

The feasibility of the earthscraper design concept

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## **Abstract**

Presently, the design basis for urban areas with a scarcity of surface space is the construction of skyscrapers. Skyscrapers, even with a lot of challenges, have been a great solution for the development of large urban areas since their introduction, per modern definition, in the early 1900's (Kelley, 2010). This has allowed us to have a "reach a new height" type of mentality, with which the industry has been able to develop new construction ideas and concepts to improve, if not reinvent, those that have been used for nearly a century.

The appreciation and application of new concepts will lead us into a progressive path to improve the overall designs within the industry. The concept of earthscrapers, best described as an underground skyscraper, is very intriguing but more than anything attractive to those in the industry. These new concepts will also bring a set of new challenges, with which solutions will arise. The concept of earthscrapers is a major game changer, with a design that offers several comparison and contrast points to skyscrapers. Some of the main focus points when discussing the approach of designing earthscrapers in comparison to skyscrapers are its space constraints, structure stability, and energy efficiency. Consequently, the paper will review the technical literature within the industry on these three subjects and evaluate their advantages and disadvantages. At the same time the paper will be reviewing the building systems of safety, mechanical, electrical and lighting applicable to this concept and discuss its challenges and effects on the overall design.

Overall, this report covers and evaluates research done surrounding this design concept as well as providing topics and information that will need further testing and investigation. Initially, it covers further description of the two design solutions being discussed, skyscraper and earthscrapers, as well as its challenges and future development. The report will follow by an

evaluation of the different ways that these designs provide a solution in regards to space scarcity in urban areas, as well as what each requires to be classified as an efficient design. Then, different engineering system implementations in these designs are introduced and a comparison is presented with the most up to date information available in the industry. All this with the purpose to give an idea of the differences in energy efficiency between designs as well as some of the social and psychological effects that these may have on the occupants and community.

Finally, an overall evaluation is made in regards to the different benefits and challenges that approaching this new design concept faces, while also providing some recommendations on what could be done within the industry in order to make this possibility a reality.

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Finally, I would like to thank those that have played an important role in my life in order to help me get to where I am today.



## **Dedication**

I would like to dedicate the hard work and commitment done in this report and throughout my college career to my little brother and parents. I would also like to dedicate this work to all those people that have come to this country with dreams and aspirations to make a better life for those around them, themselves and their future generations.

## **Chapter 1 - Introduction**

One solution to the scarcity of surface space in densely populated cities has been the construction of skyscrapers. Skyscrapers have had a huge impact in the development of cities. Finding new ways to make “buildings taller by providing much more structural support” has led to the use of bigger surface areas, the addition of stronger soil and much more material for the foundations alone (Banavalkar, 2012). In addition, skyscrapers require restrictions and codes regulating “structural, flame, smoke, mechanical and plumbing control in order to improve their quality” and safety (Jones, 2010). However, since many of these “codes were developed after the early skyscraper era, between the early 1900’s and post-World War II” (Kelley, 2010), it has led to the creation of new codes to ensure that the presence of skyscrapers does not jeopardize the quality and functionality of adjacent low-rise buildings.

On the other hand, underground civil engineering works could help solve the problems skyscrapers were meant to solve. In urban areas such as London or New York, or the chaotic, fast –growing cities of India and East Asia, there just isn’t much space on the surface. Taking a small ground footprint and building upwards into a skyscraper, the choice for maximizing space since the 1920’s, has its limitations. The earthscraper, which has been designed for a specific location in Mexico City by BNKR Arquitectura, is best described as an underground skyscraper that will provide the option to deal with the issues of not having enough surface area while not jeopardizing the important neighboring buildings (Nathan, 2015). With this in mind, if the industry wants to start implementing new concepts such as the earthscrapers that could require less use of surface area, it has to be shown that all the concerns and questions regarding their feasibility and security have been addressed.

Projects on a smaller scale are currently being completed. Even though the projects that are currently in progress may be different than earthscrapers, they deal with the main concept of underground construction (Yuan, 2008). Consequently, with this information, the report will review the concerns about space constraints, structural stability, energy efficiency and systems efficiency, so that it may be assessed as to what benefits they would have, as well as to how feasible it is to build earthscrapers.

