and new structural frames are making tall buildings become increasingly taller. Ultimately, these structural frames are the features that allow for a tall building to be constructed. The evolution of structural frames and their behavior is a part of tall buildings legacy in their quest to reach the skies.

However, if technology is what allows a tall building to be accomplished, technology may not be the main factor that is driving the construction of new tall buildings. Monetary policies have been influencing the major achievements regarding tall buildings construction, therefore it is important to understand how this is occurring and the mechanisms behind this effect. It is important to understand if there are certain economic "prerequisites" to initiate the construction the world's tallest building at a certain time. Indications of this relation seem to exist in history, and an historical pattern may be found in periods of economical development at which one or several tall buildings were constructed and broke height records.

The influence of economy on tall buildings construction has been also shaping the evolutions of the superficial features of tall buildings. Location, height and function of tall buildings have been changing in the last two decades. Regarding these evolutions, it is clear that tall buildings construction has been moving from West to East, and additional factors have been impelling buildings to become taller instead of stabilizing at a certain efficient height, as well as becoming more diversified.

The evolutions previously discussed have not yet considered the concern about the constructability of tall buildings. Prefabrication and modularization have been recently arising in tall buildings construction and may establish a sustainable alternative to conventional methods. These two innovative methods ensure a reduction in construction and environmental costs and allow for a faster construction. In times of economical crisis, these three features become heavy weight assets, which ensure competitive advantages on modularization/prefabrication. It is therefore expected that these innovations and industrialization trends on tall buildings construction may have an important role on the future of tall buildings and cities.

Tall buildings construction is driven by a complex network of forces, not all of them measurable. Magnificent tall buildings are constructed everyday and are objects of admiration by the common citizen. But what is driving buildings to become taller and taller? Why are tall buildings majorly constructed in East and Middle East now? What's their connection with economic environment? Only a deep study on all these forces behind tall buildings construction, and the relationship between them, can explain how and why tall buildings have been evolving, and more importantly, what direction is this evolution taking.

## 1.2. Objectives

Often tall buildings are seen only as flamboyant structures with audacious architecture and big glass facades. To achieve this state of the art, tall buildings have been under a series of structural innovations, which allowed them to become increasingly taller and landscape marking. One of the objectives of this dissertation is to clarify how these structural innovations have been evolving and how each of these is important for the current state of the art of tall buildings.

However, it is important to understand that the relationship between tall buildings and the economic environment is very strong, at different levels. As a real estate piece, exposed to markets fluctuations, the economic environment must be connected to the construction of tall buildings. Therefore one of the most important objectives of this study is to understand how relevant economic patterns are in the construction of the world's tallest buildings.

Tall buildings are not static urban pieces: in recent years tall buildings are changing in location, height and function . What factors are actually pushing tall buildings construction to spread around the world and making them to become more diversified? A third objective of this dissertation is to analyze economical  and demographical data, politics and symbolic motivations  which may be behind the construction of tall buildings, as well as to understand how this evolution is occurring by crossing the data available with major events related with tall buildings projects.

Constructability of tall buildings is evolving too, essentially in a similar way to the evolution observed in structural frames. However, there hasn’t been any paradigmatic change regarding tall buildings construction. The new techniques proposed are mostly improving the economical aspects and schedule performances on tall buildings construction, but it seems that these are also triggering new ways to conceive tall buildings. Prefabrication and modularization are among these techniques and the forth objective of this dissertation lies on explaining how these two techniques may enhance the construction of tall buildings.

## 1.3. Outline of the dissertation

The dissertation is divided in 6 chapters, ***Chapter 2*** deals exclusively with engineering and architectural issues of tall buildings, exploring and analyzing the major structural systems that are used for tall buildings and systematizing the architectural eras that tall buildings have been passing trough. In ***Chapter 3*** an economic index which relates the world's tallest buildings construction with major economic downturns is explored and analyzed. This study is framed within the economical environment of different times at which world's tallest buildings were constructed. ***Chapter 4*** deals with the evolution of tall buildings in terms of their location, height and function. Several factors and hypothesis are analyzed, in order to explain this evolution. Finally on ***Chapter 5*** a study about the application of prefabrication and modularization to tall buildings is carried out, in order to understand the most recent trends on tall buildings construction industrialization and how the different processes involved in tall buildings conception, structurally and logistically, using modular construction are affecting their construction and use.

## 1.4.Defining what is a tall building

Tall buildings have already been mentioned without clearly specifying what a tall building is. There is no single definition of what a tall building is, hence, along this dissertation, tall building definition follows the one established by the Council for Tall Buildings and Urban Habitat (CTBUH). A tall building is considered "tall" when it enclosures a certain element of "tallness", at least in one of the following characteristic: relatively to the surrounding buildings context, meaning it is relatively high to its surrounding buildings; its proportions, which are related to the ratio between its height and its footprint; the technologies employed on its construction, such as the adoption of special structural elements, special elevators technology, particular architectural features or others.

CTBUH also defines a specific nomenclature for buildings which overcome certain height limits: when a building has more than 300 architectural meters it is considered a "supertall" building, and when it has more than 600 architectural meters it is considered "megatall". However, this terminology may vary along the dissertation.

Other more widely spread definitions such as “skyscraper” or “high-rise building” may also be found in this dissertation and should be treated simply as synonyms of tall building.

# 2. INCEPTION AND EVOLUTION OF TALL BUILDINGS

## 2.1.Introduction

Tall buildings are one of the main technological achievements of the last century. Even though they are object of admiring and a landmark of modern societies, it is important to understand when tall building's needing was triggered, and what factors where associated with it, so it is possible to establish a turning point in big metropolis buildings construction. Associated with this, a tall building is all about strength and resistance, therefore it is possible to realize that tall buildings structural form is a must when studying tall buildings and its behavior. This chapter exposes the history of tall buildings and what makes them such unique structures, with special attention for the structural systems used the most in tall buildings and the key points of each of them.

The structural evolution of tall buildings is one of the most basic components of the explanation of the evolutionary process of these, from the early days of these to the contemporary buildings today, hence it is important to understand which innovations there were in structural terms that made tall buildings go higher. Although some decades have passed and the society evolved considerably, some of the social-economical problems which led to the development of tall buildings and to the need to optimize the land usage in urban environment still persist as prevailing discussion topics, driven by the permanent increase of the migration of the populations to the big cities. This chapter intends to provide the clear understanding about the evolution and development of the different structural systems applied in the construction of tall buildings. The systematic approach will provide a background framework for the classification and understanding of the most recent technological developments of building tall, in the context of the historical evolution of the structural and constructive systems that occurred during the past century.

## 2.2.Brief History of Tall Buildings

Tall buildings have always been object of admiring and praising. What once happened in ancient civilizations, with the construction of big structures for admiring or religious uses became, after second half of XIX century, a trend in city centers of the major metropolis in the world, which, at the time, where mostly New York and Chicago.

The necessity of building tall started when U.S.A. started to embrace an expansion in its city's population. The construction *modus operandi* shift occurred due to socio-economical problems, ignited by this increasing urban population. The terrain construction increasing price, the desire to contain urban  expansion and the need to spare important agriculture areas have all come together, forcing architects, engineers and planners to start thinking about how to build tall [1].

This construction innovation wouldn’t be possible without the creation of new structural arrangements. In 1891 masonry construction reached its peak with the construction of Monadock Building, with 17 stories. Its walls were 2,13 m thick. This feature boosted 1885's William LeBaron Jenny's concept: the construction of the 10 stories high Home Insurance Building is seen as the first skyscraper in History, because this was the first building which applied a steel frame to sustain gravity loads of the building [2].

This structural innovation was the trigger to the first skyscrapers construction phase. Tall buildings were built, in this earlier phase, almost exclusively for commercial purposes, in response to the demand by business activities to be close to each other and to the city center [2]. The preference for city center locations was further emphasized by large corporations recognizing the prestige of relating their names with magnificent tall buildings [1];[2].

Structural innovation marked the beginning of tall building construction, but tall buildings architecture also marked the blueprint of these buildings in main metropolis. The shape and look of skyscrapers can be grouped in 5 different architectural phases, influenced by the ideas of the time and the available technology.

The First phase can be represented by the style adopted in the Renaissance Palazzo, which comprised a block and slab like form and resulted in a very repetitive pattern. Its main representative city is Chicago [3]. Some patterns of this architecture were the inexistence of projected balconies or asymmetric facades. Some examples of this architecture are the Home Insurance Building, in Chicago or the Auditorium Building (Figure 1), built in 1885 and 1887, respectively [3].

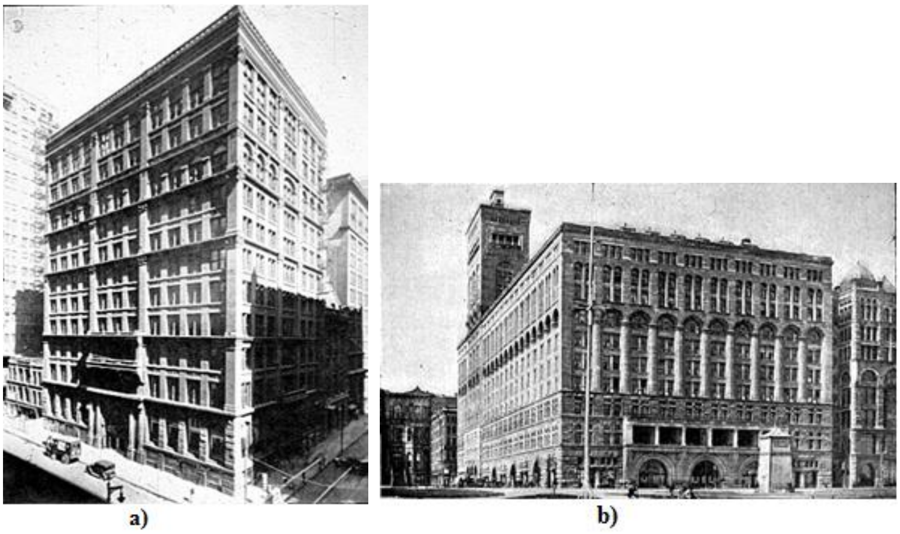


**Figure 1 - Home Insurance Building a) and Auditorium Building b) Renaissance Palazzo Buildings in Chicago (both adapted from [4])**

The second architectural phase of tall buildings was most visible in New York's buildings. This new architectural style is known as Art Deco and its most representative building is Chrysler Building, with high degree of facades ornamentation and its top spire [3].

The third phase represents the entrance in tall buildings planning of marketing experts, leading tall buildings to be more a profitable symbol rather than an artistic work [2]. By this time, tall buildings’ major driver was economy [5] and the objective was to have the maximum leased space. Tall buildings started to have as much corner offices as possible, so the rental income was higher due to the wide city views [2]. Examples of this type of building are the Willis Tower building, with all its "smaller" towers providing more office with a view of the city than its predecessors buildings (Figure 2), or the destroyed World Trade Center.

Figure 2 - Willis Tower and its coupled small towers (adapted from [6])

The fourth phase started by 1980s [5] and was an answer to the cubism period and a continuation of the marketing trend in skyscraper facade, maximizing the corner views by curves and step backs. Other main concerns about this style was to create amenities at the entrance lobby, avoid the flat roof and proclaim buildings identity trough facade representation [2]. Some examples of this building are the Sony Building (Figure 3a)) and the Wells Fargo Building (Figure 3b).

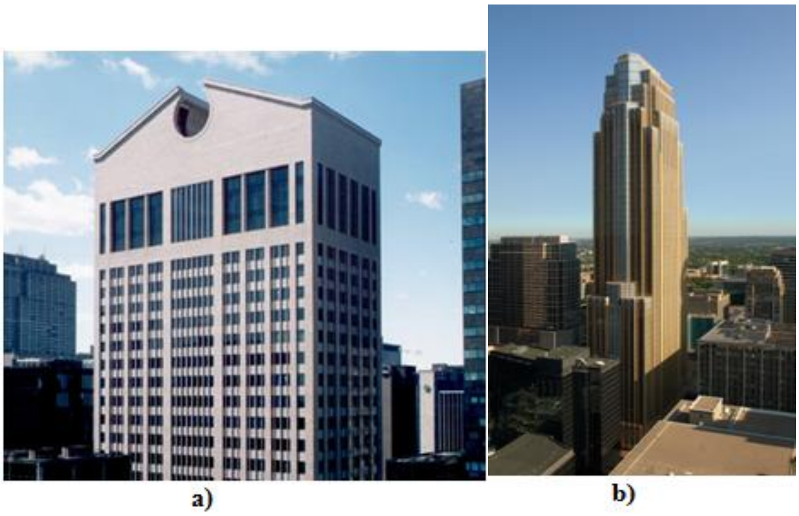
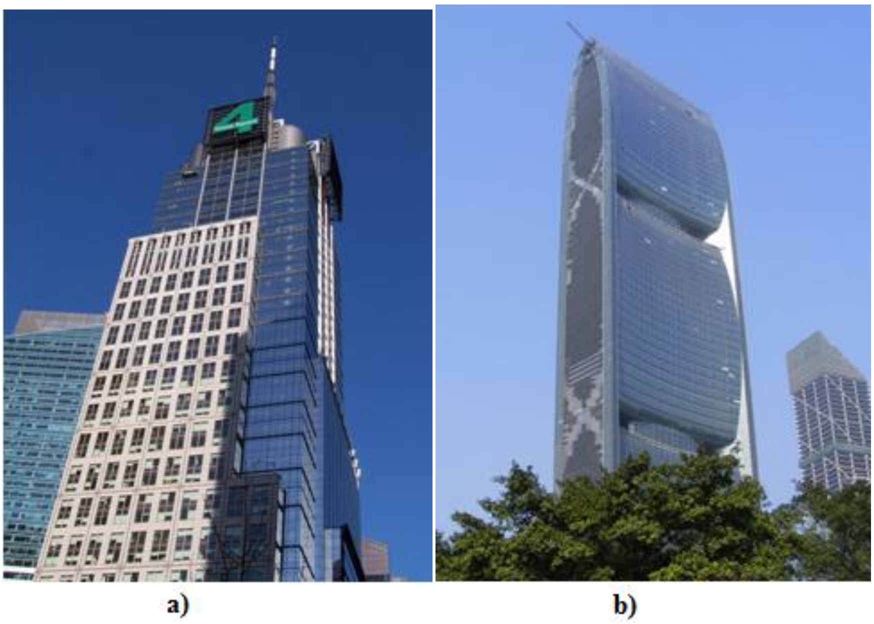


Figure 3 - Sony Building a) (adapted from [7]) and Wells Fargo Building b) (adapted from [8])

The fifth phase started at the 1990's. This phase was characterized by the modification of building shapes towards the improvement of energy efficiency. This phase mostly deals with "passive architecture" such as solar orientation and how natural light and passive control influence the architecture and engineering [2]. But energy efficiency can be achieved with more broad options: use of thermal mass of the building, improved insulation, and wind power could be the future of tall buildings sustainability [9]. Recently built tall buildings already include environment-friendly options, both at the structural design level and the applied technology. One example is the St Mary Axe Building, also known as Swiss Reinsurance Building, which was built using an innovative structural form that optimized the aerodynamic behavior, thus reducing the amount of material needed for the construction due to the reduction of wind loading. Another example is Condé Nast Building (Figure 4a), which employs high efficient window technology that allows maximizing daylight entrance without heat gain or loss and photovoltaic cells were integrated in building's facade element in the south oriented face [9]. The Pearl Tower River in Guangzhou (Figure 4b), China, was designed considering specific desired energy saving issues, including: triple-glazed facades, high efficient light systems, photovoltaic cells in facade and inclusion of wind turbines for energy production, among other features [10].



a) b)

**Figure 4 - Condé Nast Building a) (adapted from [11]) and Pearl River Tower b) (adapted from [12])**

## 2.3.Main challenges of constructing tall

The entire system of a tall buildings encloses innumerous challenges. The foundation engineering, fire safety strategies Mechanical, Electric and Plumbing (MEP) systems and how these interact with tall building's layout are some of the most important problems involved in their design. But what makes a tall building an unique piece in urban infrastructure are the combination of materials used to build it and the structural design that it entails.

As unique structural projects in terms of engineering and architecture, tall buildings are subjected to careful analysis with regards to the more appropriated structural systems and materials, despite these materials are essentially the same as those used in normal constructions. Therefore it is highly challenging for designers to match such unique demands in these projects while using common building materials. Alternative solutions are necessary to improve and innovate common structural systems in order to meet the particular requirements of tall buildings, especially regarding their appropriate behavior under loading and the limitations deriving from the question of how high to build.

The structural systems adopted in tall buildings differentiate from ordinary buildings mostly due to a fundamental requisite: the horizontal load resistance. In low-rise buildings horizontal actions are hardly prevalent in the design process. But as the height of the buildings increases the horizontal loads, wind and earthquake actions become increasingly important.

### 2.3.1. Structural Materials

In general, tall buildings are erected using structural materials that may be grouped in three main types: reinforced concrete, steel or composite solutions resulting from the combination of the former two [13]. Recently also wood has been investigated as a possible material for constructing tall, existing nowadays some proposals to built tall buildings with this material, such as a proposed 34-stories skyscraper design by a Scandinavian firm to be built in Stockholm [14].

The arise of steel structural systems for tall buildings construction occurred in 1885, when Engineer William LeBaron Jenny designed the Home Insurance Building, in Chicago, with a steel framework, which marked the birth of modern skyscrapers [2]. Steel frames became the main structural scheme used in the first third of twentieth century to build remarkable tall buildings, such as the Woolworth Building, the Empire State Building and the Chrysler Building [15]. It is still widely used nowadays, although without predominance it had in the past. High strength-to-weight ratio, easy assembly, economy in the transportation to the site, availability of various strength levels and wider selection of cross-sections seem to be the primary reasons for choosing this material [13];[16].

Concrete systems were introduced later in tall buildings industry [16]. As a structural material it's now indispensable in the most constructions of tall buildings, either it be for its moldability characteristics, natural fireproof properties and the recent advances in high strength concrete development [13];[16], or its continuous workability improvements due to development of super-plasticizers and the use of improved concreting techniques, of which concrete pumps are an important example [2]. In addition, concrete tall buildings show better performance under lateral loads in terms of damping and motion perception, providing improved stability to wind loads when compared to steel [13].

Composite systems consist in a mix of steel frames and concrete elements. These systems rely in the use of concrete and steel for the structural layout, thus providing a "hybrid frame arrangement". In broad sense almost all tall buildings are composite, since it's almost impossible to construct a tall building using just one singular material. The composite system was idealized to overcome the disadvantages of both steel and concrete and to maximize the advantages of both. The structural elements such as beams, columns, slab systems and shear walls, often employ this binary material system to achieve optimal material design and productivity. As an example, composite floor schemes (Figure 5) are nowadays widely used, also because they allow to simplify and speed up the construction process. The philosophy behind the design of composite structures is to harness the speed of steel erection and the concrete capacity to carry axial loads and provide rigidity to the building [2].

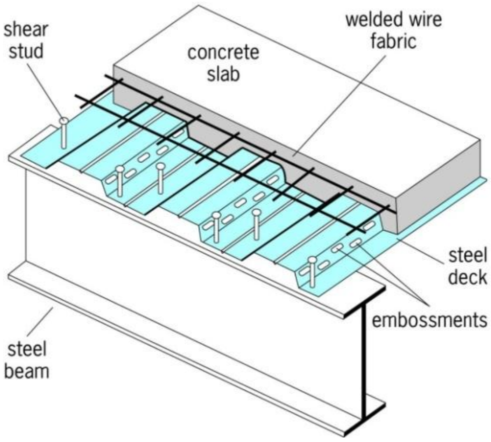


**Figure 5 - Composite floor system scheme (reproduced from [17])**

### 2.3.2. Lateral actions

Tall buildings may be distinguished from low-rise buildings by the way they behave when exposed to lateral actions. A tall building may be characterized as such when its structural design is significantly affected by lateral loads, such as wind and earthquake [2];[1];[13];[18]. Lateral loads become an important challenge as building's height increases and building's deflection and vibrations need to be kept within acceptable limits [13]. While designing a low-rise structure it is very likely that its gravity supporting members are sufficient to sustain horizontal loads as well. In contrast, when dealing with tall buildings the overturning moment and deflection due to wind and seismic loads often require additional structural engineering [2]. Wind loading becomes relevant typically at about 50 stories, and its importance increases for higher buildings [2];[1].

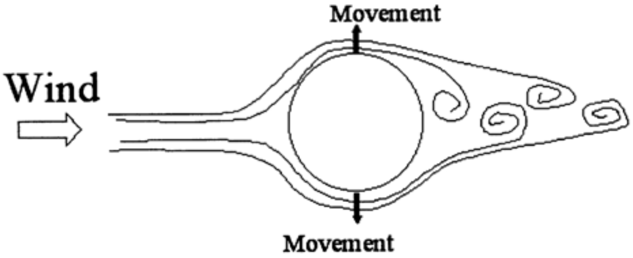


**Figure 6 - Windward movements induced by wind (reproduced from [19])**

Wind load normally induces vibration in the across wind direction (Figure 6), caused by vortex action, and this vibration is often more critical than the one induced in the wind ward direction [18];[5]. In order to mitigate these effects, tall buildings have been improving its aerodynamic properties [5];[18];[20]. Slender buildings are designed to avoid that natural frequency is not equaled by the vortex shedding [2]. The most frequently adopted aerodynamic shapes are: tappers, softened corners, cross section variation along building's height, spoilers and openings [21]. Some of these aerodynamic shapes can be easily found in contemporary buildings, like Willis Tower (Figure 2) and Petronas Towers (Figure 7).

**Figure 7 -Tapper effect in Petronas Towers (adapted from [22])**

## 2.4. Structural Systems

Structural systems are under several studies in order to properly classify them. As many authors have studied this issue and as there are new structural systems for once in a while, the view about how to classify tall buildings is also evolving, hence, in spite of much of the structural systems are closed to new analysis, there are others arising. The following sub-chapters will introduce a basic understanding about structural systems that tall buildings are relying on. Each sub-chapter presents a different structural system, exposing its resisting scheme, its advantages and limitations and intrinsic characteristics of each. These structural schemes gather the more broadly accepted concepts and introduces two new ones that are not so mainstream yet.

### 2.4.1. Rigid Frames

Rigid frames are widespread structural systems that are typically seen in low-rise buildings. They consist in columns and beams joined by moment resistant or rigid connections [1]. Rigid connections are the ones with sufficient solidity to hold the angles between members virtually unchanged under load [2];[1]. Hence, special attention must be paid  to the integrity of these joints, especially in seismic zones [16]. When used in tall buildings, this structural system carries the horizontal load through flexure of beams and columns [2], and the connections are severely loaded, therefore its efficiency to carry lateral loads is very limited.

Rigid frames can be built with reinforced concrete or steel [13], but the monolithic behavior of concrete structures make them more appropriated for this kind of structure [2];[13]. Essentially, the rigid frame is not economical for more than 25 stories [1] because the shear racking component of deflection causes the building to sway excessively [16].

### 2.4.2. Braced frames

In a braced frame the horizontal resistance of the building is provided by diagonal members, which are situated between the contiguous floors. Thus, this system virtually eliminates bending in the columns due to lateral loads, because the diagonal members absorb these loads by axial stresses, as shown in Figure 8 [2];[5];[16]. This system behaves approximately like a vertical cantilever truss [13].

**Figure 8 - Bracing systems (adapted from [23])**

The bracing system is typically composed of steel members, since both tensile and compressive stresses acting in the diagonals may be expected [2];[13]. In general, the different types of bracing systems may be classified in two different groups: concentric or eccentric braced frames [2];[5]. In the concentric design the longitudinal axis of all members intersect in a common point, while in the eccentric design the longitudinal axis of the different bracings are deliberately disconnected from the other elements, and the connection of the bracing can occur at a beam frame point, in order to increase the global system's ductility [20]. Normally, these diagonal members are situated around elevators, stairs and service shafts [13], mainly as a result of architectural constraints [2].

These structural systems were used in Empire State Building (Figure 9), as an interior bracing ([13]).

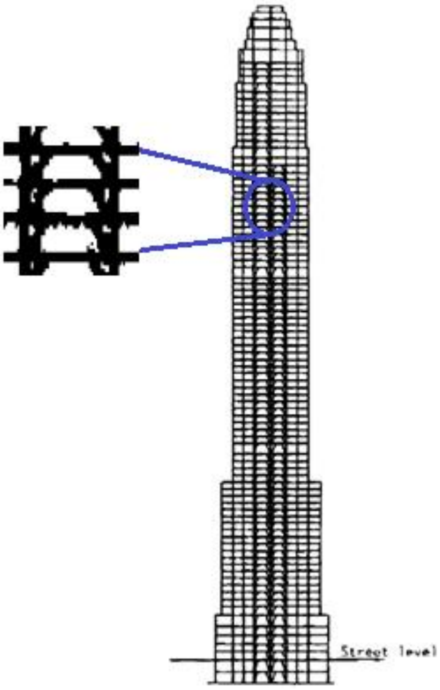


**Figure 9 - Application of Brace System in Empire State Building (adapted from [3])**

### 2.4.3. Shear Walled-frame

Shear walls may be described as vertical cantilevers, which resist lateral wind and seismic loads acting on buildings mostly by shear [13];[5];[2]. As they have very high in-plane stiffness, they can carry the total lateral loads acting in buildings and, as lateral loads can occur in multiple directions, shear walls are typically adopted in two orthogonal directions (Figure 10) [2];[1].

This type of element is mainly used when concrete or composite construction is employed [13]. In the case of buildings where steel elements are predominant, shear walls are important because they balance the strongly decreasing stiffness when the building height increases. As part of the structure of tall buildings, shear walls must be coupled to the remaining frame system [5]. Due to the great contribution that shear walls provide to the lateral stiffness, the remaining frame system can be designed to resist only to gravity loads, which may occur in a repetitive floor system [1].

Similarly to the bracing systems, shear walls are usually used as part of the elevator, service and stairs cores, [13];[16];[5];[2] and it's possible to erect buildings with 50- to 60-story height by using this system [2]. Petronas Towers, which were the tallest building from 1998 to 2004, uses this system to provide lateral stiffness to the building [13].

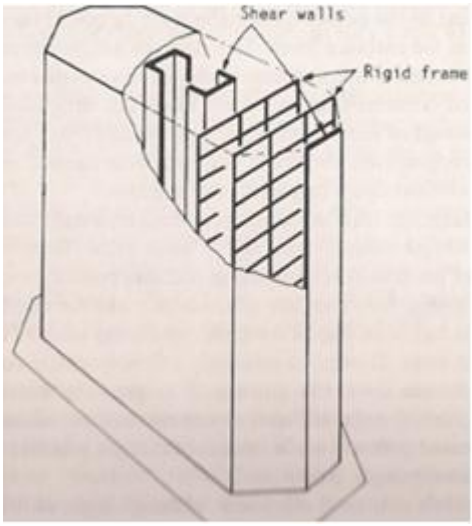


**Figure 10 - Shear Wall-Frame System (Reproduced from [1])**

### 2.4.4. Outriggers and Belt Truss frames

The Outrigger and Belt Truss frame system is a derivation of the braced frame or the shear-walled frame systems [13]. It basically consists of one of the mentioned above central core, connected to the outer columns that are in the outrigger alignment by means of "outrigger" trusses [1];[16];[20];[3]. The belt truss is used to connect the rest of the perimeter columns, those that are not directly connected to the outriggers, using another truss system around the building's face at the outrigger level [2];[13];[1]. By this way, when subjected to horizontal loading, the outrigger will restrain the movements of the central core by inducing tension and compression in the windward and leeward columns [1], reducing the overturning moment in the core and transferring part of that moment to the outer columns [5]. The belt truss will distribute the tensile and compressive forces to all the exterior columns, avoiding phenomena of differential shortening and elongation of columns [5]. In the construction of vanguard tall buildings like the Shanghai World Financial Center, the outriggers can also be supported on mega columns (columns that run across all building's facade) which are embedded in the building's facade [5]. Some of the disadvantages of this system are the large space which typically is occupied by the outriggers [5] and the visual impact of the belt trusses on the facades. To overcome these issues, generally the belt trusses are positioned at mechanical levels (stories specifically used in tall buildings for placing the mechanical and electronic equipments), so they create minimal impact in the rentable space [13];[3].