Due to the recent introduction of earthscrapers as a solution for urban areas, there is some limitation in the research and testing done within the parameters that will apply to a structure under these specific conditions. Therefore, the paper has gathered information from scientific and engineering articles relating to similar tested conditions and applicable theories by using databases provided by the Kansas State University libraries and the industry, as well as the expertise of faculty staff members within the Department of Architectural Engineering and Construction Science and Management.

## **Chapter 2 - Construction Concepts for Urban Areas**

Through reviewing current technical literature on architecture and engineering, it is found that a series of new construction methods are being applied in order to modify and improve the way the expansion of urban areas are dealt with. These new concepts are being researched and developed with the purpose to provide better solutions to the scarcity of surface space in densely populated areas.

The main design concepts that the paper focuses on, due to their current relevance as well as their major comparison and contrast points, are those of skyscrapers and earthscrapers. Each concept has distinctive strengths and weaknesses, and even though they have a lot of similarities in which to compare, they both have certain major differences that makes them stand out in different application methods. It is also found that both skyscrapers and earthscrapers are the most popular concepts to improve existing methods to construct, or find new ones, that are applicable to urban areas. Since these concepts are currently the two major forms of a solution to the scarcity of space, they are also the ones with the most potential of improvement or expansion.

Currently, scientists and engineers are thoroughly investigating and improving the construction processes for both of these concepts, in order to assure the feasibility of the expansion of each, while still obtaining the most beneficial outcome. However, some of these researches require a lot of time and funding, as some of the aspects of each concept have not been tested or faced before. In the following two sections, the paper briefly describes more in depth each design concept along with the reasons and concerns for continuing their research and development.

## Skyscrapers

Skyscrapers, per modern definition, are tall and continuously habitable building structures, with at least 12 floors, typically built well above their environment and changing the overall skyline. These structures consist of a contiguous set of floors from grade to roof, which are mostly designed for office, commercial and residential use. A typical feature of skyscrapers is having a steel framework that supports curtain walls. Modern skyscrapers' walls are not load-bearing and most skyscrapers are characterized by large surface areas of windows made possible by the concepts of steel framing. However, skyscrapers can have curtain walls that mimic conventional walls with a small surface area of windows. Through the implementation of new research, most modern skyscrapers have a tubular design structure with a wide base in order to better resist lateral loads, such as wind and seismic loads, by providing less surface area exposure to the wind and a sturdier base (Nathan, 2015). The paper discusses this design more in detail in regards to space constraints and structural stability in chapter 4 and 5 of this report.

As stated earlier in the introduction, skyscrapers have been in implementation since the early 1900's and due to their attractive features they have been able to remain as the leading construction concept for developing big urban areas. Seeing big structures take the skyline, and get higher and higher as new ones are built, is definitely a big impact for the design of urban areas. It provides a habitable and conditioned solution for densely populated areas, while also giving the cities the scenic view that sets a standard for future designs. However, these big structures also brought several complications that at the time were not foreseen. These complications, such as the loads and heights of the structure in comparison to its surroundings, have led to the creation of several codes and standards, in order to assure that both construction and design occur within various parameters, some later discussed in this report. At the same

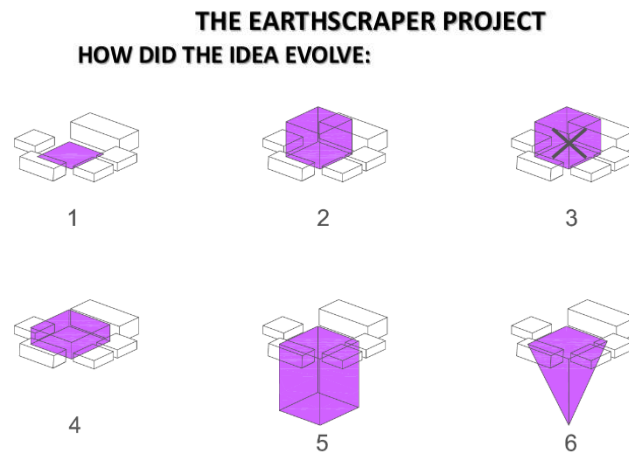
time these codes have been created with the purpose to prevent or minimize the probability of accidents or disasters that may occur due to many factors, such as earthquakes, hurricanes, and even terrorist attacks. Many of these factors are not possible to control, which is why it is important to maintain and continue the research and development of solutions and codes in order to minimize the risk of these structures failing due to any of these factors or any others.