The outrigger and belt truss system is normally used with steel and composite construction [13]. Some examples are the Jin Mao Tower, Shanghai, and the Taipei 101, Taipei (Figure 11) [13];[16].

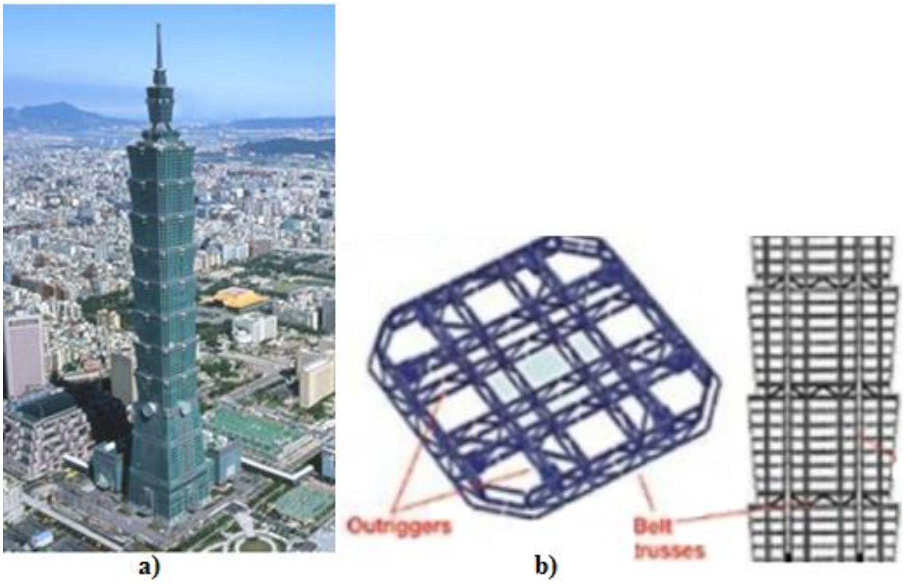


**Figure 11 - a) Taipei 101 building (adapted from [24]) and b) schematic design of outriggers and belt trusses of Taipei 101 (adapted from [25])**

### 2.4.5. Tube systems

### Framed Tube System

Framed tube systems were introduced as lateral resisting structures when structural designers realized that braced frame and shear wall frame systems were inefficient in very tall buildings [13];[3].

The tube system intents to make the building behave like a hollow tube cantilevered in the ground [2]. This behavior is achieved by using closely spaced columns along the building's exterior and deep spandrels arrangement (Figure 12) [2];[1];[3];[5] so the lateral load resisting system is manly located in the perimeter of the building [16]. The gravity loads are shared between the exterior framed tube and the interior walls or columns [13].

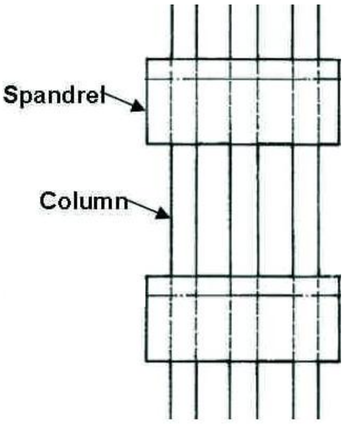


**Figure 12 - Closed column space and deep spandrels in World Trade Center (adapted from [26])**

One main structural problem of this kind of structure is the occurrence of a phenomenon known as "Shear Lag" (Figure 13), according to which the corner columns of the structure experiment greater axial stress that the center ones [1];[2];[5];[16];[20];[13];[3]. The bending of the connecting spandrel in the inner columns [3], leads to an axial force in the corner columns that is 4 times higher than in the case of an ideal tube [27].

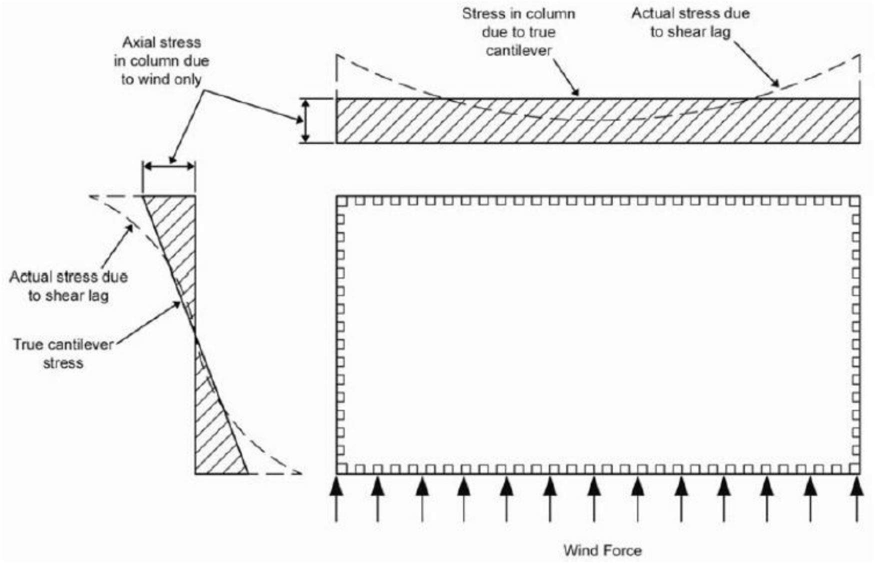


Figure 13 - Shear Lag demonstration (reproduced from [5])

From the architectural point of view, this structural system creates two main problems: the first one is the reduced views from the interior of the building, due to the large columns and deep spandrels [2], and the second one refers to the entrance levels, which are stunted owing to the closely spaced columns [1];[2];[13]. This second issue is overcome by merging the columns some levels above the entrance level, by resorting to transfer trusses, so the loads are transferred, from the columns to a shear core, thus reducing the number of columns reaching the entrance levels [27], as shown in Figure 14.

Figure 14 - Columns merging at the entrance level at World Trade Center (adapted from [28])

This structural system can be constructed based on either reinforced concrete, structural steel or composite construction [1];[2];[16];[13]. Some examples of buildings that use this structural arrangement in their layouts are the World Trade Center Twin Towers or the DeWitt-Chestnut Apartment Building [13], in Figure 15 below.

**Figure 15 - DeWitt-Chestnut Apartment Building (reproduced from [13])**

## Braced Tube System

Braced tube structures answer the demanding for using tubular systems in greater heights, improving the whole system efficiency and allowing enlarged space between the perimeter columns, by adding widely spaced diagonal bracing members in the outer faces of the tube [2];[1];[20];[13]. With this system, shear is absorbed by diagonal bracing trough axial action of these elements [2], reducing the risk of excessive axial load acting in the corner columns [13] and virtually eliminating the shear lag phenomenon [1];[2];[20]. The diagonal bracing, besides helping with resisting the lateral loads, acts as inclined columns to collect the gravity loads from the floors [1];[13].

As columns are widely spaced, it allows for larger window openings [1];[5], offsetting one of the major problems in framed tube systems. On the other hand, this system finds some difficulties associated with curtain walls as the large exterior bracing elements become an obstacle to the facade ornamentation details [13].

This system can be based in steel, reinforced concrete or composite construction [13]. The main representative of this system is the John Hancock Center (Figure 16a)) in Chicago, but there are other examples such as the 780 Avenue Building, New York, and the Bank of China Tower (Figure 16b)), which is an important variation of this system [2];[13]. This system can be used in buildings with more than 100 stories [13].

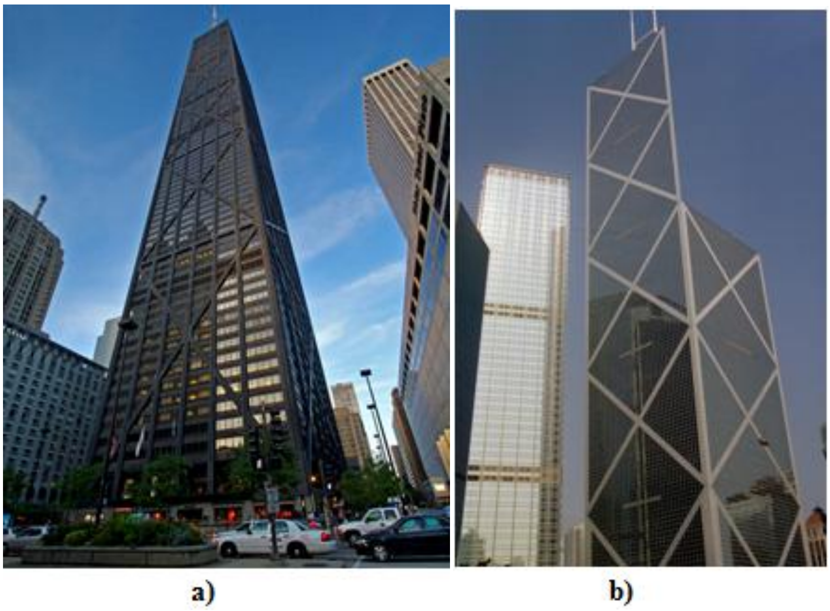

a) b)

**Figure 16 - John Hancock Center a) (adapted from [29]) and Bank of China Tower b) (adapted from [30])**

## Bundled Tube System

A bundled tube system is a structural system that consists of several tube structures which are aggregated together, in order to make the entire system to act in a coupled manner, as a single unit [2];[5];[20]. This bundled tube system allows the use of wider column spacings that those used in Framed Tube Systems because, with the use of more "tubes" in the whole structural system, more elements are available to provide resistance for lateral loads [2];[5]. The columns are typically placed with larger spacings and allow wider window openings [13], causing them to be less obstructive [1] and overcoming one of the main issues on Framed Tube Systems.  The shear lag effect on these structures is greatly reduced, as a result of the addition of interior framed web panels across the width of the building [20];[1], leading to a less significant deviation from  when compared with the case of inexistent internal frames [2].

The main advantage of this structural system is the possibility to assemble and terminate the individual tubes at any height without loss of structural integrity [2];[20] and the opportunity to erect the whole building in any configuration, such as triangular, hexagonal or semicircular [2];[13]. The disadvantage is that, with columns running across the building width, the floors are divided into tight cells, due to the inclusion of the different tubes that compose [2];[13] , as is shown in Figure 17.

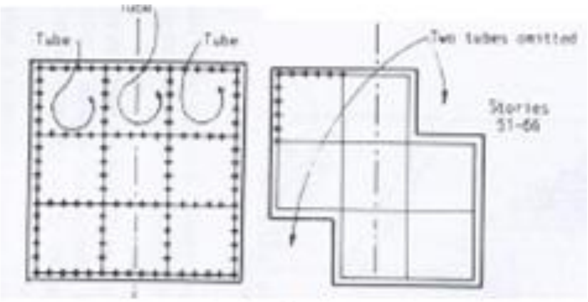


**Figure 17 - Bundled tube different possible floor plans (adapted from [1])**

These structures can be built in steel, reinforced concrete and composite construction [13], as in the case of the steel-made building Willis Tower (Figure 2) or One Magnificent Mile [5];[13], shown in Figure 18 below, built in concrete.

**Figure 18 - One Magnificent Mile Bundled Tube System (adapted from [31])**

### 2.4.6. Buttressed Systems

The buttressed core is not a very common structural system, but it is worth to be mentioned since it was the system used in the construction of the tallest building nowadays: the Burj Khalifa, as it it's a relatively new structural system.

Burj Khalifa's structure was inspired in a Korean building, erected in 2004, the Tower Palace III [32]. This Korean building used, for the first time, a high performance concrete core which was connected to the exterior composite columns by an indirect outrigger belt wall system at the mechanical levels [33]. This large concrete structural core acting as a solid tube is gaining significance in the structural systems of tall buildings [18].

The structure of Burj Khalifa consists of hexagonal high performance concrete core walls that provide torsional resistance similar to a closed tube or axle [34]in[32], with the three wings, as shown in Figure 19, clustered around it providing shear resistance [32];[35]. Similarly to the bundled tube, as the building goes higher one wing at each tier sets back, decreasing the cross section of the tower along the building's height [32]. Like in Tower Palace III, Burj Khalifa incorporated outriggers at the mechanical levels so the columns at that alignment participate in the lateral resistance [16]. The Burj Khalifa was also constructed resorting to innovative technological applications for monitoring and maintenance. These applications, among others, allowed for real-time horizontal displacement control of the building, during construction time and when the building was finished and allowed, during construction phase, to ensure the relative position of all elements according to the design. These delicate measures were necessary to control the geometrical errors at early stages of the construction, and avoid the enormous amplification of these errors with the height. This control was mostly based on GPS and geo-referenciation systems [36].

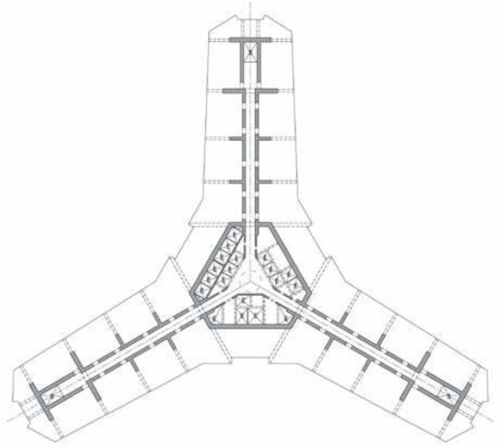


**Figure 19 - Burj Khalifa cross section (reproduced from [35])**

### 2.4.7. Diagrid Systems

The diagrid system is a relatively new structural system. It emerged as an alternative to overcome the drawbacks of braced tubes system [5];[37].

The diagrid system is more efficient than the outrigger systems and mega columns , because the diagrid acts as an exterior tube that maximizes the resistance to the overturning moment [38]. This tubular behavior is even more interesting as it allows for almost all the conventional vertical columns to be eliminated, hence eliminates the close facade of framed tube systems and the floors tight cells division of bundled tubs. This is possible because the diagonal members in diagrid can carry gravity and lateral loads due to their triangulated configuration. At the same time this system is better than an outrigger structure because it does not require the very rigid central cores to provide resistance to shear [5];[39]. However, diagrid complicated joint system between diagonal elements makes the constructability more difficult and more expensive than conventional structures [37].

The use of the diagrid system in modern buildings has generated renewed interest in architectural and structural tall buildings [5]. It opened new opportunities to make buildings that become landmarks, like in Penta-Port Project, Seoul, Korea [38] or The Bow Project in Calgary, Canada [39], shown in Figure 20. Other known projects are the 30 St. Mary Axe (Figure 20) in London and de Guangzhou Twin Towers [5]. The diagrid elements are mostly built in steel but can be made of concrete too [5].

**Figure 20 - a) The Bow (Calgary, Canada) (reproduced from [40]) and b) 30 St. Mary Axe (London, U.K.) reproduced from [41])**

## 2.5. Evolution between Structural Systems

In order to better understand how the major structural systems used in tall building initiated and evolved, it is useful to analyze the historical trend and the onset events of each new structural system. From the previous sections it becomes clear that rigid frames were the first structural systems ever applied, since this was the common way to construct typical buildings.

As buildings were becoming taller, the simple rigid frame started to show deficiencies and limitations, leading to the appearance of the first bracings, mostly in interior cores, which were formed by shear walls, due to architectural limitations. The ultimate example of this system is the Chrysler Building. Again, as new height records were reached, this system revealed important vulnerabilities. The subsequent technical developments were substantial and allowed the reaching of outstanding heights, starting the era of skyscrapers [2].

The design of tall buildings started to seriously consider the need to maximize area available to rent, therefore the structural elements for resisting lateral loads were moved to the exterior, hence motivating the appearance of the tube structural systems. The first versions of these systems were working only with closely columns in the perimeter of the building, but later the spacing these columns was increased, moving the interior brace to the perimeter of the building. The architecture later demanded for more corner offices in tall buildings, and as a result the tube behavior was updated to work as bundled tube. The destroyed World Trade Center (Framed Tube System), John Hancock Building (Braced Tube System) and Willis Tower (Bundled Tube System) are the most famous examples [2].

The architectural freedom of the facade was not a strong point of the tube system. As a consequence, in the 1980's, outriggers and belt trusses systems appeared as structural solutions, enhancing structural efficiency and architectural freedom [42]. Still regarding tubular systems, the braced tube system was not appreciated popular solution, as mentioned previously in section 2.4.7. Consequently, the diagrid system appeared with renewed architectural interest by developers [37]. One could say that diagrid system is the successor of the bracing tube system.

The buttressed core system is an entirely new structural system [35], as tubular system was, since it didn’t evolve from any other known structural system. These structural systems changed the approach of engineers and architects regarding tall building's design. The construction of the next tallest building in the world, the Kingdom Tower in Saudi Arabia, which is expected to be 1 kilometer high, will have the same structural system as Burj Khalifa, although with minor changes [43].

Figure 21illustrates the most representative buildings of each structural system described above, constituting a symbolic representation of the potentialities of each structural system and the height that is technically possible to reach.

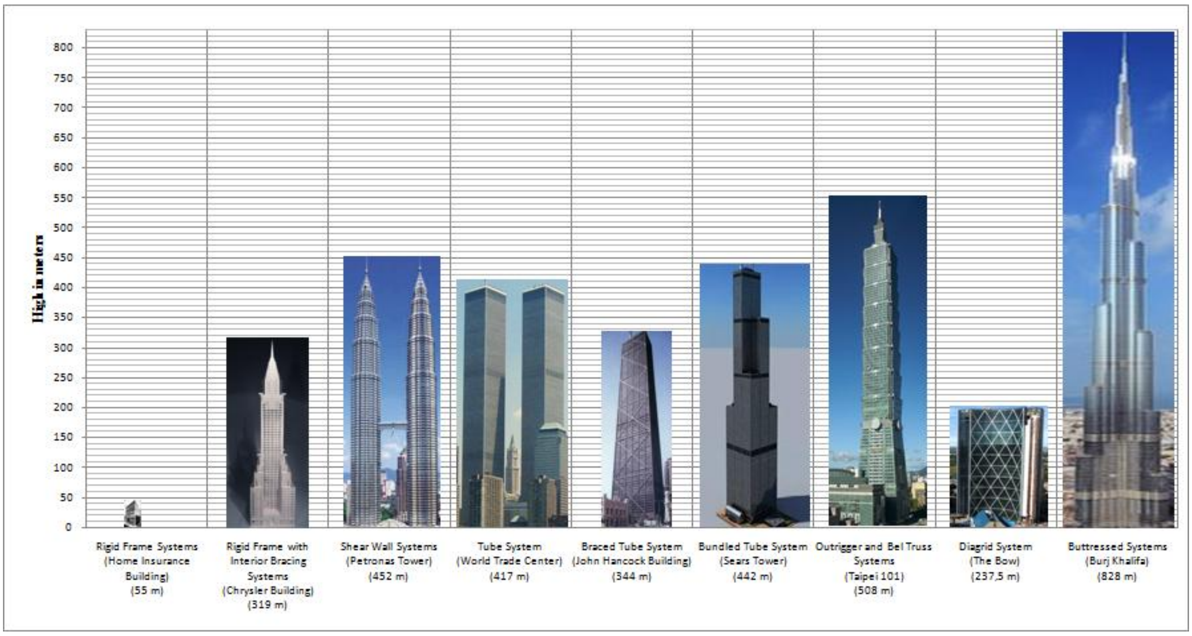


**Figure 21 - Symbolic tall buildings, their structural system and height**

## 2.6. Conclusion

This chapter tried to show why tall buildings came to scene, what makes them such singular engineering projects, what challenges they need to meet in the design phase and the evolution that the structural systems have went through in the last century. It was shown that tall buildings went through significant changes and followed a few main architectural trends associated to each era. The structural behavior of each system was also analyzed, with particular emphasis on their advantages and limitations. The main objective was to define a path in tall buildings structural evolution, from the early days until now, so the importance of the structural systems innovation for the increasing of the reached height in tall buildings could be clearly understood. The next chapters will be constructed on top of the knowledge framework exposed in the present chapter, and will refer to the concepts analyzed so that the understanding of the near future trends in tall construction may be conveniently supported by the historical evolution of the construction of tall buildings.

In this chapter, issues about the structural frame and engineering challenges about tall buildings have been addressed, however as such landmark structures, it should be important to measure "how unique" they are: in order to be built, one can guess that the social and economic environment around them should be unique too, especially when regarding the construction of the world's tallest building, which are engineering milestones that turn the page on the possibilities of "how high" is feasible to build, hence, a study on the surrounding environment should be made, in order to realize how unique this structures are and how unique is the environment surrounding their construction.

# 3. THE SKYSCRAPER INDEX

## 3.1. Introduction

Skyscraper's literature rarely deals with the macroeconomic factors that somehow influence their construction. It seems plausible to assume that a certain group of economic features must be assured to drive the construction of the tallest building in the world at a certain time. Other specific economical variables are also required, as it will be discussed after. In this chapter an economic index is presented, the Skyscraper Index, which relates business cycles with the construction of the world's tallest building [44], and how the economic feelings of the time at which the world's tallest building was built are related with its construction. In this chapter a broader view about tall buildings is attempted, aiming at widening the view about the factors and the economical mindset which underlie the construction of the tallest building at a certain moment. In this chapter awareness is provided about the fact that these technological achievements are not a product of the technological possibilities or the society demands exclusively, but rather that these are mostly a product of an artificially created environment that sets the ideal conditions for them to be built.

## 3.2. Cantillon, the Austrian Economic School Theories and Tall Buildings

In spite of the fact that tall buildings are influenced by variables such as the available technology, government rules and even ego motivations, tall buildings are intrinsically an economic product, which derives from economic motivations [44].

The economics that are inherent to tall buildings construction are not clear because there is no econometric formula that predicts the adequacy of a tall building construction. Hence, economic theories must be addressed to understand how tall buildings construction is influenced by the economic situation of the moment, in order to unveil economic patterns that can be associated to their construction. As it will be discussed subsequently, the world's tallest building construction often happens during certain economic events. The explanation of this economical pattern is necessary, in order to provide clear understanding of the relationship between business cycles and tall buildings construction.

The Cantillon theory is one of the many monetary economical theories that try to understand the business cycles. This theory was later adopted by the Austrian Economics School to understand the business cycles, especially regarding the idea that these cycles are caused by government's intervention [45]. In the Austrian view, when a central bank embraces a monetary expansion policy, by injecting money in the society, the interest rates decrease and the economy is boosted. This will lead to two different behaviors: consumers will change their consuming patterns to the present, while entrepreneurs will opt for long term investments, because it becomes cheaper to finance their investments [46]. These long term investments can vary from factories, machinery, expansion plans or even, as a symbol of the capitalist 20st century society, skyscrapers [44]. Hence, a subtle economic relation between tall buildings and economic cycles seems to exist. Tall buildings can therefore be seen as a product of artificially created economic environments.

The changes in monetary policy previously discussed can have three Cantillon effects on tall buildings construction, which are interconnected and reinforce each other: the value of land and capital cost, the size of the firm and its office demand and the technological impact in tall buildings construction [44]. Considering land cost, once the interest rates start falling land cost increases. This increase is especially noted in Central Business District (CBD) areas (Figure 22) due to its neuralgic location in cities. When interest rates fall, the demand for the best situated plots in CBD increases and their price rises. In order to increase the profitability margin, developers construct taller structures, so they have more leasable space to offset the high investment in construction. The opportunity cost of building each floor is lower than ever due to the low interest rates. These two features stimulate tall buildings construction in central locations [44]. The size of the firm is also influenced by the reduced interest rates, once again because it is cheaper for firms to grow and expand their production. In order to become more capital intensive, firms will look to establish central headquarters. These headquarters increase the demanding for office space, which is located at CBD, which in turn encourages even more intensively taller buildings construction [44]. A close look on the major companies acting in New York, that are listed in Fortune 500, show that most of them are related with capital intensive businesses like energy or financial and insurance activities [47] . The technological impact is later felt because, as taller buildings demand increases, new and different challenges ask for innovations in terms of solutions for structural schemes, services (elevators), MEP systems, etc. The installed capacity to construct more efficiently tall buildings also expands. These innovations will, in turn, open way for the construction of more and taller buildings [44].

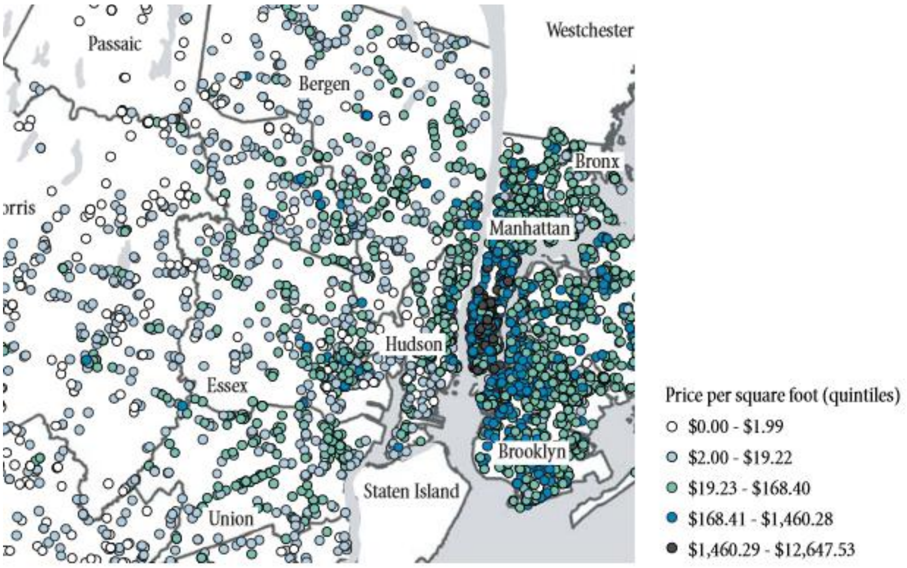


**Figure 22 - Land cost in main New York city's area (adapted from [48])**

## 3.3. The Skyscraper Index

The Skyscraper Index was created by the economist Andrew Lawrence, in 1999, as an attempt to establish a relation between the world's tallest building construction and business cycles

[44]. In general, the Skyscraper Index shows that the construction of the world's tallest building begins in a later phase of an economical expansion, and it finishes soon after the onset of the economic crisis [44]. What leads to the massive investment associated to tall buildings construction are the expansionary monetary policies, lower interest rates and in a minor basis, speculative processes [44].

As an indicator, the Skyscraper Index comes from reality verification and its further connection with some registered patterns. Hence, as it will be discussed next, the Skyscraper Index has a "testing time" of more than 100 years. The index verifies that the construction of the major world's tallest buildings were started in times of monetary expansion, with low interest rates, and were finished at the onset of an economical crisis. Verifying that the major world's tallest building construction were built, or started to be built, in times of economic expansion, with government's and bank's policies of money injection in the economy and consequent low interest rates, and that those were concluded on the beginning of big economic, some worldwide, crisis.

The next sub-chapters will refer to some of the major economic crises and will try to relate the construction of world's tallest buildings with them. The economic pattern of the time is described, in order to clarify the connection between the economical cycle and the world's tallest building construction.

## 3.4. The Panic of 1907

The Panic of 1907 was due to a series of events which begun by the failed attempt of corner the stock of United Copper Company by the business men Augustus Heinze and Charles Morse, who were also associated with numerous banks [49]. Heinze was a business man with important positions in several banks in New York and, after his failed attempt of corner the stock of United Copper Company, many banks upon which they had known influences faced bank runs, which ultimately led to the intervention of the New York Clearing House (NYCH) in order to provide enough funds to sustain these bank runs [49]. However, true panic begun when the National Bank of Commerce, an active member of NYCH [50], announced that it would stop to clear funds for the Knickerbocker Trust Company, which was also managed by a business man with connections to Augustus Heinze [49]. This resulted in one of the major bank runs in United States (US) history [44]. Concerning this crisis, it occurred when seasonal factors regarding harvesting season and the crops transport to New York, which involved money's migration from East to West of the country, met a great money shortening era (the monetary policies of the time tended to be "inelastic"). This took the financial system to a steaming point, making that any economical shock would trigger a severe economic crisis [49].