## **Earthscrapers**

Earthscrapers as briefly introduced, are best described as an underground skyscraper, but it can be explicitly defined as an underground building that has many segments of floors with a roof at ground level. However, this does not mean that an earthscraper has the same qualities or elements as those of a skyscraper. Due to its recent concept introduction, there is not a single entity that fully defines an earthscraper's parameters. However, these parameters can be initially based on the prospective project that is located in Mexico City, as a conceptual design for a 40-65 story inverted pyramid infrastructure that runs 300 meters down.

As mentioned before, even though the idea might have originated from that of a skyscraper, the earthscraper has its own features that make it completely different from a skyscraper. One of the main things that make the earthscraper stand out is its feature of being underground, and with this, not having to deal with some of the lateral loads that aboveground buildings have to take into account. With this feature it also adds the benefit of having the surrounding earth component as a structural support and distributor, as well as a natural thermal insulator for the building. The natural thermal insulator will help with the internal conditions of the building while still providing a quiet underground environment (Yu, 2011). However these features could also, by playing the role of a double-edged sword, create some concerns in regards to its structural and aesthetic lasting integrity.

When thinking more in depth about this design concept, concerns such as how much pressure the soil will actually exert on the structure, as well as how safe escape routes and safety systems can be designed for emergency cases, such as fires and floods, rise in the mind of everyone involved (Yuan, 2008). These reasons and concerns is why it is important to continue the research and development of testing, to ensure that all questions are answered to the outmost extent of knowledge, in order to pursue the best designs of current and future cities.



**Figure 2-1 Modeling of the Earthscraper Project (Recreated from BNKR Slideshare, 2012).**

As shown in Figure 2-1, the design of the earthscraper project took more than a couple of steps. Starting with the idea of the space that it is intended to be occupied (1), following with the common concept of construction, which is the skyscraper (2). However, the design was analyzed to be inadequate for the area due to its surroundings and the codes that are in place (3) (Jones, 2010). Subsequently evolving, it took the design into a different, lower, direction as well as to try to maximize the space to be occupied (4). Seeing how this was still an issue, further design development took the structure underground (5). Finally, making sure that the structure is stable, by utilizing the most appropriate and strongest structural shape, which is based on triangles forming a pyramid (6) (Nathan, 2015). This and other structural stability concepts are furthered explained in chapter 5 of this report.

## **Chapter 3 - Evaluation of Solutions for Scarcity of Space**

This paper has researched the two methods of construction as a solution for densely populated urban areas, and has evaluated them based on the following selected criteria: space constraints, structural stability, safety systems, energy efficiency, mechanical/electrical/lighting systems, and feasibility of construction.

Space constraints and structural stability are essential construction and design factors for the evaluation of which method should be used as a solution for urban areas. Therefore, the report will evaluate the different ways by which both earthscrapers and skyscrapers are constrained based on their location, space utilizations and surrounding complications with the overall project.

It is important to make sure that there are ways to assure the safety of the structure and more importantly the occupants, by providing adequate safety and special systems. The report will discuss the different methods that are currently being implemented in skyscrapers in order to assure that these systems are adequate. As well as discussing the complications and development of such systems. At the same time the report will discuss the opportunity that the earthscraper design concept provides for these systems.

Energy efficiency and the engineering systems are equally important, as they go hand in hand in order to assure that the structure will have a reliable process within the industry, as well as providing a successful outcome for the project. The report will cover some of the different engineering systems that are being implemented in current building designs. The report will also discuss the potential challenges for certain engineering system applications, as well as the challenges and developments that each offers for an earthscraper. Specific case studies of



HVAC systems and daylight harvesting are further explained in chapters 7 and 8, respectively, of this report.

Finally, it is essential to evaluate the feasibility of construction of the design concepts, as this provides the necessary information to state what improvements need to be made in the process in order to obtain a better design. In the following chapters, the paper evaluates a bit more in depth the criteria briefly described for both skyscrapers and earthscrapers as well as some of their advantages and disadvantages. The intent of this report is to provide the reader with enough information to have a better understanding of the design concept of an earthscraper as well as how its feasibility compares to that of current design concepts, such as skyscrapers.

## Chapter 4 - Space Constraints

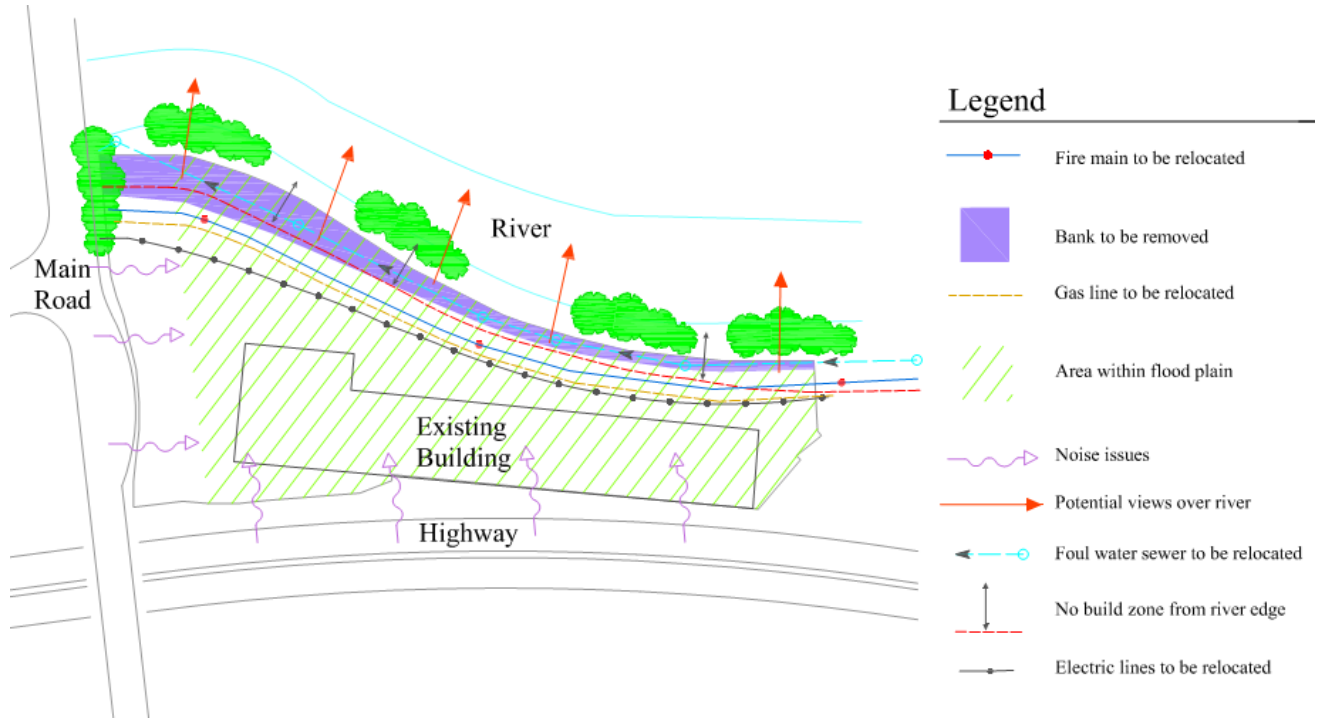
When talking about space constraints, it refers not just to the physical constraints that each method may face in regards to the area and environment, but it also “involves the limitations that each method may have in regards to the systems, resources and elements” (Rogoff, Screve, 2010) that can or cannot be implemented. In some sites, for example, it might be more suitable to use a certain type of source for heating such as electrical over gas. However in some other cases it may be better to use gas, which would require the additional design and at the same time affect the overall process and design of the structure and its terrain.