One year after the onset of the crisis the Singer Building (New York) was concluded, and one year later the Metropolitan Life Insurance (New York) was also completed. Both were the tallest buildings in the world and closed the first skyscraper era (1904-1909) [44]. The time's deregulated financial system and the arise of trust companies which offered financing to companies that wouldn't access bank's credit opportunities [49] might have led to a construction bubble in the beginning of the era and that had burst two years after the onset of the crisis, with the construction of two world's tallest buildings in one year.

## 3.5. The Great Depression

The Great Depression is one of the most studied economical events ever, but there is no consensus about what really happened. The World War I brought the US to the top of the world economies, as European countries bought their goods and war machinery from US and American banks were sustaining the economy worldwide [51]. Facing the boosting of economy, Americans started to invest in stock market, which led to an uncontrolled climbing of shares price and a financial bubble [51]. In order to chill this bubbling stock market behavior, the Federal Reserve raised the interest rates, which resulted in Americans repatriating some of their money from Europe back to US [51]. Then, in 29 October of 1929, the Dow Jones Industrial Index collapsed 20% of its value in two days, which triggered a series of bankruptcies, insolvencies and unemployment.

Although several explanations are proposed to explain the Great Depression, it is clear that after the Panic of 1907, and forward Federal Reserve creation, there were several measures that prompt the Depression to happen: the bank regulation rules, the Smoot-Hawley tariff [44] and above all, the increase in money supply (Figure 23) [44];[52] and credit availability, which had even led to a real estate bubble in 1925 [53].

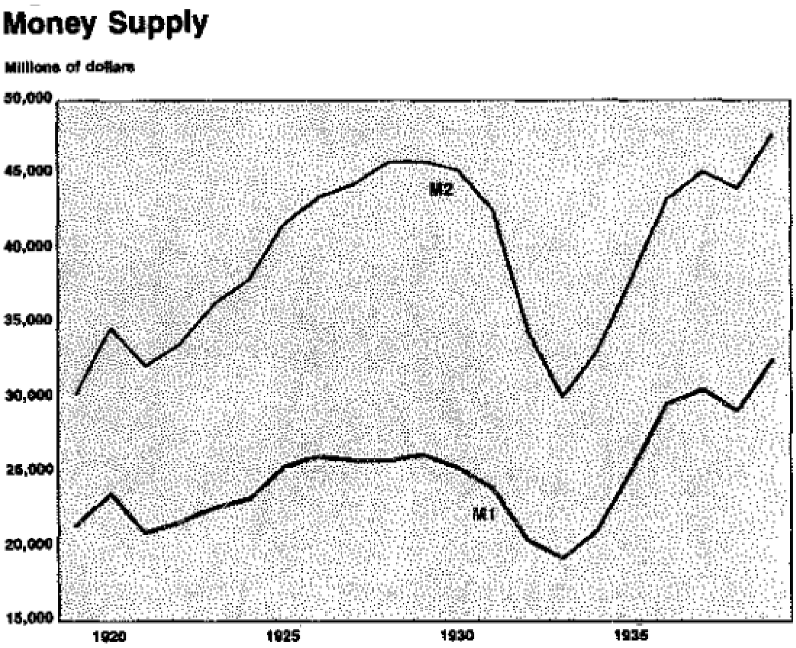


**Figure 23 - M1 is the circulating and bank deposited money, M2 represents M1 plus all time-related deposits, saving deposits and non-institutional money-market funds (adapted from [52])**

During the development of the Great Depression, there were three record breaking tall buildings construction: 40 Wall Street (later know as the Trump Building), started in 1929 and finished in 1930; the Chrysler Building, started 1928 and finished in 1930; the Empire State Building, started in 1930 and completed in 1931. This pattern is the closest one to the Skyscraper Index pattern: the buildings are started in the later phases of the monetary and credit expansion and are finished slightly after the onset of the crisis. The Empire State Building seems to deviate from these conditions but the "official" date for the onset of the crisis is near the end of 1929, so Empire's State Building case does not significantly deviate from the pattern.

As it will be discussed in the following chapter, ego and personal motivations were also triggers for this "race" to the skies in such a short period of time. Hence, considering this pure competition motivation, it can be underlined that economical variables were all very favorable to the construction of these buildings. Without favorable economic environment these "secondary" motivations would not be sufficient to drive the construction of tall buildings, therefore these are mainly a product of the economic environment. This is the most notorious argument of the Skyscraper Index analysis.

## 3.6. Stagflation in the 1970s

Stagflation is the economical event during which inflation grows and unemployment also does [54]. This event occurred during the 1970s and it is still not totally clear. It seems that for certain unemployment limits, low unemployment leads to price and wages inflation, according to the Phillips curve [55], although not all specialists agree with this view [56].

Stagflation is still an event that lacks a precise understanding, but a possible explanation is that this episode occurred due to a lag in inflation rises. Monetary expansion policies raise inflation, but this second event raises with a small lag in relation to monetary expansion. As inflation rises with a lag, it also reaches its peak when monetary expansion policies are over. This lag is estimated to be of one year [57].

Stagflation struck U.S. in the 1970s due to sharp increases in oil price and other commodity assets and due to monetary expansion policies [57] as shown in Figure 24 about the evolution of money supply in US around the 1970s.

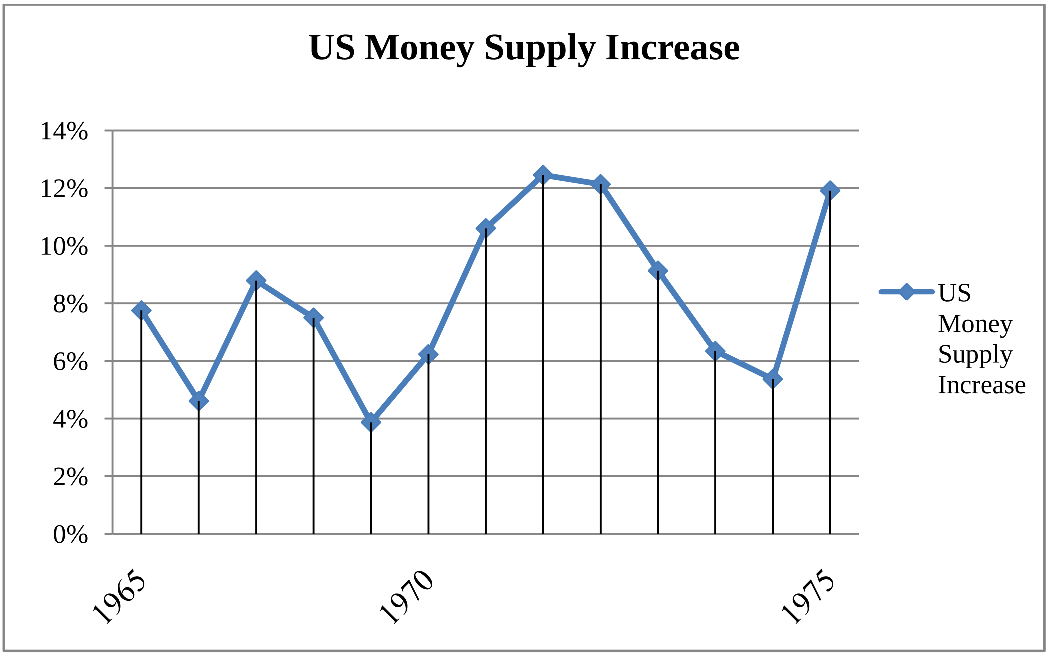


**Figure 24 - U.S. Money supply increase in the 1970s [57]**

In 1966 and 1970, the construction of the World Trade Center and the Willis Tower (formerly Sears Tower), were initiated. Again, the pattern is repeated: the construction of two world's tallest buildings started almost at the same time, like Singer Building and Metropolitan Life Building before the Panic of 1907, or the 40 Wall Street Chrysler Building and Empire State Building before the Great Depression of 1930. The economical environment was once more governed by a monetary expansion policy, with inherent low interest rates. Both tall buildings were finished in 1973, right in the beginning of the Stagflation event [57] and on the onset of a major economic downturn.

## 3.7. Asian financial crisis of 1997

The 1997's Asian crisis was an event that struck mainly Thailand, Malaysia, Indonesia and South Korea.

In the 1990's, since the wealthiest countries had opened their financial markets, the emerging economies started to receive great amounts of international capital. In Thailand, for example, the money influx ascended to 10,3% of the Gross Domestic Product (GDP) between 1990 and

1996. In the mid of 1997 bank credit rose up to 274 billion dollars between South Korea, Indonesia, Malaysia, Philippines and Thailand [58]. As a matter of fact, Malaysia banks were working into the money growth target, in order to obey the demands of a thriving economy (Figure 25) and embraced a bank credit financed economy orientation [59]. This massive increase in foreign capital inflow led banks to invest in the most promising profitable business: real estate.

Some factors have signaled the bubble implosion that followed the real estate investments: the increasing deficit in banks' current accounts, the overvalued exchange rate and the exportations reduction. With this increasing foreign investment influx, banks were under even greater risks, because they borrowed money in foreign currency and lent in local currency, which exposed banks to great losses in case of local currency depreciation. Another wrong bank strategy was to borrow money in short-term maturities and lend it in with long term maturities, which made them vulnerable to risks of run [58].

At the center of this crisis were several political and economical events that begun a run on foreign deposits in Asian banks. The first event was the sequential bankruptcy of Hanbo Steel Company, Sammi Steel and Kia Motors, which had put great pressure on commercial banks, followed by the Thai government decision of stop supporting the Finance One (a big financial company), which would make creditors incur on great losses. These two happenings accelerated the foreign money withdraw and led to the depreciation Thai Bath, which, by a contagion effect, led to funds withdraw in the rest of east Asia countries [58].

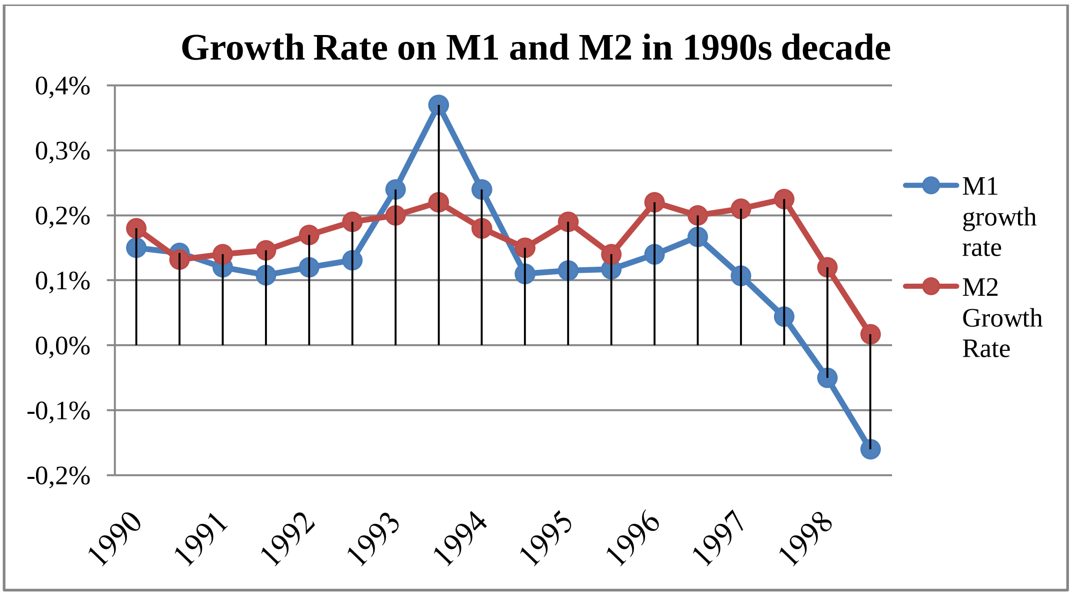


**Figure 25 - M1 (circulating and bank deposited money) and M2 (M1 plus all time-related deposits, saving deposits and non-institutional money-market funds) curves of the Malaysian economy [60]**

In 1992, when large capital inflows were happening [59], the construction of the building that would become, in 1998, the world's tallest building had started: the Petronas Towers. Again, like in previous record breaking skyscrapers, the construction of the world's tallest building was preceded by monetary expansion policies in this case mainly due to the foreign funds influx to east Asian economies. This example validates once more a pattern that begun in 1907 and seems to be valid for 1997, 90 years after. The Petronas Towers remained the world's tallest building until 2004.

## 3.8. The Great Recession

The Great Recession was a worldwide crisis that flared in 2008, but that had started in US one year before [61].

In 1981, when Ronald Reagan was elected President of the United States of America, there was a shift in the country's growing policies: from a full employment and wage growth model to a borrowing and asset price inflation model [62]. Hence, this model was built up upon financial expansions and low imports prices, which provided support to increasing debts from people and firms, and allowed to soften the wage stagnation [62]. But this model started to be unsustainable due to the wage degradation and non-productive debt creation [62], which led policy makers to decide to create the economic conditions that allowed for a speculative bubble creation: the weaker the economy became, the more speculative the bubble was needed [61]. The only speculative bubble that could cross the entire economical activity and ignite a new economical prosperity situation was a real estate bubble [62]. The *dot.com* crisis in 2001 was the trigger to the Federal Reserve's (Fed) decision to lower the interest rates in the US: in order to rehabilitate a deteriorating economy, Fed lowered the interest rates virtually to zero to increase the credit availability. However, this dramatic interest rate lowering created the conditions for a real estate bubble [63]. US was witnessing an increase on its population and a housing availability decrease, which led to rising real estate prices that made banks to focus their business in this area [63]. With this increasing demand for housing, many Americans started to face difficulties in acquiring a property, which made them to search for banks' credit solutions (Figure 26).

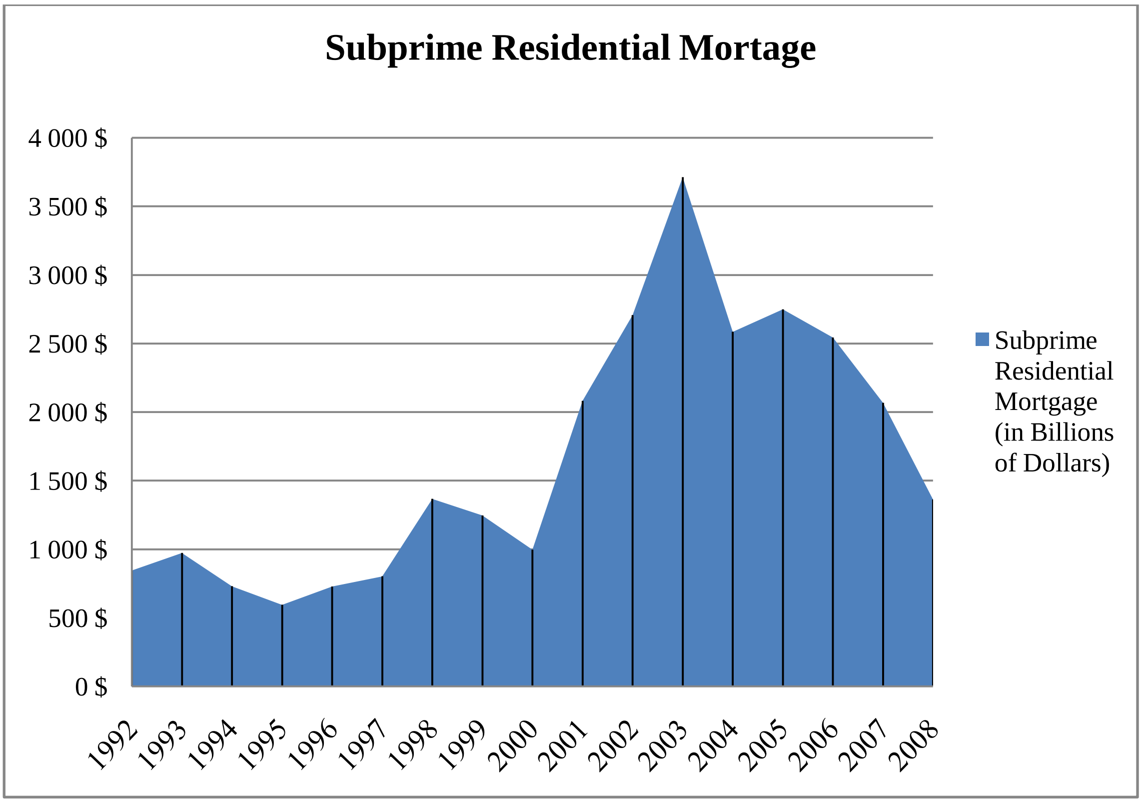


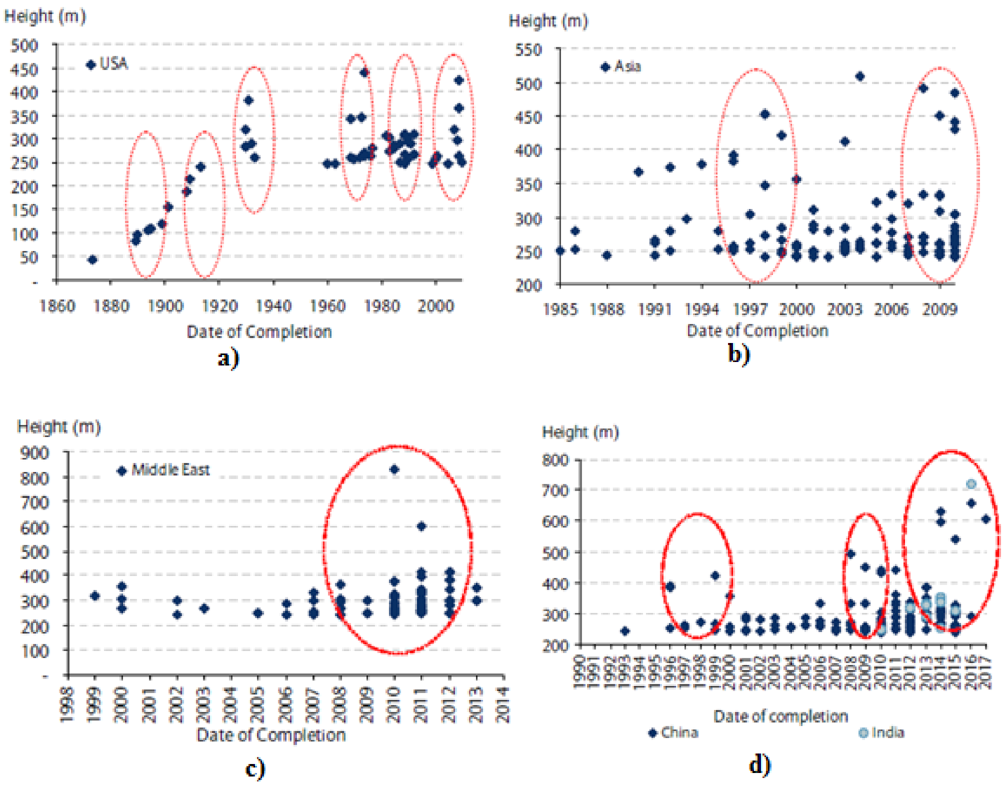
**Figure 26 - Residential Mortgage types [63]**

Among all mortgage solutions, there was the subprime. Subprime mortgages were issued to people with a lack of good record in bank payments or without a verification of their income. Hence, these were risky mortgages for banks and also highly profitable in the beginning. Banks created for these subprime clients adjustable-rate mortgages, which were upward updated after a certain period of time. Since clients' properties were becoming increasingly valuable, borrowers could refinance using properties valuation. Once the housing prices started to depreciate borrowers found hard to refinance again, thus facing high interest rates on their mortgage. As these subprime clients had difficulties in paying for their mortgages, banks faced a high level of payment default. This economic crisis spread around the world because these mortgages were sold as investment bonds for other banks and financial companies around the world [63].

At the same time that the US were embracing a real estate bubble, Dubai was witnessing the construction of the world's tallest building, which begun in 2004 and finished in 2010, the Burj Khalifa. Again, and maybe exacerbated by investment and financial openness globalization, the construction of the world's tallest building is initiated when there are explicit credit and monetary expansionary policies. After its conclusion, Burj Khalifa faced a vacancy rate of 92% and the rent prices fell by 40% [64]. This shows that even the most outstanding building is not immune to economic environment.

## 3.9. Future Crisis

In 2012, Andrew Lawrence updated its Skyscraper Index and noticed that the construction of the world's tallest building is connected with major economical downturns. He also found that these world's tallest buildings rarely are built isolated, i.e., the construction of the world's tallest building is also related with real estate bubbles [65]. Hence, what was first seen as a coincidence is seen now as an implication. Figure 27 shows how Andrew Lawrence updated assumptions are based on the number of tall buildings completed during the last decades.



a)

b)

c)

d)

**Figure 27 - Building bubble in: a) U.S.A, b) Asia, c) Middle East and China and d) India ( Reproduced from [65])**

According to Lawrence updated Skyscraper Index, investors should be cautious about Chinese economy, which was by 2012 the world's top constructor of skyscrapers by concluding 53% of all skyscrapers around the world [65].

## 3.10. The Skyscraper Index faults

In spite of the robustness of the Skyscraper Index on explaining the cycles of tall building construction in general, there are a few examples which are not sufficiently well explained. The Woolworth Building was not planned to be the world's tallest building. Instead, it was sequentially being improved to become the world's tallest building. The opening ceremonies were in 1913, and during the first quarter of this year a major economic contraction took place and lasted until 1914. This contraction included the third worst quarterly declines of the Gross Net Product (GNP) between 1875 and 1918. Hence, Woolworth building may not be a full exception to the Skyscraper Index, although it doesn't fit in Skyscraper Index standard formulation [44]. The *dot.com* bubble, which led to NASDAQ stock market crash, was also not predicted by the Skyscraper Index. Taipei 101 (2004-2010 world's tallest building) was started just two years before the NASDAQ crash. However, there is no consensus that NASDAQ stock market crisis was a massive economic downturn. Hence in spite of, somehow Taipei 101 fits in original formulation, the economical happening is not suited for Skyscraper Index definition, as it did not achieve the "dramatic economic downturn" requirement [44]. Skyscraper Index showed to be resilient to the time test. Looking at almost 100 years of tall buildings construction, Skyscraper Index can be associated with the biggest crisis that hit, not just US, but all the world. China and Middle East are now under the spotlights, testing if Skyscraper Index is a "culture-proof" proxy on major economic downturns and world's tallest buildings construction.

## 3.11. Conclusions

In spite of a still persisting lack of economical evidence to show if a tall building construction is either a good or a bad investment, macroeconomics was shown to be a good proxy and a good analyzing tool for tall buildings construction. The monetary and credit environment can partially help to explain the tall buildings construction cycles. It wasn’t the construction of the world's tallest buildings which led to a massive downturn on economy, but as discussed in this chapter it certainly is a valuable indicator that should be considered during monetary expansion, calling attention to near future events.

Within this chapter it was shown that tall buildings are also a product of economical environments, although nowadays they are widespread all over the world as evidenced by the last three world's tallest buildings that were constructed in different countries. This diversification may be related with money flux and other monetary strategies, which have been causing a series of evolutions in tall buildings construction. It might be interesting to look into deeper motivations and strategies that resulted in a shift of tall buildings location, function or even their increasing height.

# 4. GLOBAL TRENDS IN TALL BUILDINGS: LOCATION, HEIGHT AND FUNCTION

## 4.1. Introduction

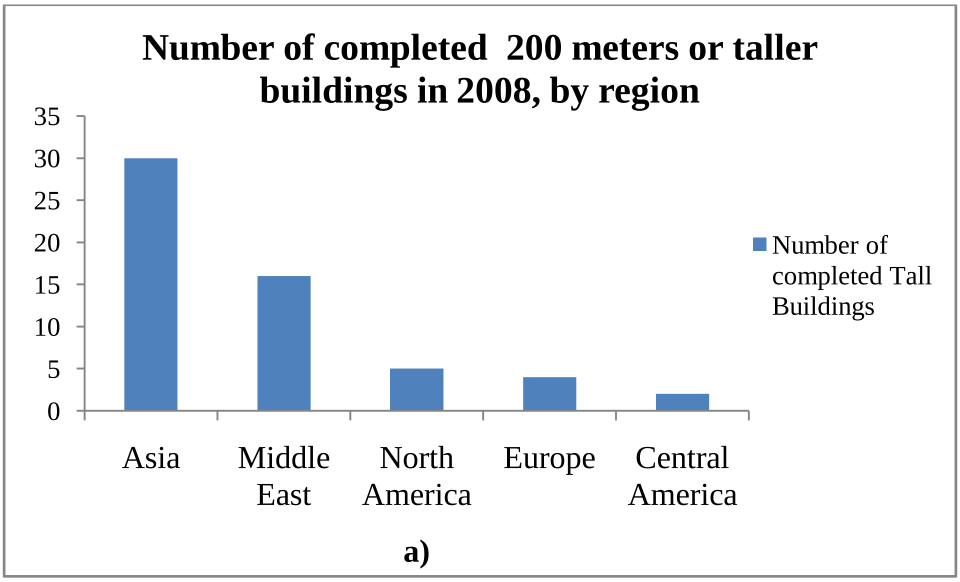
Tall buildings are not static products of architecture and engineering. Since their inception, tall buildings have been evolving regarding their mostly observable and physical characteristics: location, function and height. It's clear to see, for example, that buildings are becoming taller and that there has been a shift on their principal location: from North America to Asia and the main Middle East Cities [66];[18].

The reasons behind the shift of location, height and function of tall buildings may derive from many distinct factors. These factors are diverse and originate from a wide range of different realities. However, the understanding of these factors is crucial for the identification of the main challenges and developments that will likely characterize tall buildings in the future, and that will shape their role in modern societies.

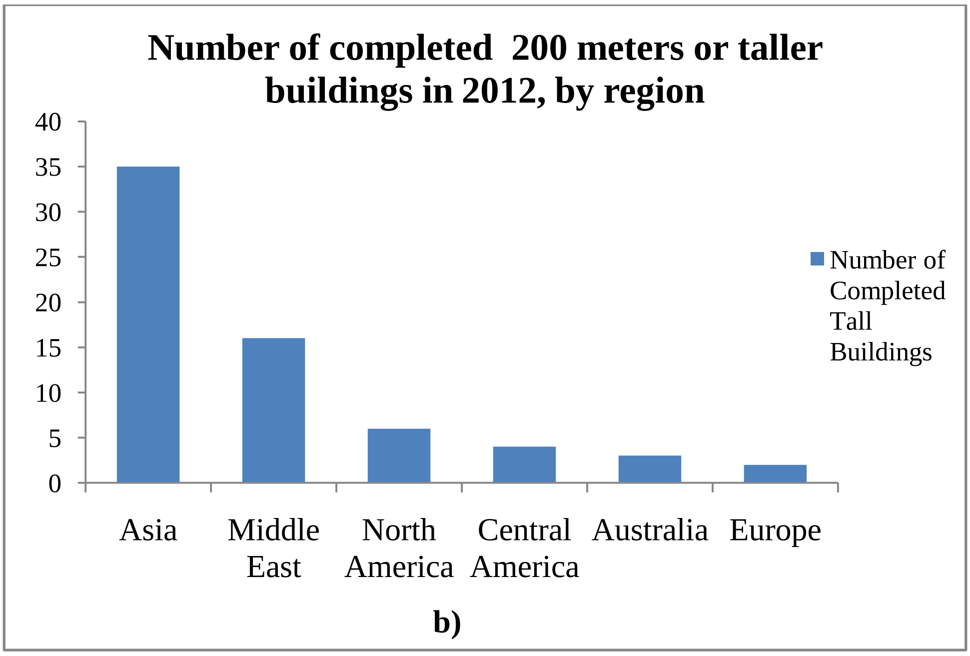
After the basic understanding in the previous chapter of how tall buildings work and are engineered, the holistic perspective of tall buildings is approached in this chapter by analyzing and understand the drastic changes operated in tall buildings location, function and height during the last decades. This perspective will allow to show that tall buildings are more than pure and simple architecture and engineering products, and that many other forces are driving the change and evolution of tall buildings. The systematic analysis of the evolution of tall buildings location, function and height will allow the identification of the main trends and patterns in the evolution of tall construction, and will eventually allow to identify which are their most important requirements.