In the architectural design of the project, space constraint is a major factor as to the direction that the project may take. The more physical space available, the more liberty there is as to what things to create. However, due to high population and commercial growth, most of today’s urban areas do not have this liberty, and have to find the most appropriate solution with the given conditions. For that reason, the development of new components and designs for different systems has been a striving force within the industry.

Space constraints help define what factors in the surrounding environment will have the biggest effects in the structure. For example, we can think of the type of use that the space is intended for, which will define the amount of space that can be designated for a given purpose. This at the same time will limit the type of systems, such as mechanical, electrical, acoustic, lighting, among others that will be used in order to condition the space to the desired levels.

However, when talking about limitations, it is not necessarily talking about a complete series of disadvantages, but rather an opportunity with parameters that guide the aspects which lead to the overall desired outcome of the project. These parameters are what make each

structure unique, while giving the design something to work towards in order to make it better than previous similar projects or the first of its kind.



**Figure 4-1 Site Constraints Map (Recreated from Rogoff, Screve, 2010).**

As shown in Figure 4-1, Constraints of all types affect the site of construction and therefore the design for the project. First, taking into account the physical limitations, that give us parameters in which to design within. Noted with a red dotted line and perpendicular arrows, is the “no building zone from the river edge”. In Figure 4-1 are also the hatched and colored areas available for design, that need modification and special attention prior and during the construction. Finally, we take into account the constraints that mainly affect the design of the systems and other aspects of the building. The main systems to be affected by the constraints in Figure 4-1 are: electrical, mechanical, plumbing and acoustics, shown by a black line with a dot, a yellow hatched line, a blue line with a red dot, a blue line with a black arrow and a purple squiggly line with an arrow, respectively.

## Skyscrapers

Skyscrapers have evolved a lot through their almost full century of being used as the main solution for scarcity of surface space. The goal is to be able to provide a better habitable, conditioned space to as much population as possible while using the least amount of surface area. In order to accomplish this, skyscrapers have to aim for reaching greater heights on every opportunity. Unfortunately, this also means that we need ways to reach the nowadays “Megatall” heights (Gorse, Johnston, Pritchard, 2012). This requires a stronger and wider base, as further explained in the structural stability chapter of this report, which is disadvantageous to the main purpose of using less surface space. However, these big structures as stated before in this report, have led to the implementation of new codes, standards and regulations that have added onto the already many existing constraints for construction. Some of these constraints derive from codes and standards such as the International Building Code, Steel Construction Manual, ASHRAE Handbook, National Electrical Code, IES Handbook and many more.

On the other hand, if the conditions are adequate, and the desired heights are able to be met, the big structures do provide a great urban landscape. However, every aspect of the surrounding environment has to be taken into consideration, and sometimes having such a large exposed surface to many influential things such as high wind loads with pollutants, large periods of sunlight, and the direct noise from the rest of the city can be jeopardizing. Having the building directly exposed to the air in a large urban area means that the air has to be conditioned in order to eradicate all contaminants and make it suitable for the interior environment, especially as contaminants tend to rise in the atmosphere. This requires specific mechanical systems that, depending on the purpose of the building, could cost highly, especially for large spaces. In regards to big periods of sunlight exposure, it can be good for the habitants of the

buildings as it has been proven to have both physical and psychological benefits (Heschong, 2009). However, space constraints may limit or over expose a structure to amounts of daylight. In addition, sunlight can drastically increase the internal thermal loads of a building and raise the cost of maintaining interior conditions by a huge factor. Finally, with noise being a big factor in urban areas, it is important to consider that the interior environment is most likely preferred to remain at low noise levels. In order to achieve these noise levels, considering space constraints, special acoustical systems need to be installed for both walls and windows which will once again raise the overall cost of construction, maintenance and future additions.

### **Earthscrapers**

Having a new challenger to the skyscrapers is surely attractive, especially when the design is considered to be as innovative as that of the earthscrapers. The goal is the same, to be able to provide a better habitable, conditioned space to as much population as possible while still using the least amount of surface area. The constraints in regards to codes and regulations are currently less than those of a skyscraper, given that many of these codes are still in development stages for many of the design aspects, as no structure exactly like this has been put into effect before. However, many of the other general constraints, standards and considerations discussed still apply.

Even though the use of surface area will be considerably less than that occupied by a skyscraper, most of the structural load can more easily transfer onto the body of soil, the underground cubic area will have a different effect on the way restrictions are dealt with by an earthscraper. First, it has to be taken in consideration whether or not the soil is suitable to sustain a building at given depths, as explained in the structural stability chapter of this report, if not there will need to be soil exchange costs. At the same time it has to be assured that throughout

this process no existing underground systems and utility lines are damaged, which may lead to many cases of rerouting, adding some cost (Yuan, 2008).

Another few constraints to take into account are those of noise, natural light exposure and future expansion. In this case however noise might be more of an advantage, as the soil surrounding the structure will act as natural noise cancellation, making it easier to obtain the desired noise levels within the structure.

As for the natural light, it is important to obtain the desired amounts of exposure in order to provide a benefit to the habitants' physical and mental conditions, which in this case can be somewhat limiting and harder to accomplish. Even though this will be harder to achieve, it can be done through the help of a series of strong glass panels at the ground surface followed by the use of glass channels and fiber optics that will help carry and diffuse the natural light throughout the structure. This will make the structure obtain the necessary natural light, and with the help of insulation naturally obtained from the soil, as further explained in the energy efficiency section and engineering systems chapter of this report, maintain low internal thermal loads from the heat.

In addition to the use of glass panels and channels, due to the constraints being discussed, the implementation of an innovative new lighting concept can be used in order to project a realistic outside view which would also help with providing psychological benefits to the occupants. An example of this is artificial natural lighting systems, which are further described in chapter 8 of this report. This adds value to the structure in the aspect of being able to obtain desired views regardless of the location of the project. However this would also add a major price tag to the overall cost of the project.

When talking about the implementation of a new design concept, such as earthscrapers, is important to acknowledge that even though this might be the next step in design, engineering and

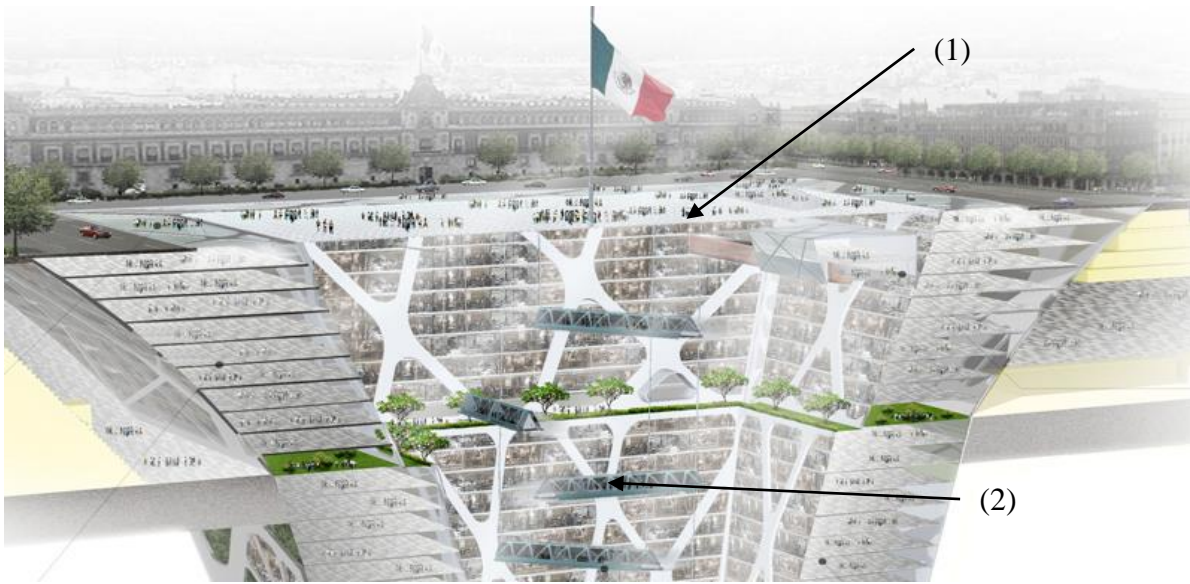
construction, a vision of future developments and expansions for this or new ideas will be needed. In order to be able to continue with the expansion of earthscrapers, the accessibility of underground space will be required. Being that this design concept is fairly new and just in prospective, it cannot yet be confirmed whether the possibility for future expansions is feasible.