## 4.2. Evolution of Tall Buildings Location

The change in tall buildings location is clearly demonstrated by the Council for Tall Buildings and Urban Habitat (CTBUH) on their annual reviews) [67];[68];[69] where it's performed a graphical analysis each year. Figure 28 shows the evolution, since 2008, of world's tallest building constructed each year.



a)



b)

**Figure 28 - Evolution of tallest buildings constructed each year: a) 2008; b) 2012; (a) [69] ; b) [70]**

Asia and Middle East are the most distinguished markets in tall buildings construction, at least since 2008.

Complementing the information gathered in figure above, in Figure 29 it can be observed that, by the end of 2012, there is already an absolute prevalence of buildings constructed in Asia and Middle East, while until the decade of 2000, North America was the greatest market for this type of building.

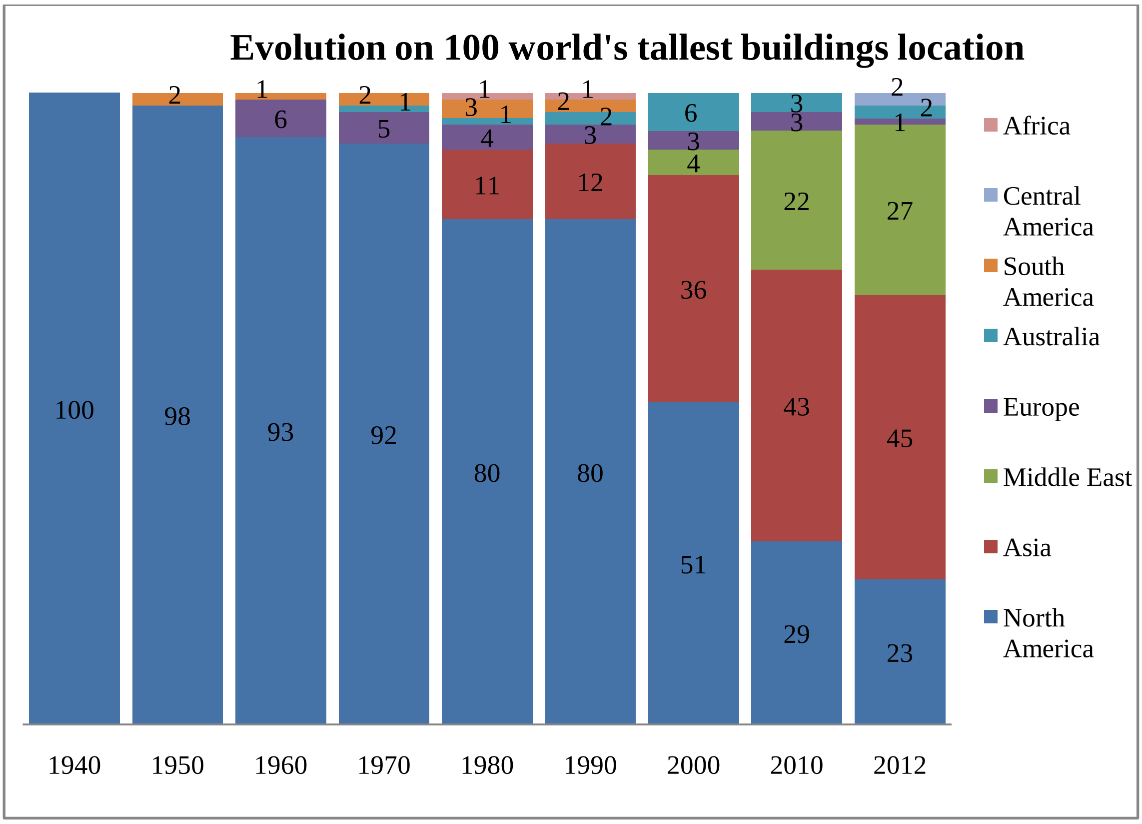


**Figure 29 - World's Tallest Buildings by location [71]-[79]**

This loss of preponderance of North America as tall building's home is actually attested by the fact that, since 1991, no North American building is featuring the "10 Tallest Completed List" of CTBUH. Furthermore, the pace at which this shift is taking place is outstanding: by 1990, 80 % of world's tallest buildings were situated in North America, while in 2010, North American tall buildings only represent 20% of the total [80].

The reduction of investment in tall buildings in U.S.A. might be related with uncertainty regarding the real estate value of these investments, the loss of urban valorization of these buildings and the psychological effects on the aftermath of terrorist attacks of 9/11. [81].

Though these might be points to keep in mind for this shift in skyscrapers location, other factors, which carry more tangible meaning, will be discussed subsequently.

### 4.2.1. Chinese Financial Openness

Since 1978, Chinese society has undergone major economic and social reforms, regarding its economical openness and market liberalization [82]. These changes in political economy and urbanization rules were followed by an increase in the Gross Domestic Product (GDP) rate from 1980 until now: the average growth rate of Chinese GDP until 2002 has been 9,2% [83]. When such an economic development occurs in a region, foreign companies and investments are attracted to this region, creating a good synergy between intern economical drivers and extern economic influence. These good synergies led to the gradual entry of Foreign Direct Investment (FDI) and Foreign Invested Enterprises (FIE). FDI in China has been present since the beginning of the reform: in 1980 China had 5% of its GDP represented in international reserves [82], while FIE became an important component of Chinese economy since 1992 and in 1995 these companies already controlled 95% of Chinese exports and controlled electronic and telecommunication industry [84]. In spite of this recognized openness to Foreign Direct Investment (FDI), China is still classified as a closed economy [85].

Liberalization of financial markets can bring several advantages to the countries, like better resource allocation, increase in domestic savings and purveyance of technological development [86]. In fact, these were technological attractive conditions that led China to open its financial market in the beginning of 1980s [84], with the establishment of 5 Special Economic Zones (SEZs) [87] and 14 coastal cities [82], as can be seen in Figure 30. Such coastal cities it's where are located the major importing and exporting industries [88]. Basically, a SEZ is a zone where economic policies are different, and as a general rule, offer foreign investment friendly conditions [87]. One of these cities is Shanghai. This research study chose Shanghai city among others due to the importance of its tall buildings, namely Jin Mao Tower, Shanghai International Financial Center and the not yet inaugurated Shanghai Tower. All these buildings are located in Pudong area, the SEZ established in Shanghai.

**Figure 30 - China's Special Economic Zones Location (reproduced from [89])**

.

Shanghai was chosen by Chinese government to become a global city, which would connect China to the world, through its new market openness approach [90]. Pudong area is not located at Shanghai city center, it actually was an undeveloped city district [87]. But the political measures adopted in this area transformed it in a great trade and business hub in China. Lujiazui Financial and Trade Zone is the heart of this Pudong area: here are located the main companies covering areas such as financial services, retail, real estate, business consulting and government services [90]. Some worldwide companies that have already established their business here are, for example: Eriksson, Philips, Xerox, General Motors, Mitsubishi, Hitachi and all current Chinese licensed foreign banks [90].

These business friendly areas tend to be decoys for multinational companies, and as they start to fixate in these places horizontal space becomes scarce, which eventually is solved by the construction of tall office buildings. Apart from providing the city's skyline a metropolitan and progressive image, these lofty tall buildings provide major incomes to the city government, while the minimum amount of area maximizes profits due to the rental incomes on office spaces. These tall buildings located in very precise and controlled spots are beneficial to all the economic agents: the companies establish themselves in areas with low tax policies and in land-marking tall buildings, which help to expand the brand, the municipalities profit from maximizing incomes in these tall buildings and place themselves on the map of cosmopolitan cities, and the country obtains massive revenues from creating exceptional conditions for FDI and FIE entry. To ensure the importance of these SEZ's for tall buildings location, analyzing China alone and looking at the 100 tallest constructed buildings, 50 are located in publicized SEZ's. If the contribution of Hong Kong is ignored by considering that this has been a state under British domain until 1997, then SEZ's representation climbs to 50 out of the 73 tallest Chinese buildings [91]. The future look of Pudong area is presented in Figure 31.

**Figure 31 - Pudong District render when Shanghai Tower (tallest one) is finished (reproduced from [92])**

### 4.2.2. Urban Demographic Growth in China

By the begging of 2012, news were released about Chinese urban demographic issues: for the first time in its history, urban population had surpass the rural areas population [93];[94]. This phenomenon has been observed in Chinese cities since the institution of the socio-economic reforms in 1978 [95];[96];[97]. Part of the reasons for this urban sprawl for over 30 years may be found at the years preceding 1978. During Mao's government years, the urban areas were privileged in expense of rural areas and the urban migration was forbidden [97]. To control the migration processes during this time, a very restrictive household registration mechanism called *hukou* was implemented [96];[97]. The *hukou* system was implemented in 1951 [98] and was extended to rural areas in 1955 [96]. Although its first main purpose was not to control rural migration but act as a monitoring mechanism, due to the failure of the Great Leap Forward action, which led to The Great Chinese Famine, rural-urban migration started to be uncontrollable and enabled the *hukou* to be a migration restrictive mechanism, avoiding "no-rules rural-urban migration" [96];[99].

Since the reforms started in 1978, the *hukou* system has been alleviated [95], and China has been experiencing a notable grow of its GDP (Figure 32). GDP development and urbanization seem to be connected concepts. Whatever which of the concepts enables the other, it is clear that urbanization and GDP growth are highly correlated in Chinese society [97]. Two decades after reforms started, in 1978, it is estimated that 174 million people moved from rural areas to urban sites, representing 75 % of all urban migrants [95]. During these two decades, the GDP growth was , in average, more than 9% each year [97], providing strong evidence about this mutual relation between GDP growth and urban migration.

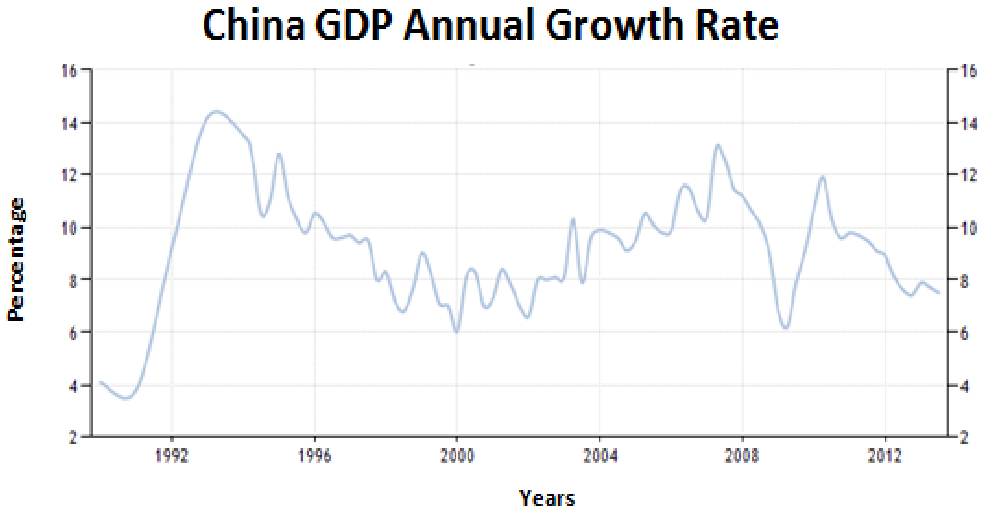


**Figure 32 - China GDP Annual Growth Rate (reproduced from [100])**

Urban population in China at the end 2011 was of 690.79 million people [101], with cities like Shanghai housing 23,57 million [102] or Beijing housing 19.61 million [103]. This rising population creates enormous pressure on urban tissue, leading to a breaking point due to the limit of horizontal sprawl caused by the increasing price of infrastructures [104] and the disorganization of urban frame. Tall commercial and residential buildings are therefore a solution to these high density cities [105]. Investments in tall buildings have been changing the cities profile layout: from 1992 to 1999, the peripheral average building's high had increased up to 74,4 meters, becoming close to the 77 meters in the city centers [106].

The Chinese housing policies privileged the "living and working on the same block" due to an industrialized approach [99];[107]. Due to the increasing population and improved urbanistic policies this approach had to be abandoned and, in order to accommodate increasing population, tall residential buildings were built and older workers neighborhoods were demolished [107]. By 2005, Chinese cities were already dedicating significant investments to high-rise residential projects, such as Skyline Mansion or Skyway Oasis Garden (226 m high), in Beijing, or Shanghai Fortune Residence, in Shanghai [108].

Meanwhile, more innovative solutions have already been achieved trying to comprise all human activities (life, work, leisure, etc.) in the same physical space. As a matter of fact, in 2009 the Linked Hybrid Complex (Figure 33) was constructed in Beijing, consisting of 8 housing towers 60 meters high. The complex comprises a series of human needs in the same physical space, such as apartments, commercial spaces, kindergarten and cinema, and where the towers are connected by means of sky bridges, housing 2500 people [18].

As shown, population pressure over de 2D dimension territory induces the need of creating a third dimension in the city by means of constructing tall buildings, not only for big companies to establish, but also to provide sustainable living styles and accommodate the incoming population.

**Figure 33 - Linked Hybrid view (reproduced from [109])**

### 4.2.3. Strategic Development in the Middle East

This section deals mostly with the Emirate of Dubai, in the United Arab Emirates. This metropolitan area was chosen as a case study because it introduces a very different factor from the ones exposed earlier: the Iconicity factor.

Dubai was, in the 19th century, a small city with an economy based on fishing, pearl business and trade. By the middle of the 20th century it was already a very developed trade center [110]. In 1966 oil was found, and as a consequence the rush for infrastructural development has started [110]. One of the infrastructures created was the Jebel Ali Port, in 1979, the largest manmade harbor in the world [111]. A few years later the construction of the Jebel Ali International Airport [111], which was concluded in 2010, opened the way for the establishment of Jebel Ali Free Zone in 1985 [111];[110].

Earlier in 1985, after the decision of investing in the International Airport, Dubai government decided to create a state-owned airline company, the Emirates Airlines, which is now one of the most successful airlines in the world [111]. In 2003, Dubai launched an on-line platform, called Dubai trade, where all international traders could be based in. The ultimate objective of this portal was to ease the complicated and bureaucratic processes of international trading in Dubai [112]. Dubai is featured on the top of the most attractive places to invest in UAE (114) clearly attesting that Dubai became a clearly financial oriented city. This business oriented policy had the Free Zones (FZ) creation as another very important infrastructure, and these worked in a similar way to the Chinese SEZs previously referred. With very good conditions for foreign companies to fixate, the main privileges were the possibility of 100 percent foreign ownership and 100 percent repatriation of capital and profits [110], and bureaucracy elimination measures [111]. With 22 Free Zones operating in the city, it is no surprise that Dubai holds now more that 20000 multinational companies [110].

Dubai governments have been committed to the creation of communication and business-friendly infrastructures, taking advantage of its central geographical position and actively attracting foreign business. The great mobility provided by the International Airport and the Jebel Ali Port, coupled with the competitive advantage of the FZs creation, attracted international companies to fix their businesses at Dubai [115]. Some well known international companies operating in Dubai are Microsoft, Siemens , Reuters and CNN [116].

After Dubai's rulers have clearly defined the strategy for their financial system, the attention was turned into another business activity: the tourism. The construction of world class hotels, shopping malls, [110]; [111] and the creation the world known artificial islands of The Palm and The World [111] were some of the milestones in this market approach, setting them as a top class world luxury tourism destination with a very solid conjuncture on this market. In 1997, Dubai Holding Group created the subsidiary Jumeirah Group, which was renewed in 2008 and is responsible for the conception and management of world class hotels [117]. Some of the world class hotels featured in Dubai are: Burj Al Arab, Jumeirah Beach Hotel, JW Marriott Marquis Hotel Dubai Tower 1 and 2 (Figure 34) and Emirates Tower Two, comprising heights from 104 meters to 355 meters [118];[119].

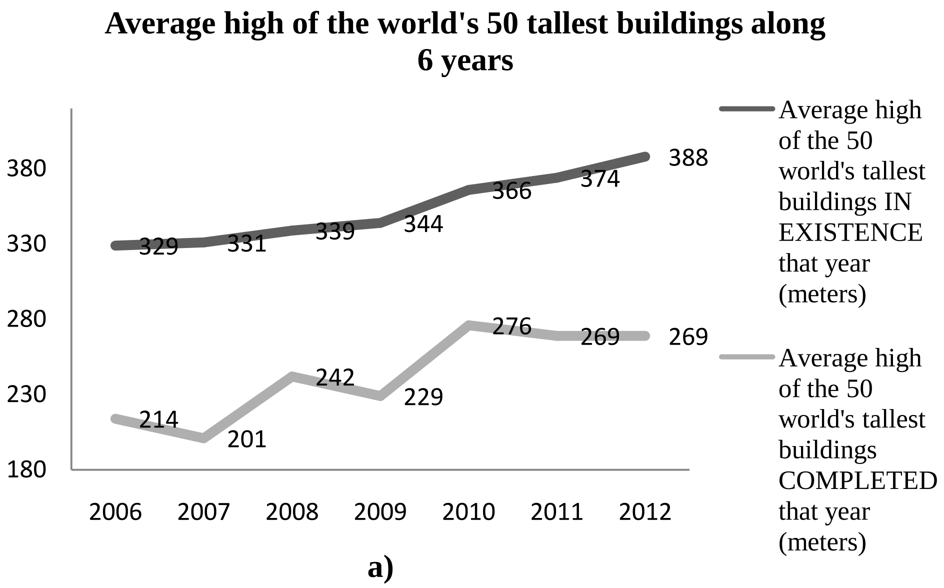
**Figure 34 - JW Marriott Marquis Hotel Dubai Tower 1and 2 (adapted from [120])**

The difference between the behaviors of Dubai's rulers about cultural openness and globalization is clear when compared to its Arabian neighbors. Dubai is not an overcrowded area as in the case of the Chinese examples mentioned above. Therefore population density is not the main driver of tall buildings construction in Dubai (the population of Dubai in 2011 was 2 million [110]. Hence, other incentives are behind Dubai's willing to build magnificent, land marking tall buildings. A less popular reason is Dubai’s ambition to become an ultra modern icon city [121]. The concept of the glamorous global city of the 21st century is connected to great centers of commerce and business, wide and efficient mobility options and first-class hotels and shopping centers that reflect the vitality of the tourism and business [121], all features that Dubai has already achieved with its airports, Free Zones and ports. However, unlike New York, London or Paris which are still admiring cities due to its history and culture and enclose symbolic structures like The Statue of Liberty, The Big Ben or Eiffel Tower, Dubai does not have this historical signature [121]. The creation of landmark high rises and technological complexes tries to ensure the Dubai's symbolic power that the poor historical past doesn't, in the 21st century modern cities context [121]. Thus the tall buildings, coupled with the outstanding developments, will guarantee that Dubai will feature the onset on the world stage of iconic cities [121], such as the mentioned above New York, Tokyo or Paris, converting it in a mandatory destination for the 21st century global, multicultural and cosmopolitan citizens. Among all the iconic projects developed in Dubai, the ones which deserve special mention are: the tallest building ever built, the Burj Khalifa, the largest manmade artificial islands, The Palm Jumeirah and The World, the two tallest hotel towers built in the world, JW Marriot Marquis Hotel Dubai Towers 1 and 2 and Rose Rayhaan by Rotana Hotel, and the three tallest residential towers in the world: Princess Tower, 23 Marina and The Torch. Dubai is now the hometown for the largest projects in the world, which magnifies its quest for the iconicity factor.

As shown, Dubai's options for becoming an ultra modern city were taken more than 30 years ago. Oil was a necessary trigger for the initial phases of this process, but Dubai's rulers didn't lay its development on oil revenues [111], making Dubai's development much more dependent on financial services and real estate business [121] creating a friendly business atmosphere and attracting the wealthiest consumers, hence projecting an image of glamour, prosperity and modern city.

## 4.3. Evolution of Tall Buildings Height

Height is the tall building’s main descriptive attribute. Over the years, since tall buildings stared to be built, their height as been increasing, as shown in Figure 35 and Figure 36. Figure 36 is of particular interest because it shows that today's tallest building, Burj Khalifa, has almost twice the height of 1974's tallest building, 1 World Trade Center, which stands as a remarkable development in less than 40 years.



a)

Figure 35 - Tall buildings height evolution [68]

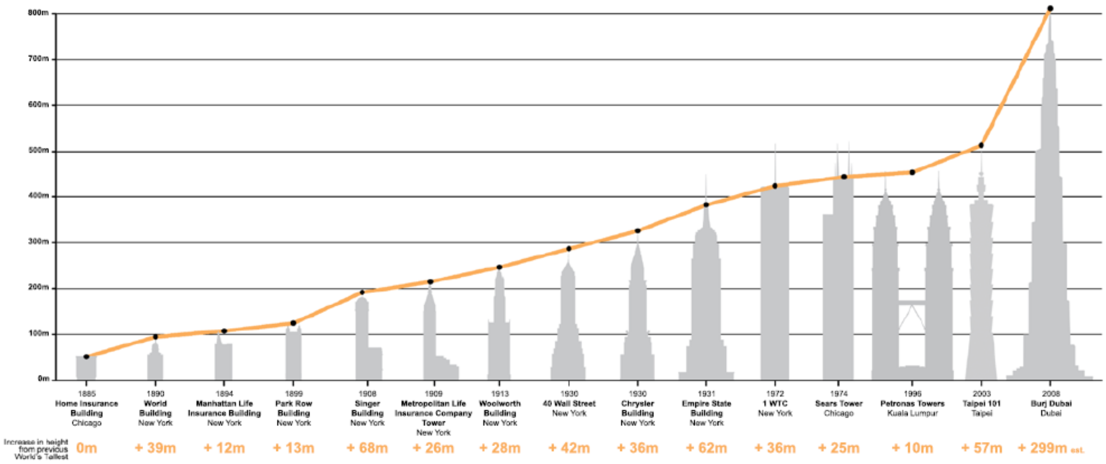


Figure 36 - Height increments in the considered tallest buildings in the world, one at its own time (adapted from [122])

The major driver to this increasing height of tall buildings might be the technological advances in terms of computing and construction technology, the increasing area of urban spaces and the inherent need of tall buildings to accomplish optimal land usage for providing working and living conditions for increasing parts of the population. Another important driver is the quest of governments and developers for worldwide recognition and social status. These two possible explanations will be explored subsequently.

### 4.3.1. Technological Development

The first "modern" tall building, Home Insurance Life, was constructed in 1885, making steel frame the most used structural strategy for tall buildings erection. This building was 10 stories high. Since then, technological innovations have been the major driver for building taller.

Technological developments have undergone several innovations, especially regarding those directly concerned with "constructability": innovations in foundation systems allowed for quicker and deeper foundation systems such as caissons, bored piles [123] or piled raft foundations, such as the ones used in Trump International Hotel & Tower [124] or in Burj Khalifa [125]. The structural innovations mentioned in chapter 2, along with others with special attention to the Tuned Mass Dumpers (TMD) use, allowed for structurally safer tall buildings.

However, tall buildings increasing height faces physical constraints such as the structural elements and core enlargement along with the buildings heights so it’s possible to resist the lateral loads and deal with the vertical transport issue [126].

The vertical transport system was one of the main triggers for the height increasing in tall buildings: since Elisha Otis created the safety brake mechanism for tall buildings, the vertical transportation system has been evolving, first adopting hydraulic devices, between 1880 and 1900 and after by inventing the electric elevator [16]. Currently, elevator single shafts are restrained to 500 meters height [127]. For example, Burj Khalifa elevator passengers must change elevator once reaching the 500 meters high [128] but the new Kone's Ultra-Rope system, made of carbon fibre and epoxy, allows now one single shaft elevator to reach 1 kilometer high [127].

Other less visible innovations were very important for reaching greater heights. The developments in computer analysis software and finite element method [3], along with the increasing proliferation of BIM approach [18], have allowed engineers and architects to create more freely and with more rigorous structural control [3]. Further innovations in fire protection strategies and quality control on issues such as ventilation, lighting and temperature control, facade engineering and evacuation strategies, are among other less visible innovations [18].

On the opposite side, the major challenges to face when creating even taller buildings are the real estate market and the tall buildings funding, along with the lack of natural light, as mentioned by a board of leading architectures and developers [129]. On the other hand, William Baker, the top engineer of one of the largest tall buildings construction firms, stated that, "We could go twice that or more (higher than the Burj Khalifa)", using the same buttressed core structure used in Burj Khalifa [129]. Furthermore, he also stated "You could conceivably go higher than the highest mountain, as long as you kept spreading a wider and wider base". This statement confirms that structural technology for constructing outstanding buildings is available, or at least, within structural engineers reach. Proposals for 4000 meters structures already exist, for example the X Seed 4000, shown in Figure 37, which was an utopian construction proposed to be built in Tokyo which would accommodate 1 million people [130].

As shown, structural and technological developments are happening since the first tall building was created. Hence, there are reasons to believe that tall buildings height will not be limited in the future by the lack of structural knowledge and innovation.

**Figure 37 - X Seed 4000 interior idealization ( adapted from [130])**

### 4.3.2. Ego and Social Status Quest

As exposed in Chapter 4.2.2 iconicity quest is in fact an important contributor for tall building's height race. It is not a recent phenomenon, ego and social status quest are one of the primary factors that lead to tall buildings construction, especially the world's tallest.

The social questions regarding tall building's height were evident in the New York's city ancient metropolitan and financial center in the beginning of the 20th century. At that time, New York was the economic and financial center of the world. Therefore, the biggest corporations sought to establish their headquarters there [131]. Examples of these big corporations are the Metropolitan Life Insurance (Insurance company), WoolWorth Company (retail), Chrysler (Motors), RCA Victor (Audio and Recording), Time Warner (Mass Media), Sony (Entertainment) and General Motors (Motors), just to name a few [131] ;[132]. Some of these companies established milestones in tall buildings construction because each one built the tallest building in the world by its time.

Metropolitan Life Insurance built the tallest building in the world, surpassing the Singer Building. Then WoolWorth company chairman decided to build the tallest building in the world, which was finished in 1913, motivated by Singer Building status in Europe and also surpassing Metropolitan Life Insurance Company Tower [133]. A conversation between Frank WoolWorth and his building's architect (Cass Gilbert) shows how the quest to have the most majestic and recognizable building in the world was important for the construction height [133]:

“How high do you want the tower now?” asked Mr. Gilbert.

“How high can you make it?” Mr. Woolworth asked in reply.

“It is for you to make the limit,” said Mr. Gilbert.

“Then make it fifty feet higher than the Metropolitan Tower.”

This conversation shows how important it was to hold the tallest building in the world title for the record breaking Metropolitan Life Insurance.

Some years later an obvious quest for the title of the world tallest building clearly begun: by April 1930, the Bank of Manhattan building and the Chrysler Building were being constructed. Bank of Manhattan building was concluded at that month, establishing a new record high of 282,6 meters [134]. Just one month later the Chrysler Building secretly added the steel spire pinnacle at its top [135], and became the world tallest building with 318,9 meters [15]. The race for the tallest building was not over yet, since in 1931 the Empire State Building was concluded taking the world's tallest building title from the Chrysler Building. The competition in this case was not restricted to pure height and recognition ambitions, but also involved personal facts: Chrysler was one of the biggest automobile constructors in US at that time, along with General Motors. After Chrysler erected its own building, General Motors vice president Jacob Raskob saw the opportunity to surpass its adversary, by erecting the Empire State Building [133], first adding just five floors more than Chrysler Building and then adding a mast to have a larger margin over Chrysler Building [135]. As such the Empire State Building overcame the Chrysler Building, with 381 meters high, and held the world's tallest building title for over 41 years until the World Trade Center Towers have been constructed [136]. Although this competition campaign was not public, it deserves attention the fact that, just 2 years after the World Trade Center Towers were completed with 417 meters, Willis Tower (formerly Sears Tower) was concluded in Chicago, with 442.1 meters. After this, Petronas Towers became the world's tallest building, deserving greater public attention than any other building before it, with Malaysian Prime Minister supporting publicly the buildings construction [5]. This fact clearly demonstrates the importance of tall buildings for governments as symbols of modernity and status [133]. As previously discussed, Dubai is the ultimate example of how tall buildings became the instruments to give visibility to societies, with its Burj Khalifa, reflecting an image of prosperity, growth and status.

This competition for height in tall buildings was not only reserved to the world's tallest. New York had a very import office based economy in the past, with major companies searching for central locations. At some stage land started to become scarce and led to the competition for height between "normal" buildings. This in turn led to a more expensive plot size in these central areas which directly influenced tall buildings height, as they dissipated the high cost of land acquisition in the higher incomes for having a taller building. The distance to the city center became a good proxy to measure how high should a tall building be [131].

As shown, iconic tall buildings are one of the triggers for worldwide recognition of a company or society, creating symbols of wealth and power and calling the public attention for these landmark signatures, leading to an increasing interest of politicians for its importance as a strategy for countries development [131];[133];[126].

Hence, social status and national pride quest were very important contributors for the increasing height of tall buildings, especially of the tallest ones, as they are the ultimate symbolic project that makes a company or country to be recognized worldwide.

## 4.4. Evolution of Tall Buildings Function

The common perception is that tall buildings are much more related with office/commercial use than with residential, hotel or other uses. This perception is accurate for tall buildings erected before the first decade of 2000. Since then tall buildings function has diversified. (Figure 38) represents the 100 tallest buildings in existence by function, providing a feasible illustration about the changes in tall buildings function. These results do not include education buildings, four governmental buildings and one abandoned, which were dispersed in all decades but 2010 and 2012. These buildings were discounted since they do not represent the functions idealized for the analysis.

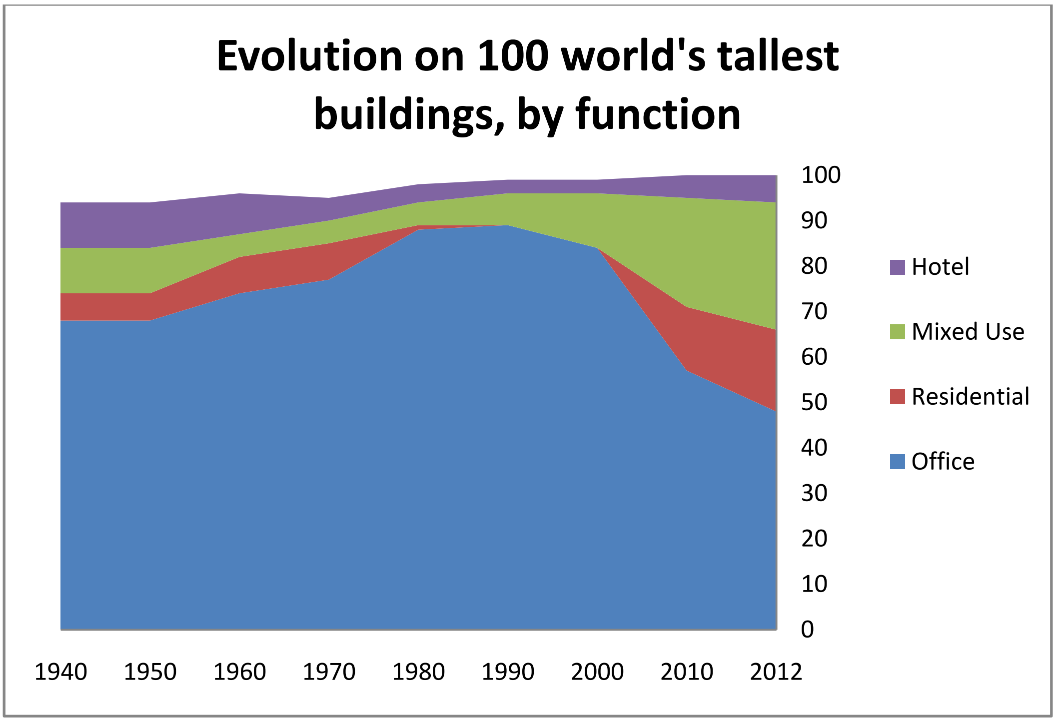


Figure 38 - Tall building's functions evolution [71]-[79]

The available literature regarding the evolution of tall buildings function is scarce, but the factors mentioned in section 4.2 , such as the increasing urbanization, are certainly leading to a new overall spectrum of tall buildings usages. Not only big corporations but also more and more citizens are moving to the city centers. Along with the diversification of the cities economical focus, which turned also to tourism and globalization, these factors are creating a new paradigm to the city of the future.

The following analysis will be carried out considering again the 100 tallest buildings as representative of the current tall buildings trend.

As previously discussed, tall office buildings remained in a stable ranking position until the 2000's decade. While analyzing the CTBUH data about the tallest buildings, it can be observed that the tallest building with exclusive office function was built in 2004, the Taipei 101 [137]. Exclusively office buildings were the major trend in tall buildings until few years ago. Before Burj Khalifa completion (mixed use building), the tallest buildings in the world were all exclusively office towers [137].

Considering the 18 tallest exclusive residential buildings in 2012,  10 of these are located in Dubai and if, instead, the U.A.E. are considered the number rises to 11, with the remaining buildings belonging to locations such as Australia (2), South Korea (3), Russia (1) and Panama (1) [138]. This is symptomatic: this tall building category is not directly connected to the establishment of big corporations but to urban population growth, or the desire to do so. Dubai is not a big metropolis in terms of population (2 million in 2011 [110], when compared with New York, Seoul or Tokyo, but this intense residential tall building industry can be framed in the previously mentioned tourism strategy. Moreover these tall residential buildings, designed with such high quality and symbolism, are made to attract the wealthiest ones (Princess Tower apartments price go from 250,000 dollars up to more than 2,500,000 [139]) thus making Dubai a fashion and elite destination.

In spite of this big "commercial facade" of tall residential buildings in Dubai, the reality is that residential purposes in tall buildings are in fact a commitment in well established cities: if the 100 tallest buildings in New York are analyzed, one observes that 12 of them are in fact exclusively used for residential purpose. If mixed use buildings with residential functions are added, this number raises to 25 out of the 100 tallest [140], which shows some concern with the big population in this city and the need to provide homes for them, in spite of the fact that some of these buildings are also accessible only to the wealthiest (rents in Eight Spruce Street Building [Figure 39] range from 2920 dollars and 12350 dollars [141]).

**Figure 39 - Eight Spruce Street Building, the tallest residential building (adapted from [142])**

Analyzing Figure 38, there are 6 exclusive hotel tall buildings among the top 100 buildings of the world. Five of these six buildings are located in Dubai (the other one is located in Bangkok) [79]. As previously discussed in Section 4.2.2, it's not a surprise that Dubai frenzy for symbolism and globalization, along with its dedication to tourism industry, led to the construction of the highest exclusive hotel buildings, although hotel exclusive tall buildings are still a small percentage of the 100 tallest in the world. Nevertheless, if the analysis is conducted considering mixed use tall buildings including hotel functions, this number rises up to 31, representing almost a third of the tallest completed buildings. This difference may be explained by two distinct factors. Firstly, tourism is a seasonal business, there are times of high occupation on hotels and others when the occupancy rate is not so high. A tall building is a capital intensive investment, hence it cannot be exposed to such external factors in order to be profitable and sustainable, and this is why joining other functions may lower the risk exposure. Secondly, tourism in the major metropolis is oriented to elites and people with a good income basis, hence major hotels are located in cities like Dubai, Hong Kong and other

Asian cities [79], which are experiencing a substantial development and becoming iconic cities.

Mixed use tall buildings now represent 27 of the 100 tallest in the world, according to Figure 38, and this option has been increasing since the 2000s. Mixed use tall buildings are becoming very important on the overall tall building market. This may be happening due to market fluctuations, business seasonality and even demographic pressure on urban frame, as previously discussed. To prevent tall buildings from being too sensitive to these factors, the inclusion of one or two additional functions may be a solution to maximize the utilization efficiency during low business periods. As an example, in a hotel/office tall building, when hotel business is in a downward cycle, the office occupation can offset the major losses that the building would have if it was only used with hotel functions, and vice versa [18]. This increasing interest in mixed use tall buildings may lead to a new concept of urban frame, concentrating all human activities in one single building, creating vertical cities, ultimately like the one mentioned earlier, the X Seed 4000, where humans would have all their activities (house, work, sports, leisure, farms, etc.) concentrated in one single building. A landmark building that is ready to be inaugurated in 2014 is Shanghai Tower (Figure 40) which, once completed, will reach 632 meters high.

**Figure 40 - Shanghai Tower, a office and hotel tall building that will be finished by 2014 (adapted from [143])**

Functions in tall buildings are changing, especially since the 2000's, and are taking a path of diversification instead of specialization. Tall buildings are losing their "stand alone" connotation of glass box offices where few people could go in.

## 4.5. Conclusion

This chapter issued a more holistic view about skyscrapers and which factors are they really dependent of. Economic reforms can make a place suitable for great investments, hence generating an all synergetic cycle between investment and development. This development creates conditions in these areas, for new companies to establish, making their brand to expand. In its turn, this will call for opportunities for common citizens to improve their life situation. This will create conditions for migration to cities, taking horizontal demographic pressure to a steam point. These two factors converge in tall buildings construction: either for host new companies seeking business opportunities and for citizens who seek a better life. On the other hand, new challenges are imposed in the 21st century globalized world. Politicians and developers aim for their cities and companies worldwide recognition, thus creating economic, trade and touristic conditions, in order to attract world's attention. Tall buildings are the used object, as few other urban pieces call for so much world attention. Although, as capital pieces, tall buildings are not immune to economic conditions. Developers are embracing, since the Great Recession, more flexible layouts for their tall buildings, making them suitable for work, leisure and housing. These three main functions compile the strands that make tall buildings adapt to economic, politic and social realities. All this makes tall buildings evolution drivers far harder to understand than their structural behavior, being possible to assess that tall buildings flow to where progress is flowing.

This chapter concluded that tall buildings are strategic-driven objects, however, pragmatic approaches about tall buildings are also being taken in some places. Some new tall buildings are constructed with a much more environment-friendly and in faster pragmatic way than lofty and breathtaking Asian and Middle East skyscrapers. It is important to understand in what this technology is based on and what could be its chances in the tall buildings construction world.

# 5. RECENT TRENDS ON TALL BUILDINGS INDUSTRIALIZATION AND INNOVATIVE CONSTRUCTION METHODS

## 5.1. Introduction

Tall buildings have been evolving in their most superficial characteristics. However, one can observe that no major improvements in the construction methods have been occurring. Tall buildings remain heavy weight constructions, taking large amount of resources like labor, materials and capital. This approach of the last 100 years needs to be altered. An alternative way to build tall buildings is necessary, either because of the resulting environment hazards, the need to reduce construction cost and to confer faster adaptability to changes in cities demographics. As an answer to this requirements, a more logical and pragmatic approach may arise in tall buildings construction, stepping aside the iconic motivation and the flamboyant structures. . This approach will require new technologies and procedures for faster and more efficient construction and the adoption of environmentally friendly solutions. Nowadays it is believed that these requirements can be ensured by the inclusion of pre-fabricated and modularization processes in tall buildings design.

After analyzing the structural trends in tall buildings (Chapter 2), how macroeconomics influence tall buildings construction (Chapter 3) and how tall buildings evolution has been influenced by other exogenous factors (Chapter 4), this final chapter will focus on new construction methods. These new construction methods will focus on pre-fabrication and modularization as alternative means to construct tall buildings.

## 5.2. Prefabrication as a Sustainable Tool for Tall Building Construction

Prefabricated techniques were first introduced after World War II in Europe to rebuild cities and its buildings. In 1996, the worldwide leader in prefabricated technology application was Denmark [144];[145]. However in Denmark the application is not so much on tall buildings.

The literature shows that the main center of tall buildings construction using pre-fabrication techniques is located at Singapore and Hong Kong [144]-[149].

Precast concrete is the process where a concrete element is casted out of its final application site, whether it be a few meters away of the its final position or in a factory controlled environment [144]. Attention must be paid to the definition scope of prefabrication: prefabrication, preassembly and modularization are terms which use often depends on who is using it and his experience on the field [149]. In the context of this research, prefabrication will enclose all the concepts above presented except modularization, which will have its own section.

Hong Kong has been experiencing, along with other Asian cities, an increasing housing demand, which led to massive house construction under the public housing programs, which in turn resulted in the adoption of prefabrication since 1980s [144];[145];[148]. However, prefabrication was not extensively used by private construction sector until 2001, when governmental actions and mechanisms stimulated the wider use of prefabrication processes in high rise residential buildings [144];[145]. The prefabricated elements which are more frequently used in tall buildings construction in Hong Kong are made of concrete and include: hollow-core walls (these walls are prefabricated in order to achieve lighter elements which enable the easier vertical transport), wall panels, precast facades, staircases, parapets, semi-precast slabs and even volumetric units of bathroom [144];[145];[147];).These elements are ordered from a manufacturer or casted on the building site.

### 5.2.1. Key advantages of prefabricated elements utilization

Several advantages can be identified from the use of prefabricated elements in tall buildings. Research studies have identified some of the main advantages of using prefabricated elements in tall buildings, especially among Hong Kong residential [144];[145];[146];[148]:

- Waste reduction;
- Faster construction process;
- Improved quality of elements;
- Improved construction safety;

- Less noise production;

When considering the waste reduction, onsite the major material waste comes from the concreting process. Waste can be generated either from "direct" pieces concreting, like surpluses and spilled concrete, and when the finishing works are ongoing. Rebar cuttings and shuttering timber boards are also great waste generators. When the concreting processes are moved to a factory controlled environment, the waste production is significantly reduced. Moreover, when dealing with large concrete parts, like precast facades or wall panels, the necessary finishing is also made out of the construction site, which leads to other significant waste reduction [150].

The construction process is accelerated by the discretization of works. By splitting the independent procedures (for example: production and assemblage of elements) for factory and building site crews, respectively, the efficiency is increased because each entity is responsible for a finite and well determined number of tasks, thus eliminating the redundant work.

[145] have analyzed the quality of produced elements when using prefabrication and the main conclusion reached was that the quality of the produced elements was clearly improved. The fact that the elements are manufactured in a controlled environment, with proper equipment and organization, allows for a continuous and  industrialized production process [146], while in construction site the products quality is highly dependable of other variables [145]. Moreover, when delegating specific works to external entities, the contractor also loses its risk on elements quality assessment, passing that risk to the sub-contracted manufacturing crews, thereby having fewer obligations in the final overall quality of the building [151]. Construction safety is also improved due to works delegation: if critical works are removed from the building site (concreting operations, rebar cutting operations, etc.) there will be further improved safety conditions [146]. Coupled with this, the prefabrication on assembly lines will decrease the number of lifting operations, thus enhancing safety too. The reduced number of on-site workers, , will also contribute for improved safety on the building site because of disorganization avoidance.

### 5.2.2. Limitations and challenges of the utilization of prefabricated elements

Despite the key advantages previously identified, prefabrication also entails some limitations and challenges. Some of these are [150];[148];[152];[145]:

- Longer time for design;
- Higher initial cost;
- Construction site space and elements weight dependency;
- Possible higher fragmentation of works;

Prefabricated construction requires longer time for designing, planning the construction sequences and carrying out the procurements and approval procedures [149]. Planning cranes, teams allocation, and materials delivery and provision are also coordination issues that call for the construction actors attention [150].

Initial cost is generally much higher than in the case of in situ construction. Some of the causes are: the need for specialized areas for storage of the prefabricated elements [150], the cost of elements manufacturing [146], the transportation costs and the overall logistics with materials [144], man-power and coordination. This higher initial cost is mitigated by the smaller construction crews on site and faster construction processes, which will decrease the overall cost [150].

Construction site dependency is one of the major limitations of prefabrication technology. The need for large storage spaces can be an eliminating factor when choosing between cast in situ and a prefabricated construction. For ideal construction conditions, construction site space would not be a problem, as long as perfect coordination between delivery and assembly at the building would be achieved by creating a continuous chain of supply/assembly [144].

The advantages of prefabrication (work delegation; team coordination) can become its worst shortcoming also. If there is lack of interoperability between different construction development fields, this can lead to problems in coordination of works between the pre-fabrication and the assembly responsible teams [152].

Prefabricated elements have been mostly used in public house and private residential projects, thus excluding office. This is not a coincidence: office towers very often contain a large open plan design and long spans to ensure few columns are placed inside the rentable area. This will ask for deep beams to hold loads, which are not compatible with the prefabrication requisites of transportation and low weight components [146].However, more recently this has been possible to achieve by transporting the lateral load resistant structure to the elevator core, allowing the remaining frame to carry only vertical loading. The elevator's concrete core is typically made of cast in-situ concrete, which becomes critical in the fast construction approach of pre-casting, although the suitability of a precast concrete core construction has been recently studied [151]. This study found that a precast concrete core only leads to 3,3% more lateral displacement than a cast in situ core at an equivalent height [151].

The high repetition rate along the floors is necessary to make the prefabrication profitable [144]. Hence very standard design of floors along building's height is required, leading to a very rigid pattern on architectural and structural arrangement [147];[150]. This highly standardized construction is suited for housing and "common" residential buildings [150], however, it is not suited for magnificent land marking tall buildings.

## 5.3. Modularization in Tall Buildings

"Modular construction is a manufacturing process defined by the use of prefabrication and preassembly at a remote location to compose volumetric components (modular structures) which are transported as largely finished components to a building site" [153].

Modular construction allows to increase the speed of construction, the quality, the economy of scale and to reduce waste [154]. To achieve these merits, volumetric parts are manufactured in a controlled factory environment, allowing precise works protected from weather conditions. The modular manufacturer transports the volumetric parts to the building site assembling them and erecting the whole building. Speed of construction is achieved mainly because this construction system allows for parallel works to occur on the building site while the volumetric parts are being manufactured. For example building site preliminaries, foundation works, etc., can happen while manufacture is happening, enhancing construction time efficiency as shown in Figure 41[155].

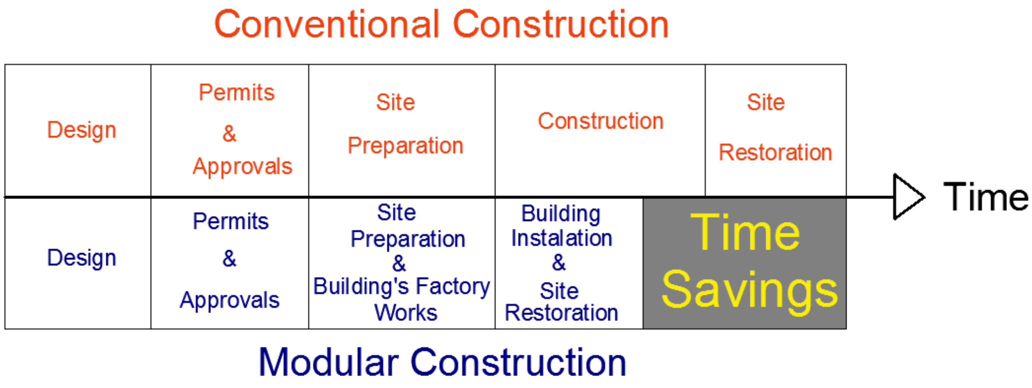


**Figure 41 - Time savings in Modular Construction [155]**

Modular construction is not an impressively new approach but the upgrade of a well known construction type. The ancient remarkable modular building, Chrystal Palace, was built for the Britain's Great Exhibition of 1851 using modular techniques, which allowed it to be built in few months and dismantled afterwards to be assembled in another location [156]. In 1900s, modularization was started in U.S. by Sears and Aladdin companies: their modular houses could be ordered via mail, and the client would receive a complete kit of parts to assemble the house. Massive modular fabrication was later achieved, first during the World War II to accommodate military functions and later, in Europe and Japan, to reconstruct devastated cities [156];[157].

In spite of being a technology known for decades, current improvements in automation, materials and computer technology, such as Building Information Modeling (BIM), offer a new impulse to the adoption of modular construction. The stigma of cheapness and poor quality buildings may be changed, taking advantage of new productive and efficient technologies [157].

### 5.3.1. Factory, Transport and Onsite Operations

What distinguishes modularization from conventional construction is how the construction project is developed. Once the architect's design is finished, the building's plans are sent to the manufacturer and, depending on the design details, the largest possible number of finishes can be provided right at the factory (Figure 42), allowing the 60%-90% finish level [158]. However, the services that the manufacturer can fulfill depends on its own level of experience on this industry. The factory production is often lead by lean construction methods, which allows for the reduction of wasted materials and promotes integration and collaboration between all the stakeholders on the project [157].

**Figure 42 - Factory environment on modular construction (adapted from [159])**

Modules' height, width, length and weight are all influenced by the normative rules of road transportation [153] and by the truck physical limits as well (Figure 43). The amount of restrictions lead to a feasible transport distance limit of around 600 kilometers from the manufacturing site [160]. Thus, the managing of all constraints to find a feasible solution for the transport planning can be critical for the adoption of modular construction. Moreover, the location of the construction is important too: depending on the location, rural or urban building site, the transports will face other constraints such as local traffic, lack of parking space, etc. Ultimately, this will constrain even the volumetric modules layout [153]. Thus, one can assume that transportation constraints are critical for modular construction adoption.

**Figure 43 - Truck Transport of a Modular House (adapted from [161])**

After factory and transport issues are overcome, the onsite works are the final part of a modular construction. When the modules are finished in factory they are shipped to the site and coupled ones in others, and onsite works are used to provide finish works that could not be done in factory environment, such as cladding and roofing and big internal spaces [158]. Often, MEP connections, interior finishes and exterior finishes are also completed at the building site [156]. One major detail that should be addressed when planning construction on the building site, is the crane systems and operations: as cranes are one of the more expensive part of the final set, its work load must be carefully planned, in order to achieve maximum efficiency along the time that's in the building site [160].

### 5.3.2. Decision making process

The modular construction project is composed by 4 stages: the first is about design and regular approvals, the second is the module components assembly in factory, the third is the transport operations to the building site and the fourth is the erection of the modular units to conclude the building [155].

One of the fundamental characteristics of modular design is that, often, clients seeking modular solutions have to coordinate their ideas with the manufacturer. Modular construction is about standardization from the beginning and clients' projects have to be compatible with the volumetric templates that the industry has to offer and not vice versa [162]. Some of these limitations are imposed by manufacturers not only because of economy and compatibility on the factory but also because of economy of transportation [154].

In spite of these challenges on modular design, an increasing number of companies are trying to embrace modular construction in their projects catalog. The primary drivers are the improved productivity (through project schedule reduction and project budget), competitive advantage, greater Return On Investment (ROI), owner/client demand and the modular green features, as shown in Figure 44 [157].

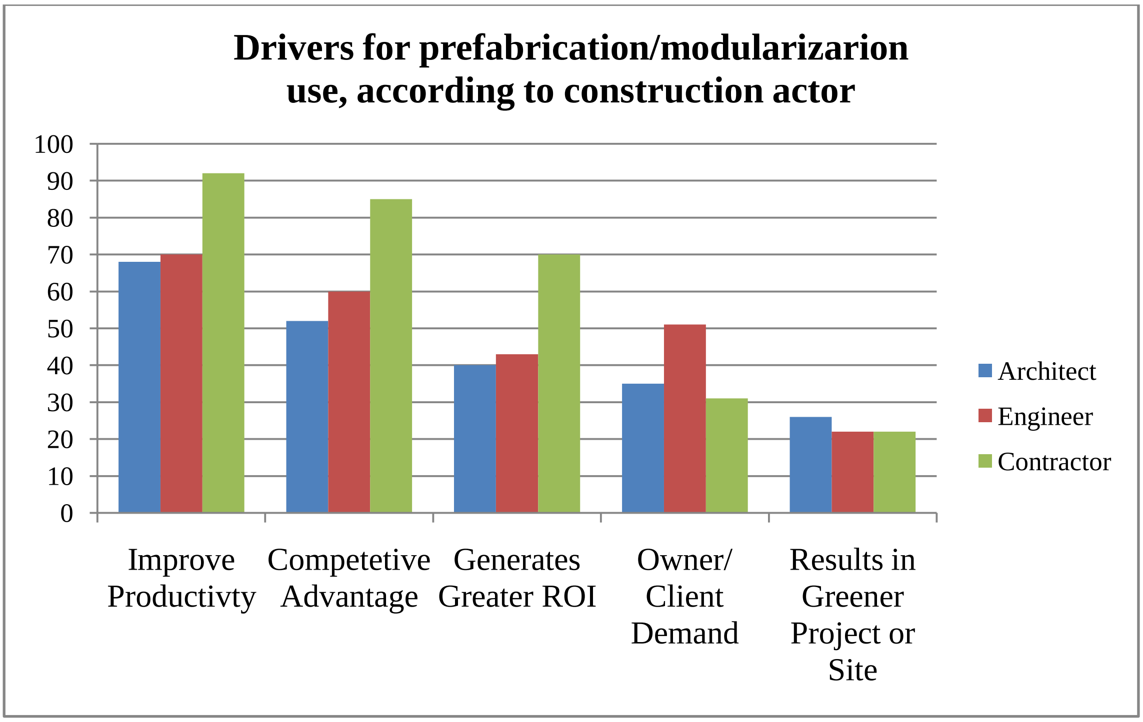


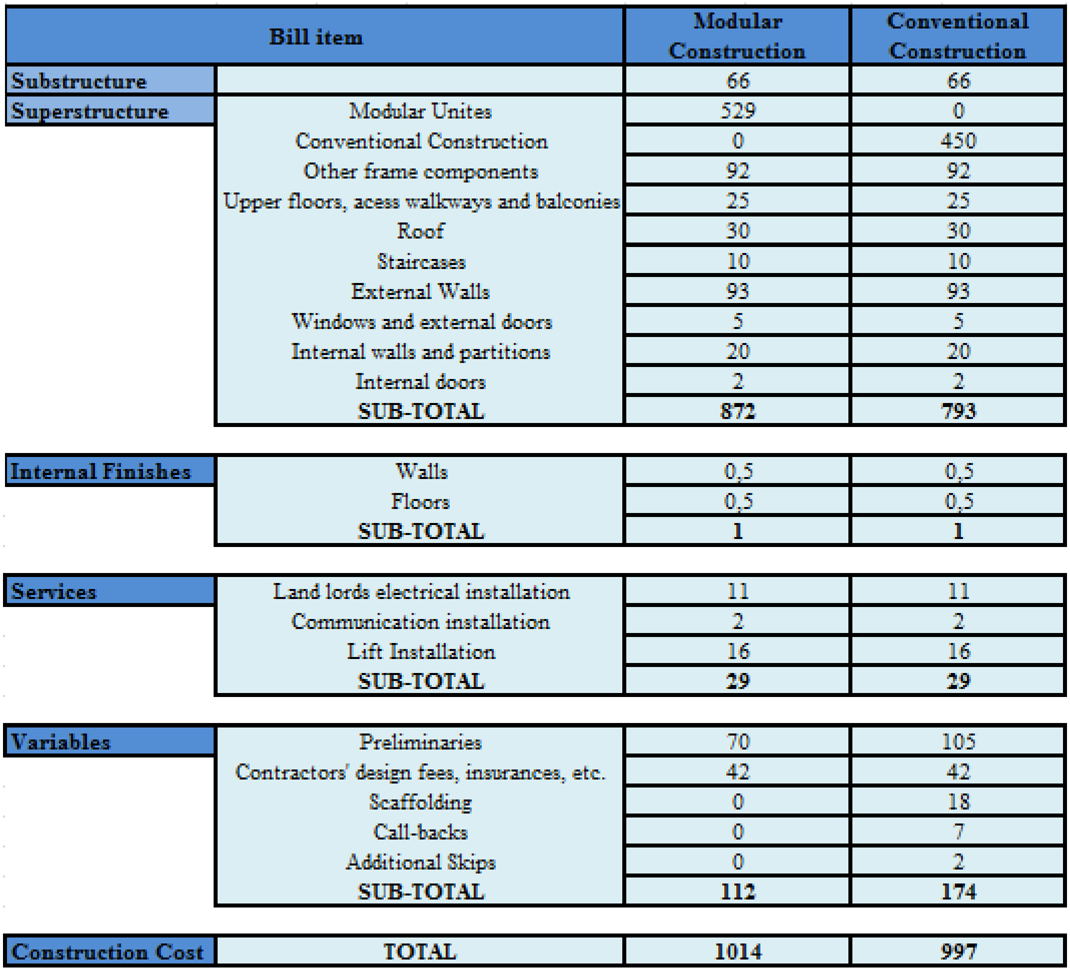
**Figure 44 - Current Drivers to use prefabrication/modularization [157]**

Due to its repeatable volumetric units, modular construction fits better in projects which also involve a high degree of repetitions and standardization such as hotels and multifamily projects [156];[163].

### 5.3.3. Modularization Advantages and Limitations

The most visible advantages of modularization are the following **[**154];[157]**:**

- Project schedule reduction: reduced site preliminaries, construction program is more controlled; simultaneous work on-site and off-site improve time rentability; weather impact control;
- Project budget reduction: reduced on site work leads to lower costs even if modularization tends to be more expensive at the onset of the project (Figure 45); extra costs due to delays and unexpected situations are avoided; as building is finished earlier, owner has a earlier return on investment;
- Quality issues: reliability on factory quality process; manufacturer procurement induces a major responsibility on prefabricated elements; experience by the manufacturers in modules construction and testing;
- Site safety: the reduced need of on-site works largely reduces the risk for accidents to happen because there are no scaffolding or tight spaces to work in, but, even with works on site, the standard works of elevation and fixation of volumetric elements enhance a systematic approach which reduces risks for workers;
- Waste reduction: factory production enhances productivity which turns on improved waste management; reduced on site work reduces local pollution hazard; remaining factory steel waste can be recycled;



| Bill item | | Modular Construction | Conventional Construction |
|---|---|---|---|
| **Substructure** | | 66 | 66 |
| **Superstructure** | Modular Unites | 529 | 0 |
| | Conventional Construction | 0 | 450 |
| | Other frame components | 92 | 92 |
| | Upper floors, acess walkways and balconies | 25 | 25 |
| | Roof | 30 | 30 |
| | Staircases | 10 | 10 |
| | External Walls | 93 | 93 |
| | Windows and external doors | 5 | 5 |
| | Internal walls and partitions | 20 | 20 |
| | Internal doors | 2 | 2 |
| | **SUB-TOTAL** | **872** | **793** |
| **Internal Finishes** | Walls | 0,5 | 0,5 |
| | Floors | 0,5 | 0,5 |
| | **SUB-TOTAL** | **1** | **1** |
| **Services** | Land lords electrical installation | 11 | 11 |
| | Communication installation | 2 | 2 |
| | Lift Installation | 16 | 16 |
| | **SUB-TOTAL** | **29** | **29** |
| **Variables** | Preliminaries | 70 | 105 |
| | Contractors' design fees, insurances, etc. | 42 | 42 |
| | Scaffolding | 0 | 18 |
| | Call-backs | 0 | 7 |
| | Additional Skips | 0 | 2 |
| | **SUB-TOTAL** | **112** | **174** |
| **Construction Cost** | **TOTAL** | **1014** | **997** |

**Figure 45 - Quantity bill for a typical 4 storey residential building in London [154]**

On the other hand, some limitations are still holding back a broader use of construction modularization. These are not immediate disadvantages, but rather some stereotypes that modularization still has to overcome. As shown in the Figure 46 some examples of these challenges are the need to have architects and owners more aware of modularization advantages, the need of more prefabricated elements suppliers and the association of modular homes to people with low incomes and low quality house components.

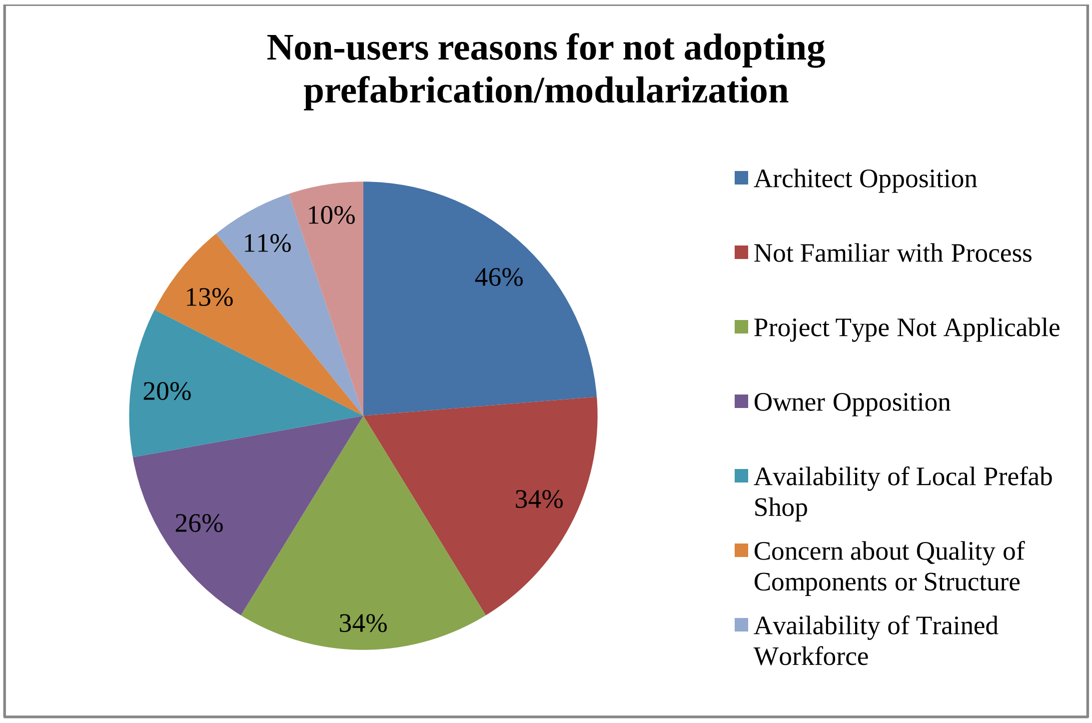


**Figure 46 - Non users reasons to don't include modularization in their projects [157]**

### 5.3.4. Design of Modular Tall Buildings

Modular construction still has a meaningless expression on tall buildings, mostly due to the resistance of traditional tall buildings developers to embrace the change. Detailed structural analysis studies are still necessary to optimize and validate the available solutions, although some projects of tall buildings were already successfully implemented using modularization. The modular buildings are constructed through the assembly of several components. Therefore, the structural design of these modules is closely linked to their manufacturing process, creating two main types of modular structural system [163]:

- Load bearing modules, where vertical loads are transferred by the perimeter walls. The wall sections are normally constituted by "C" steel sections, and its compression resistance governs the section dimensions [164]. Current heights of these buildings are limited to eight stories [165];
- Corner supported structures, where the vertical loads are transmitted by the perimeter beams to the columns. These perimeter beams are normally deeper than the load

bearing modules [163] and they are often constituted by steel Square Hollow Section (SHS) [164]. The building's height is only limited by SHS size [165];

Due to the low range of different module templates available, the whole structural arrangement will be tied to an "orthogonal commitment" and consequently, two major buildings' layouts are more common [164]:

- A closely square layout, where the modules are accessed from the central elevator/stairs core, or from small corridors closed to the core (Figure 47a)) [164];
- A rectilinear layout, where modules are accessed by corridors than run the entire width of the floor layout (Figure 47 b)) [164];

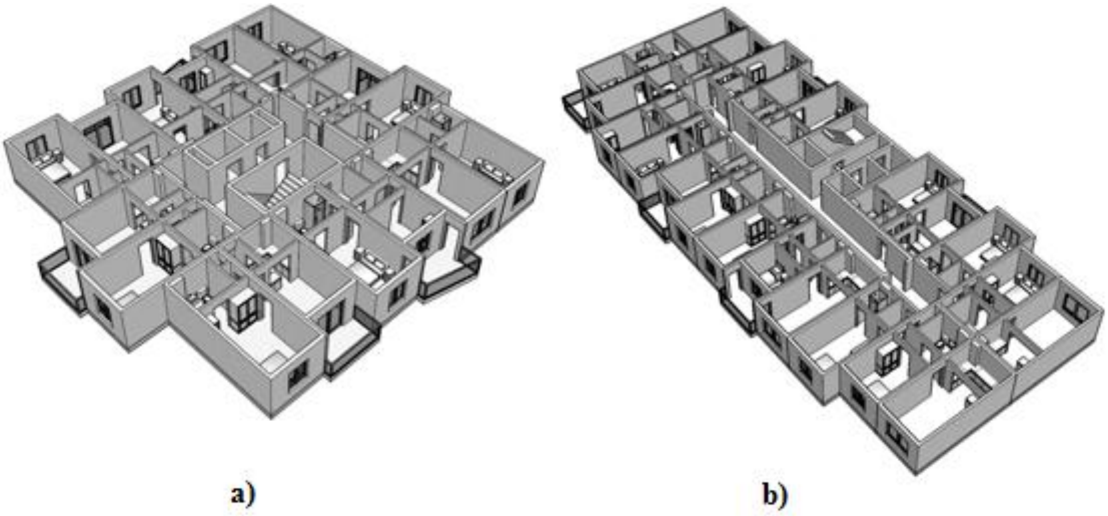


Figure 47 - Generic modular buildings' layout (adapted from [164])

In case modular tall buildings require a horizontal resistant scheme, there are several options available, some of them already mentioned and discussed in Chapter Two. As a consequence, the height of modular buildings is not limited by the horizontal load carrying capacity.

The most common strategy for horizontal load carrying capacity in modular buildings consists on the adoption of bracings in inner walls (Figure 48) or the simple diaphragm action of exterior walls. These strategies are only suitable up to 6 stories high [164]; [165].

**Figure 48 - Corner supported module (reproduced from [164])**

For buildings from 6 to 10 stories high, a more convenient structural strategy consists on the adoption of a separate steel braced scheme, located on the elevator and stairs areas [164];[165]. For higher buildings, the structural system usually adopts a hybrid solution consisting of a reinforced concrete core, providing the horizontal resistance, connected with the modules which provide vertical resistance. Horizontal load transfer from the farthest modules to the core is guaranteed by in-plane trusses placed along the corridor walls [165]. The distance between the farthest module and the core is ruled by the shear force transfer capacity of the trusses [164]. Often, for buildings taller than 10 stories, a podium structure is normally attached on the lower floors, enhancing greater flexibility in buildings height an internal planning [163]. This podium normally consists on a structural "base" which can be used as car-parking sites, made of steel, where the habitable modules are lied on. Another alternative structural system consists on applying a lateral bracing to the building core and place structural columns on the building's perimeter [156].

In all these systems the modules are coupled through the corners so they act together on resisting to lateral loads. This system provides redundant load paths in case of damage and the structural integrity is ensured [165]. Special care must be dedicated to the accidental eccentricities resulting from installation and construction. Small eccentricities have large effects on reducing failure load [165]. Also second order effects, due to modules displacement, have significant importance in design process [164].

Modular buildings require a certain degree of standardization and repeatability to be profitable. In contrast, this is not the typical pattern on tall buildings with open facades, sky lobbies, open areas, etc. For tall modular buildings to become competitive with the remaining tall buildings industry, modular systems have to be flexible to incorporate new materials, high ends and broader floor layouts. These improvements should be achieved without losing modularization competitive advantage of time and economy [156].

### 5.3.5. Modular Tall buildings

Modular tall buildings are still uncommon, as shown in following Figure 49. But a few examples demonstrate that modular construction is an option to be considered. Modularization is most applied in healthcare facilities, higher education and manufacturing buildings. This happens maybe because these three kinds of buildings are the ones which have the greatest standardization basis, making them the best suited for modular construction. Three brief examples are shown as paradigmatic examples of modular tall buildings construction: The Paragon project, west London [164], Victoria Hall, in Wolverhampton and the Atlantic Yards project in Brooklyn, New York.

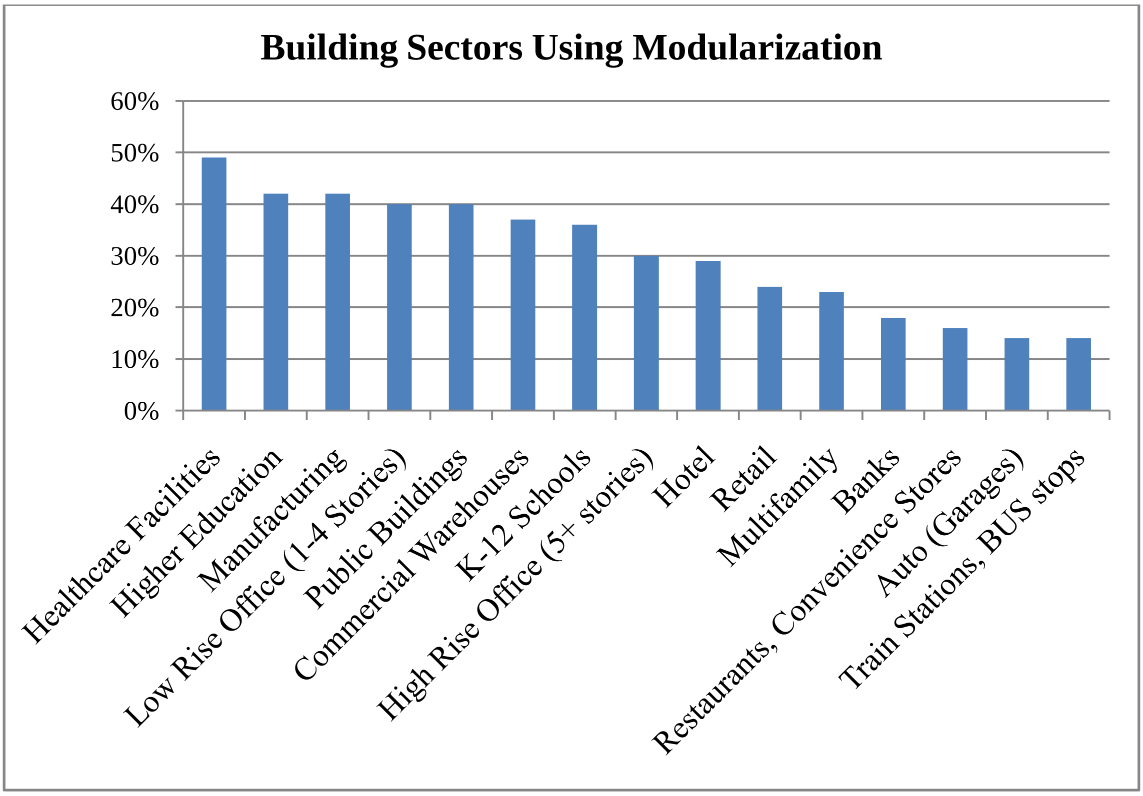


**Figure 49 - Building sectors using modularization [157]**

Paragon building in London is a tall modular project, the tallest tower is 17-stories high. Its modules are built with corner post resistant strategy, thus columns are built in the corner of each module and the floor rests on deep beams running through the modules perimeter. The horizontal load strategy is based on a central concrete core. The floor layout has an "L" shape (Figure 50), with the concrete core staying at the middle of the floor plan. A bracing system was adopted along the corridors and these were manufactured as a part of each module, in order to distribute the horizontal load from the outer modules to the core [164].

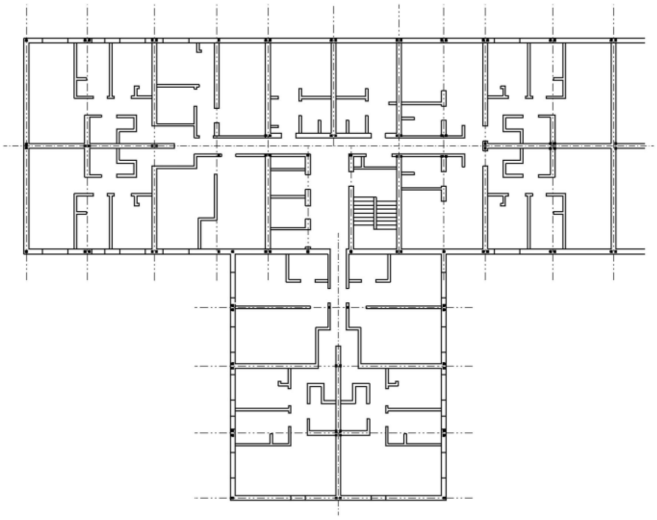


**Figure 50 - Paragon development floor layout (adapted from [164])**

Victoria Hall (Figure 51) in Wolverhampton, UK, is another example of the adoption of modularization on the construction of tall buildings. It consists of a student accommodation development [166] built from July 2008 until August 2009 and is 25 stories high. The modular technology employed in this building saved 45% of the construction time, when compared to the construction using traditional means. The total project consisted on 824 modules which took 32 weeks to assemble, with teams of 8 workers and 2 site managers. Together with the manufacture teams, this system allowed for savings in labor force of 36% in manufacture, 9% in transport and 55% in the construction of the rest of the building.. The manufacturing waste reduction decreased the need for landfill by 70% [164].

**Figure 51 - Victoria Hall tallest building (adapted from [167])**

The third example discussed in this research is the Atlantic Yards project, in Brooklyn, New York. When finished, it will have a main tower 32 stories high and it will be the world's tallest modular building. Atlantic Yards encloses diverse valences, such as the residential units, a sports and entertainment area, office and retail space (Figure 52) which is expected to cost 20% less than what it would by traditional means. The modules resistant structure is corner supported and will be almost finished in factory, including all the MEP systems, interior and exterior finishes. The building has central cores for lateral resistance but, as this building is higher than any other constructed before, steel bracing was necessary to couple modules and transfer vertical loads downward without depending on the concrete core. The 6430 modules dedicated to housing and retail space push the economy of scale to a new level [156].

**Figure 52 - Atlantic Yards full project render (reproduced from [168])**

## 5.4. Case Studies

Two case studies are presented in this sub-chapter. Tall buildings have been evolving for more than 100 years, preserving essentially the same construction methods and varying the structural schemes and architectonic features. The following case studies are presented as the two major achievements of industrialization of tall buildings construction. Hence, these achievements may represent the first two examples of a completely new era in tall buildings construction, marking the beginning of an innovative type of construction, just like the Home Insurance Building did in 1884.

The first case presented, Hotel T30, is a complete new product of construction innovative technology, and the second one, the Sky City, may establish a new pattern in the way how developers realize cities and their organization.

### Hotel T30

Hotel T30 is a modular tall building, in China, constructed in the end of the year 2011. This building became worldwide famous due to the time-lapse video released by Broad Sustainable Building (BSB) in the beginning of 2012, showing the entire building construction evolution. As shown in the video, the 5-star hotel was built in 15 days, which is by it-self a remarkable achievement for modular tall buildings, taking the modularization and industrialization buildings as really option in the near future. All the construction process, as it's possible to see in the video, is revolutionary: the building is composed by series of "main boards" including floor and ceiling, made in factory and which embody the internal shafts for lighting, water supply, water drainage and ventilation. Then, still in factory, all the needed structural elements such as columns and bracings, as well as architecture features as doors, windows, walls and sanitary equipments, are placed along with the main board, making a "floor block" which is transported (Figure 53) by a single truck to the building site [169].

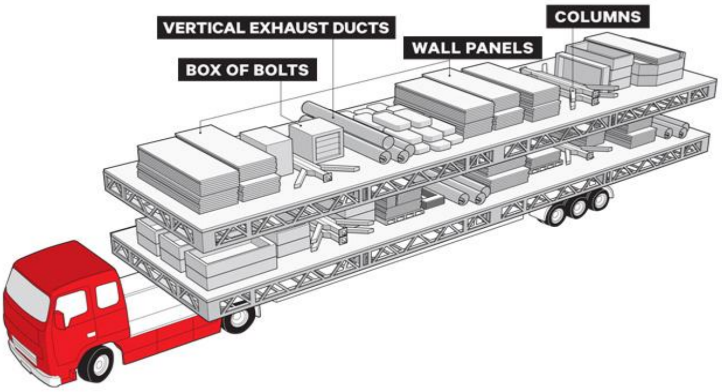


**Figure 53 - Standard Floor Block composition (adapted from [170])**

The building is almost completely made of steel (Figure 54), reducing the amount of concrete by 80% when compared to a traditional building. This induces a structural innovation: as buildings go taller, there is the need to stiffen them for sway and displacement control. This typically requires a concrete stabilizing concrete core. In Hotel T30, the resistant core is also built in steel, which could create problems in terms of sway under wind or earthquake load. However the building structural design was proven to be even more efficient than other classical systems of tall buildings: hotel T30 structural model proved to resist to a 9 Richter magnitude earthquake. Additionally, the building's floor span is of 7.8 meters, much more than 3,8m-5m of conventional building. The life span of the building was also designed to be monumental: the expected building life span is about 600 years [169].

**Figure 54 - Hotel T30 steel construction(adapted from [171])**

But the most important characteristic of Hotel T30, according to the developer, is the environmental performance of the building: Hotel T30 has an energy consumption footprint of 2,2 million kWh a year, which compares to the11 million kWh of a typical 5 star hotel . This significant energy saving is the result of: the 15 cm thick rock-wool insulation and 4-paned windows, the energy savings with air conditioning , the lower needed of electricity for lighting, , the power generation technology during up and down travels in elevators, the LED lighting, among others. Construction waste reduction is also remarkable, with a generation of just 1% of the waste produced in normal buildings site [169].

However, apart from the buildings' propaganda machine, two factors are not taken into account and certainly had influence on the feasibility of such revolutionary building: location and architecture. It is possible to verify in the time-lapse video that the building is located in a very remote area. As previously discussed, this provides much more flexibility in construction logistics and operations. The space constrains are minimum and the necessary precautions towards urban conditions such as traffic, noise regulation and night works are minimal. Hence, the major constrains that the construction of urban tall buildings face are not present in this case. The prefabricated elements were very quickly transported, could the trucks were allowed to stay waiting for their turn to deliver their load easily as there was no need for time control by public authorities and there was enough space for safe works. The real challenge for this company and for this innovative construction system is to reproduce these results in a very crowded urban area, the typical habitat of tall buildings.

The other factor is related with the architecture. Modular/prefabricated elements need to have a certain commitment with orthogonal shapes, in order to be economically feasible. Hence, in the case of this revolutionary pre-fabricated building, this commitment is further increased. Hotel T30 has a purely square configuration that may become aesthetically uninteresting and monotonous, which is not compatible with the current state of art of tall buildings. Moreover, in order to build the hotel lobby, an awkward pyramid was attached at the building's base [171], creating a very unpleasant effect in terms of the overall building aesthetics.

Hotel T30 was the first of its kind being built. Much marketing interest were coupled with this building construction. One can think that the major achievement for BSB was not the building for itself but the recognition that this company had worldwide. Either way, T30 proved to be possible to build in super-fast time a building with little more than 100 meters high. Despite the fact tall buildings have inherent worldwide architectural recognition needs, this improvement in construction technology enhances a way for architects, developers and even politicians to embrace a new paradigm in construction. This paradigm may arise within few years, when horizontal city limits are near to rupture and it's required to accommodate people coming to cities and in increasingly growing number. As possible cities' future infrastructures, tall buildings will need to be also increasingly cheaper. This feature is also provided by prefabrication and modularization, hence, Hotel T30 with its reduced cost and fast construction may become an example to  be followed by developers who need to build cheap, but with quality, in the future. Again, buildings' location issues will be a handicap for prefabrication and modularization. Even if there is a complete shift in the way how tall buildings are addressed, if there are "spatial" constraints, the shift will need to extend even until the own cities laws about traffic organization and products transport. Another way to overcome these problems is to realize different means of transport the building's components, like making components ever smaller and lighter or even find a cheaper way to transport those as they are manufactured nowadays.

## Sky City

The Sky City is the gigantic building project proposed by BSB to become the world tallest building when completed, reaching 838 meters high and surpassing the Burj Khalifa by 10 meters (Figure 55).

**Figure 55 - Sky City render (adapted from [172])**

After de success of Hotel T30 construction, BSB propose itself to built the tallest building in the world, setting another mark on construction time: 90 days [173]. The main feature of this building would be the one that BSB already announced with Hotel T30, that is the sustainability. The measures undertaken to pursue this objective were: the adoption of 20 cm thick insulated walls and 3 paned windows, exterior window shading for energy conservation, a power generation plant using waste heat [174] and the energy producing elevators [173].

These sustainability features allow BSB to state that this building will be 5 times more efficient than conventional buildings [174]. The building is expected to include 5000 residential units, one hotel, one hospital, five schools and office space, housing 31000 people [172].

Similarly to Hotel T30, not much documental information exists about the Sky City, which is leading several engineering specialists to question the feasibility of this project [175]. The most important questions concern fire security, horizontal loads strategy, the building's cost and construction time [173];[175].

Fire safety and evacuation are among the most important worries: a Chinese architect stated that "China's best fire-fighting equipment and technology can do nothing for a fire above the 70th floor" [176]. Other specialist stated that " with so many people living and working in the building, there will be risks everywhere" [173].

Horizontal load strategies (Figure 56) are also a concern because, similarly to T30, the Sky City's model was also tested for earthquake resistance and also proved to be resistant to a 9-Richter's magnitude earthquake [176]. However, about wind load there is no available information, leading some specialists to question about the true strategy, or if there is any [175].

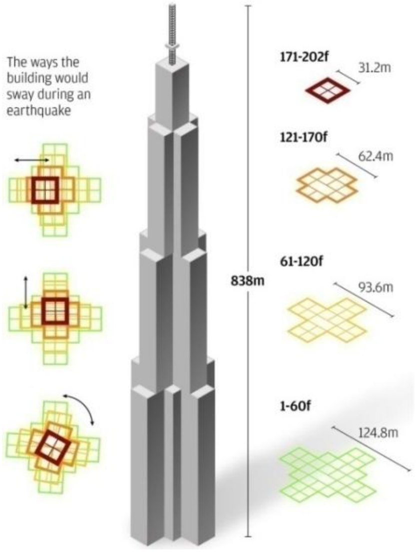


Figure 56 - Sky City's floor plan and sway movements (adapted from [177])

The building cost is also questionable because the price is set to be nearly half of the current world's tallest building cost, Burj Khalifa. Bart Leclercq, skyscrapers structural engineer, stated "The Burj Khalifa is all about the stiffness and the strength. The skyscraper is a structural element - it is a pin stuck in the ground. If you are saying you can do it for half the money I don’t believe that is the case. You have to pay for every cubic meter of concrete that goes in there - that’s what your price is based on.” [178]. The comparisons with Hotel T30 are dangerous because in this case the building was 100 meters. The Sky City is a test that cannot fail, so all the processes since the design to construction techniques must be carefully planned and not simply extrapolated from Hotel T30.

The construction schedule has suffered systematic halts and delays: in the first setup of the building BSB said that it would take 90 days to be built and it would be started in November 2012 and finished by January 2013 [175]. However, the construction starting date was delayed to March 2013 and the construction time was also changed, from 90 days to 7 months [179]. Then the construction starting date was changed again and the groundbreaking ceremonies happened in July 2013. The building was set to be finished in April 2014 [177], but just four days after the groundbreaking the construction was halted again, apparently due to a delay on  government permissions [179].

Given all these delays and the lack of a systematic and confident working progress, it is clear to see that many things are already going wrong about the Sky City construction. The next months will be crucial in order to understand if China will really break a technological barrier or if Sky City was just propaganda used by BSB to put themselves on the map.

Sky City has not been a so successful project as Hotel T30 was. It's construction has always been involving in controversy and lack of credibility by experienced people in skyscraper engineering. In any case, Sky City has reborn the concept of vertical magnificent city, first supposed in the X Seed 4000, where a city is enclosed inside a building. If Sky City's construction is ever completed, certainly many cities, especially in the Asian continent, will think about the feasibility and the human sustainability of such project. Consulted specialists have claimed for the risks of such project, but, if cities get to such a rupture point and the risks are overcomed, Sky City might become the prototype of future cities, where people work, live, learns, get amusement, etc., in the same vertical space. Not mentioning the psychological effects of such option, the reality is that it seems increasingly likely that future cities will be like Sky City, due to the ever more migration to cities, the need to contain urban sprawl and even the environment benefits of such option. Again, like in Hotel T30, building's architecture and location is not object of pride for BSB: Sky City will be located in a remote area and architecture is purely orthogonal, in spite of the cross sections variations along building's height. Sky City has many challenges to overcome and proofs to provide: it's wind strategy is unknown, which is a great handicap in terms of structural engineering innovation recognition, it will be constructed not in one of the major cities in China and in a not-inhabited area, which doesn't deal with logistical cities' issues and finally still needs to prove that it's safe for human full time occupation.

## 5.5. Conclusions

This chapter addressed the recent trends on the use of the prefabrication and modularization in tall buildings.  Prefabrication and modularization are in a quest to become feasible options on tall buildings construction. Tall buildings evolution in terms of structural technology and superficial features ignored the evolution in terms of constructability and efficient construction measures, opening space for prefabrication and modularization to offer a new paradigm on tall buildings construction.

Although still considered as low range options, prefabrication and modularization have indeed strong chances to become important innovations in the construction of tall buildings. The necessary commitment with floors' standardization, the fewer options on elements diversity available (prefabrication) and the transportation logistics issues in the case of modularization are clear drawbacks in these technologies. Nevertheless, the research carried out on the integration of prefabricated elements in resistant structural schemes of tall buildings seem to indicate that prefabrication as not yet reached its full potential. Growing implementation of modularization on tall buildings is also attesting the suitability of this technology, regarding tall buildings. The time saving feature of this technology, coupled with its virtues in terms of environmental and overall construction cost reduction, certainly will be taken into consideration in future constructions. In a changing world the need of faster and cheaper construction seems to be central, where prefabrication and modularization seem to be perfectly fitted. Furthermore, the improved quality of products and the safer construction sites also provide a strong motivation for the implementation of this technology.

Tall buildings have witnessed evolutions in their structural systems, "comfort" technologies and superficial features. Constructability has been disregarded, since conventional construction was mostly focused on accomplishing the most outstanding skyscrapers. However, constructability might be the next great revolution in tall buildings, and the way how they are constructed may become one of the most important evolutions. Furthermore, fast and cheaper construction might be the ultimate thrust to realize the concept of vertical cities of the future, like the Sky City  seems to state.

# 6. CONCLUSIONS

## 6.1. General Conclusions

Innovation on structural solutions and the development of new ways to build ultra-efficient, either structurally and environmentally, tall buildings is constant. The same way as tall buildings structural and architectural solutions have been evolving since early rigid frames to nowadays hybrid solutions, the evolutionary trend will continue. With the improvement of techniques, computers capacities and materials, the challenge to go higher and keep beating height records will remain. If one could foresee the future, pure engineering abilities will not be the limitation to go higher, as they never have been. With a record of more than 100 years, it is not expectable that these engineering abilities fall short on following the demand for increasing height. Hence, the main conclusions about structural innovations are:

- Structural solutions will keep improving;
- New techniques, computation capacities, materials, and the intrinsic evolution of engineering will provide the necessary needs for new and higher tall buildings;

Similarly to structural solutions that have been under a registered evolutionary path, also the influence of macroeconomics in the world's tallest buildings construction has followed an historical pattern. Skyscraper Index postulations can be verified and seen in almost all the documented height world record breaks. Skyscraper Index points expansionary monetary policies, with money injection and credit ease coupled with low interest rates, as the prime evidences of an artificial economic climate. With this artificial economic climate, skyscrapers are projects that do not conform with the normal behavior of economy, anticipating a massive economic downturn. As economic rulers and policies have been showing a similar and unchanged pattern along skyscrapers history, one could expect that they remain like this in the future. Hence, the main conclusions about macroeconomics influence in tall buildings are:

- Skyscraper Index will remain as a good proxy, when evaluating the relationship between economy and tall buildings, because it has resisted to changes in world's political centers and it is present even in the globalized world (Great Recession);
- Real estate bubbles preclude the construction land marking tall buildings (as shown in the end of Chapter 2) and world's tallest buildings are indeed the voluptuous bubble bursting;
- China and Middle East should be under watch as they are, respectively, the world's leader in tall buildings construction and the place that hosts the future world's tallest building (Kingdom Tower);

Skyscraper Index has been surviving to deep changes in world economy, although tall buildings have changed. Tall buildings have been evolving in their superficial characteristics such as location, height and function. There is no Index to explain why skyscrapers moved to Asia, why they keep being higher and higher and why they lost their specialized function. However, part of the explanation was found on three main factors: financial openness, demographic pressures and political strategies are driving tall buildings to East and Middle East. Evolution in tall buildings' height was related to technological improvements, but its importance was paired to other less rational factor, that is, height is also the product of a quest for social status and recognition. Again, without elevators for example, tall buildings would not be feasible or practical, but technology had to be adapted to the irrational desire of building taller and taller, proving that egocentric motivations indeed pulled skyscrapers forward. The evolution of tall buildings function is a product of more economic needs: as tall buildings are increasingly responsive to surrounding economic environment, investors need to isolate them from economical uncertainties. The solution is to diversify their use in order to balance the profitability of their demand, minimizing potential losses in low demand times. Hence, the main conclusions about the evolution of tall buildings superficial characteristics are:

- Tall buildings' location will keep its trend to moving to Asia and Middle East, mainly because the countries from these areas face a thriving economy, have increasing populations and seek to be recognized as world class standard cities. Tall buildings have been once identified with US, now they will increasingly become a symbol of China, Dubai and others. Increasing urban populations will ultimately, in the future, require the adoption of tall buildings as an infrastructure in every city. Therefore, after these imbalances in USA, China and Dubai, one could expect that tall buildings will spread around the world;
- Motivations behind buildings becoming taller and taller are ego-motivated, from the beginning. Except for urban sprawl contention, infrastructure over expansion and agricultural areas preservation, there is no rational motivation for the construction of tall buildings. Companies and countries seek for world recognition and this is what leads to the search for majestic tall buildings. In a very distant future, maybe this motivations will dissipate, due to the absolute need of constructing tall buildings for urban contention. Until then, pride and social achievement will remain as the main motivations;
- Tall buildings in the future will have as many different uses as possible. Developers are already attending for the virtues of tall buildings diversification, regarding office, hotel and residential uses. If this trend becomes firmly established, tall buildings will house hospitals, schools, courts, shopping areas, sports facilities and others. Today’s tall buildings diversification trends may hence lead to new born concepts of vertical cities, like X Seed 4000 (Figure 37);

Superficial evolutions and structural innovations have not seriously considered the constructability issues of tall buildings. Prefabrication and Modularization are arising as innovative and paradigmatic shifters on tall buildings construction. Prefabrication has been used in tall buildings mainly in Asia and for social housing programs. This use mostly regards single elements instead of block pieces, such as staircases, floor slabs and wall panels. The lack of historical record on the use of prefabricated elements in resistant parts of a tall building is pulling back their widespread adoption: constructors prefer conventional technologies and are not willing to take risks on broader implementations of prefabrication. The restriction imposed by the need to standardize and repeat elements and floors is also a drawback since it doesn't allow for architectural freedom. Modularization has a better perception in by the public since it has been used with different functions in many years. Tall buildings still remains as a less desirable application for modularization, due to the restrictions in terms of architectural freedom. Additionally, transportation logistics arise as the main disadvantage in modularization, since volumetric pieces have to be transported to the construction site, demanding for time and space, which is not so readily available in urban sites. However, studies have been carried on in order to attest the adequacy of prefabrication and modularization. Their advantages in terms of waste reduction, schedule reduction and control, and improved man-power productivity deserve to be attended and might play a great role in tall buildings construction. The good performance of these techniques along these fields place them as first option methods, in order to construct tall buildings, avoiding their inherent massive high cost of nowadays. In spite of being also used as marketing tools, Hotel T30 and Sky City are the two most challenging evidences that prefabrication and modularization are indeed being ascertained as innovative ways to construct tall buildings. T30 may have started the cheaper and fast constructed tall buildings, while Sky City, if finished, may realize the first futuristic vertical city of the world. These two buildings might open way for their replication along the world, starting a new paradigm in tall buildings construction. Hence, the main conclusions about the recent trends on tall buildings' prefabrication and modularization are:

- Prefabrication will, in the short run, remain as a low range option. However, in the future design of cities and especially residential buildings, prefabrication may become the predominant construction technology. Its advantages in terms of time and productivity fit perfectly well the concept of new born suburbs, which may be necessary in the future at some Asian or even US cities;
- Modularization may establish as an alternative way to construct tall buildings. Atlantic Yards in New York attest the safety or this strategy, proving that the transport logistics obstacles can be overcome and the assemblage of modules is already fitting the high standards of New York buildings;
- Advantages of both techniques in waste reduction, construction schedule reduction and control, and man-force productivity are indeed relevant with respect to traditional construction. The necessary conditions are created for a paradigm shift. Hotel T30, Sky City and Atlantic Yards are only the first of their kind, offering a strong evidence of the attractiveness of such techniques, so firm steps can be now given, in order to explore and even improve prefabrication and modularization application to tall buildings construction.

- Prefabrication and Modularization could contribute to the concept of vertical cities. Sky City is already a statement in this "prefabricated city" prototype.

## 6.2. Future Prospects

Inevitably, the suggestions and predictions made along this dissertation are not definite and many external factors can significantly alter the future trends identified in this research. In any case, some of the issues approached in this research deserve further analysis, and in some cases other issues that could not be included also need attention. Among those, the following are highlighted::

- Scrutinize and dissect what is the level of absolute connection between Skyscraper Index and the construction of the world's tallest buildings;
- Skyscraper Index data should be analyzed in order to find the connection between the trilemma: competitors world's tallest buildings (Chrysler Building and Empire State Building), egocentric motivations and the magnitude of the consequent economic downturn (Chrysler Building, Empire State Building, and the Great Depression; World Trade Center, Willis Tower and Stagflation Crisis);
- Further studies may be carried out on the evolution of the different characteristics of tall buildings: further investigate the connection between tall buildings location shift to Asia and China's financial market openness; measure the importance of the competitive motivations to the increments of height in tall buildings. Attest the importance of the Asian financial crisis in the shift of tall buildings use, considering the major shifts in use that have been occurring since the beginning of 2000's.
- Investigate techniques to improve the incorporation of prefabricated elements in the resistant schemes of tall buildings. Studies are still needed to make these elements achieve a full scale potential of implementation in tall buildings resistant schemes.
- Study new structural schemes suitable for taller modular buildings. Atlantic Yards is an attractive project, but still hasn't the magnificent height of world class tall buildings. Efficient and structurally safe schemes which allows for assemblage of modules for big heights are needed, in order to place modularization at the same level as conventional techniques for tall building construction.

# 7. BIBLIOGRAPHY

[1] Smith, B; Coull, A. *Tall Building Structures: Analysis and Design*. United States of America: John Wiley & Sons; 1991

[2] Taranath, B. *Structural Analysis and Design of Tall Buildings*. Singapore: McGraw-Hill Book Company; 1988

[3] Chok, K. *Lateral Systems for Tall Buildings*. Master Thesis. Massachusetts Institute of Technology; 2004

[4] University of Oklahoma: *History of the American Built Environment.*[Online]. Available from: www.ou.edu/class/arch4443/Skyscraper%20East%20and%20West/Skyscraper.htm [Accessed 18 October 2013]

[5] Ali, M; Moon, K. Structural Developments in Tall Buildings: Current Trends and Future Prospects. *Architectural Science Review Vol. 50.*[Online]. June 13rd 2007. pp 205-223. Available from: DOI: 10.3763/asre.2007.5027 [Accessed 16 September 2013]

[6] The Skyscraper Center: *Willis Tower.*[Online]. Available from: http://skyscrapercenter.com/chicago/willis-tower/169/ [Accessed 18 October 2013].

[7] University of Oklahoma. *History of the American Built Environment.*[Online]. Available from: www.ou.edu/class/arch4443/Skyscraper%20East%20and%20West/Skyscraper.htm [Accessed 18 October 2013]

[8] Stubby. Social and Cultural Studies. *The Architecture Thread.*[Online].30 March 2013. Available from: http://www.saloforum.com/index.php?threads/the-architecture-thread.2858/ [Accessed 18 October 2013].

[9] Ali, M; Amstrong, P. *Strategies for Integrated Design of Sustainable Tall Buildings*. University of Illinois. 2006

[10] Frechette, R; Gilchrist, R. Towards Zero Energy: A Case Study of the Pearl River Tower, Guangzhou, China. In: Council on Tall Buildings and Urban Habitat (CTBUH). *Tall & Green: Typology for a Sustainable Urban Future: Proceedings of the CTBUH 8th World Congress, CTBUH 8th World Congress,3-5 March 2008, Dubai.* Council on Tall Buildings and Urban Habitat;2008. p. 252-262

[11] Panoramio. *4 Times Square.*[Online]. Available from: http://www.panoramio.com/photo/6848062 [Accessed 18 October 2013].

[12] Lindner. *Plafotherm® heated/chilled ceilings for the skyscraper of the future.*[Online]. Available from: http://www.lindnerusa.com/news/newsdetail.html?tx_ttnews[tt_news]=1877&cHash=a4e68901637deab729ebe62dacf3f974 [Accessed 18 October 2013]

[13] Gunel, M; Ilgin, H. A proposal for the classification of structural systems of tall buildings. *Building and Environment* [Online] 2007; 42(7): 2667-2675. Available from: http://www.sciencedirect.com/science/article/pii/S0360132306001855 [Accessed 13 September 2013]

[14] Dezeen Magazine. *C. F. Møller designs the world's tallest wooden skyscrapers.*[Online]. Available from: http://www.dezeen.com/2013/06/18/c-f-moller-designs-worlds-tallest-wooden-skyscraper/ [Accessed 18 October 2013].

[15] Emporis. *Chrysler Building.*[Online]. Available from: http://www.emporis.com/building/chryslerbuilding-newyorkcity-ny-usa [Accessed 18 October 2013]

[16] Valente, J. *Tall Buildings and Elevators: Historical Evolution of Vertical Communication Systems.* Master Thesis. Instituto Superior Técnico; 2012.

[17] The Free Dictionary by Farlex. *Composite Beam.*[Online]. Available from: http://encyclopedia2.thefreedictionary.com/composite+beam [Accessed 18 October 2013].

[18] Ali, M; Al-Kodmany, Kheir. Tall Buildings and Urban Habitat of the 21st Century: A Global Perspective. *Buildings* [Online] 2012; 2(4): 384-423. Available from: DOI:10.3390/buildings3010173 [Accessed 31 August 2013]

[19] Machinery Vibration Consultants. *Vortex Shedding.*[Online]. Available from: http://www.vibrationconsultants.com/vortex_shedding/index.htm [Accessed 18 October 2013].

[20] Kourakis, I. *Structural Systems and Tuned Mass Dampers of Super-Tall Buildings: Case Study of Taipei 10.* Master Thesis. Massachusetts Institute of Technology; 2007

[21] Irwin, P; Kilpatrick, J; Frisque, A. Friend or Foe, Wind at Height. In: Council on Tall Buildings and Urban Habitat. *Tall & Green: Typology for a Sustainable Urban Future: Proceedings of the CTBUH 8th World Congress, CTBUH 8th World Congress,3-5 March 2008, Dubai.* Council on Tall Buildings and Urban Habitat;2008. p. 336-342

[22] My Travel Photos. *Petronas Twin Towers Pictures*.[Online]. Available from: http://mytravelphotos.net/category/malaysia/ [Accessed 18 October 2013]

[23] Structure. *On Designing with Buckling-Restrained Braced Frames.*[Online]. Available from: http://www.structuremag.org/article.aspx?articleID=717 [Accessed 18 October 2013]

[24] Kruger. *Taipei 101: Project in Taiwan.*[Online]. Available from: http://www.krugerfan.com/projects_taiwan_taipei101.php [Accessed 18 October 2013].

[25] Archinomy: Bridging the Gap. *Taipei 101: A Case Study.*[Online]. Available from: http://www.archinomy.com/case-studies/671/taipei-101-a-case-study [Accessed 18 October 2013]

[26] Christopher Bollyn . *The "Huge Bullet Hole" in the South Tower and Analysis of Missile Evidence.*[Online]. Available from: http://www.bollyn.com/the-huge-bullet-hole-in-the-south-tower-and-analysis-of-missile-evidence/ [Accessed 18 October 2013].

[27] Jayachandran, P. *Design of Tall Buildings: Preliminary Design and Optimization.* [Lecture]. National Workshop on High-Rise and Tall Buildings. University of Hyderabad, India. May 2009

[28] Great Buildings. *World Trade Center - More Images.*[Online]. Available from: http://www.greatbuildings.com/cgi-bin/gbi.cgi/World_Trade_Center_Images.html/cid_wtc_mya_WTC_const.2.html [Accessed 18 October 2013]

[29] Open Buildings. *John Hancock Center.*[Online]. Available from: http://openbuildings.com/buildings/john-hancock-building-profile-1408/media#!buildings-media/21 [Accessed 18 October 2013]

[30] Holyday Impressions. *Hong Kong 23-26 November 2004.*[Online]. Available from: http://www.math.ethz.ch/~hjfurrer/holidays/HongKong/large/BankOfChinaTower_Large.jpg [Accessed 18 October 2013]

[31] Gold Cost Condos: Your Key To Chicago Real Estate. *One Magnificent Mile, Chicago.*[Online]. Available from: http://www.goldcoastcondos.com/950-n-michigan-one-mag-mile.php [Accessed 18 October 2013]

[32] Subramanian, N. Burj Khalifa World's Tallest Structure; *New Building Materials & Construction World (NBM & CW)* 2010;(7): 198-210

[33] Abdelrazaq, A; Baker, W; Chung K.R. Integration of Design and Construction of the Tallest Building in Korea, Tower Palace III, Seoul, Korea. In: Council on Tall Buildings and Urban Habitat. *Tall Buildings in Historical Cities - Culture & Technology for Sustainable Cities. Council on Tall Buildings and Urban Habitat Conference,10-13 October 2004, Seoul.* Council on Tall Buildings and Urban Habitat; 2004

[34] Baker, W; Pawlikowski, J. The Design and Construction of the World's Tallest Building; *Structural Engineer* 2009;(12): 12-19

[35] Baker, W; Pawlikowski, J. Higher and Higher: The evolution of the Buttressed Core; *Civil Engineering* 2012;(9): 58-65

[36] Abdelrazaq, A. Validating the Dynamics of Burj Khalifa; *Council on Tall Buildings and Urban Habitat Journal* 2011;(2): 18-23

[37] Moon, K; Connor, J; Fernandez, J. Diagrid structural systems for tall buildings: characteristics and methodology for preliminary design. *The Structural Design of Tall and Special Buildings Vol. 16.*[Online]. 2007. pp 205-230. Available from: DOI: 10.1002/tal.311 [Accessed 12 September 2013]

[38] Soo, K; Sik, K; Hee, L. Structural Schematic Design of a Tall Building in Asan using the Diagrid System. In: Council on Tall Buildings and Urban Habitat. *Tall & Green: Typology for a Sustainable Urban Future: Proceedings of the CTBUH 8th World Congress, CTBUH 8th World Congress,3-5 March 2008, Dubai.* Council on Tall Buildings and Urban Habitat;2008

[39] Charnish, B; McDonnell, T. The Bow: Unique Diagrid System for a Sustainable Tall Building. In: Council on Tall Buildings and Urban Habitat. *Tall & Green: Typology for a Sustainable Urban Future: Proceedings of the CTBUH 8th World Congress, CTBUH 8th World Congress,3-5 March 2008, Dubai.* Council on Tall Buildings and Urban Habitat; 2008

[40] Peri. *Skyscrapers: The Bow.*[Online]. Available from: http://www.peri.de/ww/en/projects.cfm/fuseaction/diashow/reference_ID/2312/referencecategory_ID/6/currentimage/1.cfm [Accessed 18 October 2013]

[41] Urbika. *30 St. Mary Axe.*[Online]. Available from: http://www.urbika.com/projects/view/1743-30-st-mary-axe [Accessed 18 October 2013]

[42] Choi, H; Ho, G; Joseph, L; Mathias, N. *Outrigger Design for High-Rise Buildings: An Output of the CTBUH Outrigger Working Group.*[Online]. Chicago. Council on Tall Buildings and Urban Habitat; 2012. Available from: https://store.ctbuh.org/PDF_Previews/Books/2012_CTBUHOutriggerGuide_Preview.pdf [Accessed 12 September 2013]

[43] Brown, J; Williams, J. The Buttressed Core Structural System. In: University of Pittsburgh Swanson School of Engineering. *2013 Freshman Engineering Conference, 2013 Freshman Engineering Conference, 13 April 2013, Pittsburgh.* University of Pittsburgh; 2013

[44] Thornton, M. Skyscraper and Business Cycles. *The Quarterly Journal of Austrian Economics* [Online] 2005; 8(1): 51-74. Available from: http://mises.org/journals/qjae/pdf/qjae8_1_4.pdf [Accessed 7 October 2013]

[45] Thornton, M. Cantillon on the Cause of the Business Cycle. *The Quarterly Journal of Austrian Economics* [Online] 2006; 9(3): 45-60. Available from: http://mises.org/journals/qjae/pdf/qjae9_3_3.pdf [Accessed 5 October 2013]

[46] Oppers, S. *The Austrian Theory of Business Cycles: Old Lessons for a Modern Economic Policy?*[Online] 2002. Available from: http://www.imf.org/external/pubs/ft/wp/2002/wp0202.pdf [Accessed 16 May 2013].

[47] CNN Money. *Fortune 500* [Online] Available from: http://money.cnn.com/magazines/fortune/fortune500/2012/full_list/ [Accessed 11 May 2013]

[48] Haughwout, A; Orr, J; Bedoll, D. The Price of Land in the New York Metropolitan Area. *Current Issues in Economics and Finance* [Online] 2008; 14(3): 1-7. Available from: http://www.newyorkfed.org/research/current_issues/ci14-3.pdf [Accessed 14 May 2013]

[49] Tallman, E; Moen, J. Lessons from the Panic of 1907. *Federal Reserve Bank of Atlanta Economic Review* [Online] 1990; 75(May/June): 2-13. Available from: http://www.frbatlanta.org/filelegacydocs/ern390_tallman.pdf [Accessed 27 May 2013].

[50] Moen, J; Tallman, E. *Close but not a Central Bank: The New York Clearing House and Issues of Clearing House Loan Certificates* [Online] 2013. Available from: http://www.clevelandfed.org/research/workpaper/2013/wp1308.pdf [Accessed 1st October 2010]

[51] Matziorinis, K. *The Causes of the Great Depression: A Retrospective* [Online] 2007. Available from: http://www.canbekeconomics.com/research_papers/The_Great_Depression_and_Europe.pdf [Accessed 3rd October 2013]

[52] Wheelock, D. Monetary Policy in the Great Depression: What the Fed Did, and Why. *Federal Reserve Bank of St. Louis Review* [Online] 1992; 74(2): 3-28. Available from: http://research.stlouisfed.org/publications/review/92/03/Depression_Mar_Apr1992.pdf [Accessed 1st October 2013]

[53] Eichengreen, B; Mitchener, K. *The Great Depression as a credit boom gone wrong* [Online] 2003. Available from: http://www.bis.org/publ/work137.pdf [Accessed 27 May 2013]

[54] The New York Times - The Opinion Pages. *The Stagflation Myth* [Online] Available from: http://krugman.blogs.nytimes.com/2009/06/03/the-stagflation-myth/?_r=0 [Accessed 17 May 2013]

[55] Fuhrer, J. The Phillips curve is alive and well. *New England Economic Review of the Federal Reserve Bank* [Online] 1995; March/April:41-56

[56] Atkeson, A; Ohanian, L. Are Phillips Curves Useful for Forecasting Inflation? *Federal Reserve Bank of Minneapolis Quarterly Review* [Online] 2001; 25(1): 2-11

[57] Barsky, R; Kilian, L. *A Monetary Explanation of the Great Stagflation of the 1970s* [Online] National Bureau of Economic Research; 2000. Available from: http://www.nber.org/papers/w7547.pdf?new_window=1 [Accessed 5 October 2013]

[58] Radelet, S; Sachs, F. *The Onset of the East Asian Financial Crisis* [Online] University of Chicago Press; 2000. Available from: http://www.nber.org/chapters/c8691.pdf [Accessed 30 May 2013]

[59] Cheong, L. *Globalization and the operation of the monetary policy in Malaysia* [Online] Bank of International Settlements; 2005. Available from: http://www.bis.org/publ/bppdf/bispap23q.pdf [Accessed 5 October 2013]

[60] Cheng, M. Economic Fluctuations and Growth: An Empirical Study of the Malaysian Economy. *The Journal of Business in Developing Nations* [Online] 2003;7(?): 51-73

[61] Palley, T. America's flawed paradigm: macroeconomic causes of the financial crisis and the great recession. *Empirica* [Online] 2011; 38: 3-17. Available from: DOI: 10.1007/s10663-010-9142-3 [Accessed 30 May 2013].

[62] Palley, T. *America's Exhausted Paradigm: Macroeconomic causes of the financial crisis and great recession* [Online] Institute for International Political Economy (IPE); 2009. Available from: http://econstor.eu/bitstream/10419/59308/1/718077881.pdf [Accessed 31st May 2013].

[63] Fligstein, N; Goldstein, A. *Catalyst of Disaster: Subprime Mortgage Securitization and the Roots of the Great Recession* [Online] Institute for Research on Labor and Employment, UC Berkeley; 2011. Available from: http://www.irle.berkeley.edu/workingpapers/113-12.pdf [Accessed 6 October 2013].

[64] The National. *Burj Khalifa rents tumble 40%* [Online] Available from: http://www.thenational.ae/business/property/burj-khalifa-rents-tumble-40 [Accessed 22 May 2013]

[65] Barclays Capital. *Skyscraper Index: Bubble Building* [Online] 2012. Available from: http://static.nzz.ch/files/6/2/0/Skyscraper+Index+-+Bubble+building+100112+%282%29_1.14300620.pdf [Accessed 28 April 2013]

[66] Moon, K.. Dynamic Interaction between Technology and Architectural Aesthetics in Tall Buildings. *Journal of Urban Technology* [Online] 2013; 20(2): 3-24. Available from: DOI: 10.1080/10630732.2012.735479 [Accessed 6 September 2013]

[67] Council on Tall Buildings and Urban Habitat. 2011: A Tall Building Review. *CTBUH Journal* [Online] 2012; (1): 36-37. Available from: http://www.ctbuh.org/LinkClick.aspx?fileticket=deFaAW6qCec%3d&tabid=1108&language=en-US [Accessed 10 April 2013]

[68] Brass, K; Wood, A; Carver, M. Global Tall Buildings Completions Drop, But Uptick Expected in 2013. *CTBUH Journal* [Online] 2013; (1): 38-45. Available from: http://www.ctbuh.org/LinkClick.aspx?fileticket=6zv7GRUpvwo%3D&tabid=4212&language=en-GB [Accessed 18 September 2013]

[69] Council on Tall Buildings and Urban Habitat. 2008: A Tall Building Review. *CTBUH Journal* [Online] 2009;(1): 44-45. Available from: http://www.ctbuh.org/LinkClick.aspx?fileticket=9aSBwI4tGmk%3d&tabid=1108&language=en-GB [Accessed 7 September 2013]

[70] Council on Tall Buildings and Urban Habitat. 2012: A Tall Building Review. *CTBUH Journal* [Online] 2013; (1): 46-47. Available from: http://www.ctbuh.org/LinkClick.aspx?fileticket=q7dKr6M9XGo%3d&tabid=1108&language=en-GB [Accessed 7 September 2013]

[71] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH.* [Online] Available from: http://skyscrapercenter.com/create.php?search=yes&page=0&type_building=on&status_COM=on&list_continent=&list_country=&list_city=&list_height=&list_company=&completionsthrough=on&list_year=1940 [Accessed 18 October 2013]

[72] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH.* [Online] Available from: http://skyscrapercenter.com/create.php?search=yes&page=0&type_building=on&status_COM=on&list_continent=&list_country=&list_city=&list_height=&list_company=&completionsthrough=on&list_year=1950 [Accessed 18 October 2013].

[73] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH.* [Online] Available from: http://skyscrapercenter.com/create.php?search=yes&page=0&type_building=on&status_COM=on&list_continent=&list_country=&list_city=&list_height=&list_company=&completionsthrough=on&list_year=1960 [Accessed 18 October 2013].

[74] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH.* [Online] Available from: http://skyscrapercenter.com/create.php?search=yes&page=0&type_building=on&status_CO

M=on&list_continent=&list_country=&list_city=&list_height=&list_company=&completionsthrough=on&list_year=1970 [Accessed 18 October 2013].

[75] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH*. [Online] Available from: http://skyscrapercenter.com/create.php?search=yes&page=0&type_building=on&status_COM=on&list_continent=&list_country=&list_city=&list_height=&list_company=&completionsthrough=on&list_year=1980 [Accessed 18 October 2013].

[76] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH*. [Online] Available from: http://skyscrapercenter.com/create.php?search=yes&page=0&type_building=on&status_COM=on&list_continent=&list_country=&list_city=&list_height=&list_company=&completionsthrough=on&list_year=1990 [Accessed 18 October 2013].

[77] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH*. [Online] Available from: http://skyscrapercenter.com/create.php?search=yes&page=0&type_building=on&status_COM=on&list_continent=&list_country=&list_city=&list_height=&list_company=&completionsthrough=on&list_year=2000 [Accessed 18 October 2013].

[78] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH*. [Online] Available from: http://skyscrapercenter.com/create.php?search=yes&page=0&type_building=on&status_COM=on&list_continent=&list_country=&list_city=&list_height=&list_company=&completionsthrough=on&list_year=2010 [Accessed 18 October 2013].

[79] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH*. [Online] Available from: http://skyscrapercenter.com/create.php?search=yes&page=0&type_building=on&status_COM=on&list_continent=&list_country=&list_city=&list_height=&list_company=&completionsthrough=on&list_year=2012 [Accessed 18 October 2013]

[80] Oldfield, P; Wood, A. Tall Buildings in the Global Recession: 2008, 2020 and Beyond. *CTBUH Journal* [Online] 2009; (1): 20-26. Available from: http://www.ctbuh.org/LinkClick.aspx?fileticket=WG9W1hWjV3w%3D&tabid=141&language=en-US [Accessed 3rd May 2013]

[81] Formaneck, S. Skyscrapers and Economic Strategy and Development: The Case of Bahrain's Proposed Murjan Tower. *Journal of Economics, Business and Management*

[Online] 2013; 1(4): 350-354. Available from: DOI: 10.7763/JOEBM.2013.V1.76 [Accessed 7 November 2013]

[82] Chinn, M; Ito, H. *Financial Globalization and China* [Online] 2011. Available from: http://web.pdx.edu/~ito/Chinn_Ito_Global_China_0307hi.pdf [ Accessed 9 September 2013]

[83] World Bank, China GDP Growth (annual %). *World Development Indicators*. [Online] 2013. Available from: http://data.worldbank.org/country/china [Accessed 10 September 2013]

[84] Huang, Y. The Role of Foreign-Invested Enterprises in the Chinese Economy : An Institutional Approach. [Online]. In: Chen, S (ed.); Wolf, C. (ed.). *China, the United States and the Global Economy*. United States of America: RAND; 2001. pp 147-191

[85] Wacziarg, R; Welch, K. Trade Liberalization and Growth: New Evidence. *The World Bank Economic Review* [Online] 2008; 22(2): 187-231. Available from: DOI: 10.1093/wber/lhn007 [Accessed 9 September 2013]

[86] Aizenman,J; Chinn, M; Ito, H. *Surfing the Waves of Globalization: Asia and Financial Globalization in the Context of the Trillema* [Online]. National Bureau of Economic Research; 2010. Available from: http://www.nber.org/papers/w15876.pdf?new_window=1 [ Accessed 9 September 2013]

[87] Sang, B. Pudong: Another Special Economic Zone in China?- An Analysis of the Special Regulations and Policy for Shanghai's Pudong New Area. *Northwestern Journal of International Law & Business* [Online] 1993; 14(1): 130-160. Available from: http://scholarlycommons.law.northwestern.edu/cgi/viewcontent.cgi?article=1377&context=njilb [Accessed 10 September 2013]

[88] Bekaert, G; Harvey, C; Lundblad, C. *Financial Openness and the Chinese Growth Experience* [Online] 2007. Available from: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=991640 [Accessed 10 September 2013]

[89] BBC News. *Quick Guide: China's economic reform: China has the world's fastest-growing major economy it has been a rocky road from socialism to consumerism*. [Online] Available from: http://news.bbc.co.uk/2/hi/asia-pacific/5237748.stm [Accessed 8 September 2013]

[90] Lai, K. *Developing Shanghai as an International Financial Centre: Progress and Prospects*. [Online] 2006. Available from: http://www.nottingham.ac.uk/cpi/documents/discussion-papers/discussion-paper-4-shanghai-international-financial-centre.pdf [Accessed 10 September 2013]

[91] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH.* [Online] Available from:

http://skyscrapercenter.com/create.php?search=yes&page=0&type_building=on&status_COM=on&list_continent=AS&list_country=CN&list_city=&list_height=&list_company=&completionsthrough=on&list_year= [Accessed 18 October 2013].

[92] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH*. [Online] Available from: http://skyscrapercenter.com/shanghai/shanghai-tower/56/ [Accessed 18 October 2013].

[93] The New York Times. *Majority of Chinese Now Live in Cities* [Online] Available from: http://www.nytimes.com/2012/01/18/world/asia/majority-of-chinese-now-live-in-cities.html?_r=0 [Accessed 15 September 2013]

[94] Bloomberg. *China's Urban Population Exceeds Countryside for the First Time* [Online] Available from: http://www.bloomberg.com/news/2012-01-17/china-urban-population-exceeds-rural.html [Accessed 15 September 2013]

[95] Zhang, K; Song, S. Rural-urban migration and urbanization in China: Evidence from time-series and cross section analyses. *China Economic Review* [Online] 2003; 14(4): 386-400. Available from: DOI:10.1016/j.chieco.2003.09.018 [Accessed 15 September 2013]

[96] Liu, S; Li, X; Zhang, M. *Scenario Analysis on Urbanization and Rural-Urban Migration in China*. [Online] Austria: International Institute for Applied Systems Analysis; 2003. Available from: http://webarchive.iiasa.ac.at/Admin/PUB/Documents/IR-03-036.pdf [Accessed 17 September 2013]

[97] Chang, G; Brada, J. The paradox of China's growing under-urbanization. *Economic Systems* [Online] 2006; 30(1): 24-40. Available from: 10.1016/j.ecosys.2005.07.002 [Accessed 11 September 2013]

[98] Zhao, Z. *Rural-Urban Migration in China - What Do We Know and What Do We Need to Know*. [Online]. China Center for Economic Research, Perkin University 2003. Available from: http://www.cenet.org.cn/cn/CEAC/%E7%AC%AC%E4%B8%89%E5%B1%8A%E5%85%A5%E9%80%89%E8%AE%BA%E6%96%87/%E5%8A%B3%E5%8A%A8%E7%BB%8F%E6%B5%8E%E5%AD%A6%E4%B8%8E%E4%BA%BA%E5%8A%9B%E8%B5%84%E6%BA%90/%E8%B5%B5%E5%BF%A0-Rural_Urban_Migration.pdf [Accessed 11 September 2013]

[99] Huang, Y. Urban Development in Contemporary China. [Online]. In: Veeck, G, Pannel, C; Smith, C; Huang, Y. *China's Geography: Globalization and the Dynamics of Political, Economic and Social Change*, Boulder, Colorado: Roman & Littlefield Publishers; 2007. pp 233-262

[100] Trading Economics. *China GDP Annual Growth Rate* [Online] Available from: http://www.tradingeconomics.com/china/gdp-growth-annual [Accessed 23 October 2013]

[101] National Bureau of Statistics of China. *China's Total Population and Structural Changes in 2011* [Online] Available from: http://www.stats.gov.cn/english/newsandcomingevents/t20120120_402780233.htm [Accessed 23 October 2013]

[102] Global Times. *Shanghai population surges to 23.47 million* [Online] Available from: http://www.globaltimes.cn/NEWS/tabid/99/ID/707874/Shanghai-population-surges-to-2347-million.aspx [Accessed 18 October 2013]

[103] Global Times. *Statistics Beijing* [Online] Available from: http://www.globaltimes.cn/NEWS/tabid/99/ID/690403/Statistics-Beijing.aspx [Accessed 18 October 2013]

[104] Islam, S. *Physical Density and Urban Sprawl: A Case of Dhaka City.* Master Thesis. Kungliga Tekniska Högskolan; 2012

[105] Blackman, I; Picken, D. Height and Construction Costs of Residential High-Rise Buildings in Shanghai. *Journal of Construction Engineering and Management* [Online] 2010; 136(11): 1169-11780. Available from: DOI: 10.1061/_ASCE_CO.1943-7862.0000226 [Accessed 9 September 2013]

[106] Longyu, S; Guofan, S; Shenghui, C; Xuanqi, L; Tao, L; Kai, Y; Jingzhu, Z. Urban Three-dimensional Expansion and its driving forces - A Case Study of Shanghai, China. *Chinese Geographical Science* [Online] 2009; 19(4): 291-298. Available from: DOI: 10.1007/s11769-009-0291-x [Accessed 9 September 213]

[107] Wu, W. City Profile: Shanghai. *Cities* [Online] 1999; 16(3): 207-216. Available from: http://sites.tufts.edu/wuweiping/files/2011/02/Cities-Shanghai.pdf [Accessed 15 September 2013]

[108] The New York Times. *China Builds its Dreams, and Some Fear a Bubble* [Online] Available from http://www.nytimes.com/2005/10/18/business/worldbusiness/18bubble.html?pagewanted=all&_r=0 [Accessed 14 October 2013]

[109] Nikolas Koenig. *Architecture* [Online] Available from: http://www.nikolaskoenig.com/architecture/ [Accessed 16 October 2013]

[110] Dubai FDI. Why Dubai [Online] Department of Economic Development-Dubai; 2013. Available from:

http://www.dubaifdi.gov.ae/en/NewsEvents/Press/Documents/Dubai%20FDI%20Why%20Dubai%20report.pdf [Accessed 9 September 2013]

[111] Matly, M; Dillon, L. *Dubai Strategy: Past, Present and Future* [Online] Harvard Business School; 2007. Available from: http://belfercenter.hks.harvard.edu/files/matly_paper1.pdf [Accessed 9 September 2013]

[112] Emirates Competitiveness Council. *Policy in Action: Dubai Trade - Building Competitive Advantage Through Collaboration* [Online] Emirates Competitiveness Council; 2012. Available from: www.ecc.ae/en/getfile.aspx?ftype=dwn&file=22032012010719.pdf [Accessed 15 September 2013]

[113] Dubai FDI. Why Dubai [Online] Department of Economic Development-Dubai; 2013. Available from: http://www.dubaifdi.gov.ae/en/NewsEvents/Press/Documents/Dubai%20FDI%20Why%20Dubai%20report.pdf [Accessed 9 September 2013]

[114] Khaleej Times. *Dubai among top FDI hubs* [Online] Available from: http://www.khaleejtimes.com/biz/inside.asp?xfile=/data/uaebusiness/2013/September/uaebusiness_September84.xml&section=uaebusiness [Accessed 20 September 2013]

[115] Gulfnews. *Dubai: A Trade Hub connecting cultures and commodities* [Online] Available from: http://gulfnews.com/business/economy/dubai-a-trade-hub-connecting-cultures-and-commodities-1.1151376 [Accessed 15 September 2013]

[116] Forbes. *Dubai Inc.* [Online] Available from: http://www.forbes.com/2006/03/02/dubai-DPWorld-Emmar_cx_daa_0302dubai.html [Accessed 15 September 2013]

[117] Jumeirah Group. *Corporate Responsibility Report 2008*. [Online] 2008. Available from: This is the html version of the file https://www.hotelschool.cornell.edu/research/chr/events/roundtables/sustainability/documents/Jumeirah_Group_CR_Report_2008.pdf [Accessed 15 September 2013]

[118] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH - Jumeirah Beach Hotel*. [Online] Available from: http://www.skyscrapercenter.com/dubai/jumeirah-beach-hotel/15143/ [Accessed 16 September 2013]

[119] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH - JW Marriott Marquis Hotel Dubai Tower 1*. [Online] Available from: http://www.skyscrapercenter.com/dubai/jw-marriott-marquis-hotel-dubai-tower-1/237/ [Accessed 16 September 2013]

[120] Daily Mail. *Better not take the stairs: World's Tallest Hotel opens in Dubai towering 1,100ft over the skyline with 72 floors* [Online] Available from: http://www.dailymail.co.uk/news/article-2284971/JW-Marriott-Marquis-Worlds-tallest-hotel-opens-Dubai-towering-1-100ft-skyline-72-floors.html [Accessed 23 September 2013]

[121] Acuto, M. High-rise Dubai urban entrepreneurialism and the technology of symbolic power. *Cities* [Online] 2010; 27(4): 272-284. Available from: DOI:10.1016/j.cities.2010.01.003 [Accessed 11 September 2013]

[122] Council on Tall Buildings and Urban Habitat. The Tallest Buildings in the World: Past, Present and Future. *CTBUH Journal* [Online] 2008; (2): 40-41. Available from: http://www.ctbuh.org/LinkClick.aspx?fileticket=M7nXrLx8g0M%3D&tabid=1108&language=en-GB [Accessed 10 April 2013]

[123] Chew, M. *Construction Technology for Tall Buildings*. 3rd Edition. [Online] Singapore: World Scientific Publishing Co. Pte. Ltd.; 2009. Available from: http://books.google.pt/books?id=3muYagmwSPUC&printsec=frontcover&dq=Chew,+2009&hl=en&sa=X&ei=1dd_Ur7CK4GG0AXW9IDoBg&ved=0CC0Q6AEwAA#v=onepage&q=Chew%2C%202009&f=false [Accessed 18 September 2013]

[124] Baker, W; James, P; Tomlinson, R; Weiss, A. Case Study: Trump International Hotel & Tower. *CTBUH Journal.* [Online] 2009; (3): 16-22

[125] Baker, W; Korista, D; Novak, L. Engineering the World’s Tallest – Burj Dubai. In: Council on Tall Buildings and Urban Habitat (CTBUH). Tall & Green: Typology for a Sustainable Urban Future: Proceedings of the CTBUH 8th *World Congress, CTBUH 8th World Congress,3-5 March 2008, Dubai.* Council on Tall Buildings and Urban Habitat;2008. p. 43-52.

[126] Abu - Ghazalah. Skyscrapers as Tools of Economic Reform and Elements of Urban Skyline: Case of Abdali Development Project at Amman. *Journal of the Faculty of Architecture (Middle East Technical University)* [Online] 2007; 24(1): 49-70. Available from: http://jfa.arch.metu.edu.tr/archive/0258-5316/2007/cilt24/sayi_1/49-70.pdf [Accessed 11 June 2013]

[127] Council on Tall Buildings and Urban Habitat. *CTBUH Names 2013 Innovation Award Winners and Finalists* [Online] 2009. Available from: http://www.ctbuh.org/LinkClick.aspx?fileticket=F3amfNFsqug%3d&tabid=4653&language=en-US [Accessed 17 September 2013]

[128] New Scientist. *Ultra elevator takes you higher with carbon-fibre tape* [Online] Available from: http://www.newscientist.com/article/dn23681-ultra-elevator-takes-you-higher-with-carbonfibre-tape.html#.Un_j2-ISprM [Accessed 12 September 2013]

[129] The Atlantic Cities. *Is there a Limit to How Tall Buildings can Get?*[Online] Available from: http://www.theatlanticcities.com/design/2012/08/there-limit-how-tall-buildings-can-get/2963/ [Accessed 12 September 2013]

[130] Inhabitat. *X Seed 4000: World's tallest tower will house 1 million people* [Online] Available from: http://inhabitat.com/self-contained-tokyo-highrise-eco-city-x-seed-4000/ [Accessed 12 September 2013]

[131] Barr, J; Cohen, J. *Why are Skyscraper so Tall? Land Use and the Spatial Location of Buildings in New York* [Online] 2010. Available from: http://www.aeaweb.org/aea/2011conference/program/retrieve.php?pdfid=352 [Accessed 18 September 2013]

[132] Barr, J. Skyscrapers and the Skyline: Manhattan, 1895-2004. *Real Estate Economics* [Online] 2007; 38(3): 567-597. Available from: DOI: 10.1111/j.1540-6229.2010.00277.x [Accessed 18 September 2013]

[133] Ali, M. The Skyscraper: Epitome of Human Aspirations. In: Council on Tall Buildings and Urban Habitat (CTBUH). Renewing the Urban Landscape: Proceedings of the CTBUH 7th *World Congress*, *CTBUH 7th World Congress, 16-19 October 2005, New York.* Council on Tall Buildings and Urban Habitat; 2005

[134] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH - The Trump Building.* [Online] Available from: http://www.skyscrapercenter.com/new-york-city/the-trump-building/ [Accessed 19 September 2013]

[135] Helsley, R; Strange, W. A game-theoretic analysis of skyscrapers. *Journal of Urban Economics* [Online] 2008; 64(1): 49-64. Available from: DOI: 10.106/J.JUE.2007.08.004 [Accessed 16 September 2013]

[136] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH - One World Trade Center.* [Online] Available from: http://skyscrapercenter.com/new-york-city/one-world-trade-center/200/ [Accessed 19 September 2013]

[137] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH - One World Trade Center.* [Online] Available from: http://skyscrapercenter.com/taipei/taipei-101/117/ [Accessed 17 September 2013]

[138] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH*. [Online] Available from: http://skyscrapercenter.com/create.php?search=yes&page=0&type_building=on&status_COM=on&function_residential=on&list_continent=&list_country=&list_city=&list_height=&list_company=&completionsthrough=on&list_year=2012 [Accessed 20 October 2013]

[139] Dream Property Dubai. *Princess Tower Apartments* [Online] Available from: http://www.dreampropertydubai.com/princess-tower-apartments-dubai-marina-1122010120525 [Accessed 17 October 2013]

[140] Council on Tall Buildings and Urban Habitat. *The Skyscraper Center: The Global Tall Building Database of the CTBUH*. [Online] Available from: http://skyscrapercenter.com/create.php?search=yes&page=0&type_building=on&status_COM=on&function_residential=on&list_continent=&list_country=&list_city=&list_height=&list_company=&completionsthrough=on&list_year=2012 [Accessed 20 October 2013]

[141] City Realty. *New York By Gehry*. [Online] Available from: http://www.cityrealty.com/nyc/financial-district/new-york-by-gehry-8-spruce-street/35081 [Accessed 14 October 2013]

[142] E-architect. *8 Spruce Street Manhattan : New York by Gehry* [Online] Available from: http://www.e-architect.co.uk/articles/8_spruce_street.htm [Accessed 15 October 2013]

[143] Ideasgn. *Shanghai Tower Gensler 014*. [Online] Available from: http://ideasgn.com/architecture/shanghai-tower-gensler/attachment/shanghai-tower-gensler-014/ [Accessed 17 October 2013]

[144] Jaillon, L; Poon, C. The evolution of prefabricated residential building systems in Hong Kong: A review of the public and the private sector. *Automation in Construction* [Online] 2009; (18)3: 239-248. Available from: DOI:10.1016/j.autcon.2008.09.002 [Accessed 24 October 2013]

[145] Jaillon, L; Poon, C. Sustainable construction aspects of using prefabrication in dense urban environment: a Hong Kong case study. *Construction Management and Economics* [Online] 2009; (26)9: 953-966. Available from: DOI: 10.1080/01446190802259043 [Accessed 22 October 2013]

[146] Corum, Ip. *Sustainable Precast Construction Methods for Tall Office Buildings in Hong Kong* [Online] 2007. Available from: http://bst1.cityu.edu.hk/e-learning/building_info_pack/tall_building/paper_corum_ip.pdf [Accessed 21 September 2013]

[147] Fong, C. Estate Renewal Through Development of Prefabricated Super High-Rise Buildings. In: Council on Tall Buildings and Urban Habitat (CTBUH). Renewing the Urban Landscape: Proceedings of the CTBUH 7th *World Congress, CTBUH 7th World Congress,16-19 October 2005, New York.* Council on Tall Buildings and Urban Habitat;2005

[148] Tam, C; Deng, Z; Zeng, S. Evaluation of construction methods and performance for high rise public housing construction in Hong Kong. *Building and Environment* [Online] 2001; 37(10): 983-991. Available from: DOI: 10.1016/S0360-1323(01)00081-6 [Accessed 21 September 2013]

[149] Wong, R; Hao, J; Ho,C. Prefabricated Building Construction Systems Adopted in Hong Kong. In: International Association for Housing Science. Proceedings of the *World Congress on Housing: Process and Product, 23-27 June 2003, Montreal.*

[150] Baldwin, A; Poon, C; Shen, L.; Austin, S; Wong, I. Designing out waste in high rise residential buildings: Analysis of precasting methods and traditional construction. *Renewable Energy* [Online] 2009; 34(9): 2067-2073. Available from: DOI:10.1016/j.renene.2009.02.008 [Accessed 22 September 2013]

[151] Tolsma, K. *Precast Concrete Cores in High- Rise Buildings.* Master Thesis. Delft University of Technology; 2010

[152] Lu, W. Enhancing housing production in Hong Kong through BIMatizing offshore production. *Building Journal* [Online] 2013; 12-15. Available from: http://www.building.hk/forum/2013_0326housing.pdf [Accessed 21 September 2013]

[153] Schoenborn, J. *A Case Study Approach to Identifying the Constraints and Barriers to Design Innovation for Modular Construction.* Master Thesis. Virginia Polytechnic Institute and State University; 2012

[154] Rogan, L; Lawson, R; Brkljac, N. *Better Value in Steel: Value and Benefits Assessment Construction* [Online] London: The Steel Construction Institute; 2000. Available from: http://www.designforhomes.org/wp-content/uploads/2012/03/ModularSteel.pdf [Accessed 5 August 2013]

[155] Modular Building Institute. *Permanent Modular Construction* [Online] 2011. Available from: http://www.modular.org/documents/document_publication/2011permanent.pdf [Accessed 5 August 2013]

[156] Velamati, S. *Feasibility, Benefits and Challenges of Modular Construction of Modular Construction in High Rise Development in the United States: A Developer's Perspective*. Master Thesis. Massachusetts Institute of Technology; 2012

[157] McGraw Hill Construction. *Prefabrication and Modularization: Increasing Productivity in the Construction Industry* [Online] 2011. Available from: http://www.asce.org/uploadedFiles/Industry_Outlook_-_New/MHC%20Prefabrication%20%20Modularization%20SMR%20%282011%29.pdf [Accessed 5 August 2013]

[158] Buildings: Smarter Facility Management. *Modular Construction: Alternative Building in a Though Economy* [Online] Available from: http://www.buildings.com/article-details/articleid/13275/title/-modular-construction-alternative-building-in-a-tough-economy.aspx [Accessed 4 August 2013]

[159] Architecture Lab. *Modular Construction is gaining popularity across New York City* [Online] Available from: http://architecturelab.net/2013/03/modular-construction-is-gaining-popularity-across-new-york-city/ [Accessed 8 August 2013]

[160] Cameron, P; Carlo, N. *Piecing Together Modular: Understanding the Benefits and Limitations of Modular Construction Methods for Multifamily Development*. Master Thesis. Massachusetts Institute of Technology; 2007

[161] Wired. *Meet the Man Who Built a 30-Story Building in 15 Days* [Online] Available from: http://www.wired.com/design/2012/09/broad-sustainable-building-instant-skyscraper/all?pid=924 [Accessed 8 August 2013]

[162] Doran, D; Giannakis, M. An examination of a modular supply chain: a construction sector perspective. *Supply Chain Management: An International Journal* [Online] 2011; 16(4): 260-270. Available from: DOI: 10.1108/13598541111139071 [Accessed 23 September 2013]

[163] Lawson, R; Ogden, R. 'Hybrid' light steel panel and modular systems. *Thin - Walled Structures* [Online] 2008; 46(7-9): 720-730. Available from: DOI:10.1016/j.tws.2008.01.042 [Accessed 23 September 2013]

[164] Lawson, R; Ogden, R; Bergin; R. Application of Modular Construction in High Rise Buildings. *Journal of Architecture and Engineering* [Online] 2012; 18(2): 148-154. Available from: DOI: 10.1061/(ASCE)AE.1943-5568.0000057 [Accessed 30 September 2013]

[165] Lawson, R; Richards, J. Modular design for high-rise buildings. *Proceedings of the Institution of Civil Engineering - Structures and Buildings* [Online] 2010; 163(3): 151-164. Available from: 10.1680/stbu.2010.163.3.151 [Accessed 30 September 2013]

[166] Victoria Hall. *Student Accommodation* [Online] Available from: http://wolverhampton.victoriahall.com/ [Accessed 30 September 2013]

[167] Architectural Profiles Limited. *Victoria Hall: Architectural Profiles Limited and Europe's tallest modular building* [Online] Available from: http://www.archprof.co.uk/news/victoria_hall.php [Accessed 30 September 2013]

[168] Archdaily. *Atlantic Yards: B2Bklyn/SHoP Architects* [Online] Available from: http://www.archdaily.com/187144/atlantic-yards-b2-bklyn-shop-architects/

[169] Broad Sustainable Building (BSB). *T30 Tower Hotel: Technical Briefing* [Online] Broad Sustainable Building; 2012. Available from: http://www.greenindustryplatform.org/wp-content/uploads/2013/07/Broad-Group-BSB-T30-Tower-Hotel_Technical-Briefing.pdf [Accessed 30 September 2013]

[170] Wired. *Meet the Man Who Built a 30-Story Building in 15 Days* [Online] Available from: http://www.wired.com/design/2012/09/broad-sustainable-building-instant-skyscraper/all?pid=959 [Accessed 11 August 2013]

[171] Wired. *Meet the Man Who Built a 30-Story Building in 15 Days* [Online] Available from: http://www.wired.com/design/2012/09/broad-sustainable-building-instant-skyscraper/all?pid=923 [Accessed 11 August 2013]

[172] Daily Mail. *What could possibly go wrong? Chinese company plans to build world's tallest skyscraper - in just three months* [Online] Available from: http://www.dailymail.co.uk/sciencetech/article-2236300/Chinese-company-plans-build-worlds-tallest-skyscraper--just-THREE-MONTHS.html [Accessed 23 August 2013]

[173] China Daily USA. *Sky City falls short in safety features: Critics* [Online] Available from: http://usa.chinadaily.com.cn/epaper/2012-11/29/content_15971613.htm [Accessed 24 August 2013]

[174] Treehugger. *One Building, One City: World's tallest prefab, Sky City, is breaking ground in June* [Online] Available from: http://www.treehugger.com/modular-design/one-building-one-city-worlds-tallest-prefab-breaking-ground-june.html [Accessed 11 August 2013]

[175] Arabian Business. *Can China build its Burj beater in 90 days?* [Online] Available from: http://www.arabianbusiness.com/can-china-build-its-burj-beater-in-90-days--469055.html?page=0 [Accessed 11 August 2013]

[176] South Morning China Post. *Changsha skyscraper faces brickbats and praise as safety concerns raised* [Online] Available from: http://www.scmp.com/news/china/article/1288748/changsha-skyscraper-faces-brickbats-and-praise [Accessed 13 August 2013]

[177] Treehugger. Ground broken on Sky City, the world's tallest prefabricated (or any kind of) building [Online] Available from: http://www.treehugger.com/modular-design/ground-broken-sky-city-worlds-tallest-prefabricated-or-any-kind-building.html [Accessed 11 August 2013]

[178] Arabian Business. *Can China build its Burj beater in 90 days?* [Online] Available from http://www.arabianbusiness.com/can-china-build-its-burj-beater-in-90-days--469055.html?page=1 [Accessed 11 August 2013]

[179] Designboom. *World's tallest building, sky city will break ground next month in China* [Online] Available from: http://www.designboom.com/architecture/worlds-tallest-building-sky-city-will-break-ground-next-month-in-china/ [Accessed 16 August 2013]