Focusing on the aspect of space constraints, the possibility of expanding an underground structure of this magnitude, without causing damage to itself or its surroundings, is narrow. Until further research and testing is done in regards the possibility of being able to expand this structure after years of being built, is another aspect of space constraints that would not be as flexible. However, when talking about how the space constraints affect the amount of usable floor space in a structure in comparison to the net gross floor area, earthscrapers could allow for better ratios as shown in Table 4-1. Skyscrapers require a series of structural supports that occupy much of the usable floor space, but earthscrapers would reduce that need.

**Table 4-1 Office Building Efficiency Ratios (Created from information obtained in Aysin and Ozgen, 2009).**

<b>Number of Stories</b>	<b>Skyscraper Efficiency (%)</b>	<b>Earthscraper Efficiency (%)</b>
<b>2-4</b>	83-86	90-93
<b>5-9</b>	79-83	87-90
<b>10-19</b>	72-80	84-89
<b>20-29</b>	70-78	82-86
<b>30-39</b>	69-75	78-82
<b>40+</b>	68-73	76-80

Table 4-1 shows the ratios (efficiency), of usable space and the net floor space, within a structure for offices and other needed spaces. Table 4-1 also shows a comparison of what has been observed and recorded for skyscrapers and what would be expected for an earthscraper.



**Figure 4-2 Earthscraper Cross Section Rendering (Adapted from van Dronkelaar, 2014).**

As shown in Figure 4-2, the cross section of the earthscraper shows the light coming in through the ground surface glass (1) and using the channels to transmit the light throughout the entire structure (2) as described in this chapter.



## **Chapter 5 - Structural Stability**

One of the aspects when it comes to the overall design of a structure and its outcome is that of structural stability. This is due mainly to the fact that ever since structures have been constructed, there have been many successes as well as failures based solely upon this factor. Uncontrollable events and sometimes the inexperience with different factors, such as fully taking in account all the possible loads that apply to a specific structure in a specific location, are crucial in order to sustain it. Along with this, is important to address that many failures have also taken place due to the poor performance of contractors and engineers. Therefore, it needs to be a priority to make sure that no load and stability factors are missed in the process of calculating for the design of structural stability.

This chapter will generally discuss what some of the issues are for earthscrapers and how the development and study of these will allow for better future designs. This chapter, however, will not discuss in detail and will not provide any specific data of the factors that need to be taken into consideration for any specific given project.

### **Skyscrapers**

One of the main challenges over the past century in regards to skyscrapers has been how to keep expanding our building up without the necessity to occupy more surface space. Unfortunately, unless we want to spend all of the allocated money in obtaining super high structural supports or proper core designs, it is crucial to find ways in which to transfer all the loads to the biggest area in contact, the ground.

One way that modern structures, such as the Burj Khalifa in Dubai, have managed to reach such massive heights is due to the expansion of their base and shape of it. The base of such structures needs to occupy bigger surface areas in order to sustain its height as well as to

provide the necessary support for the loads in effect. The shape of the base is also crucial, for example the Burj Khalifa being a three-legged triangular shape, it allows for a proper distribution of the loads in the structure. It also sets the structural and geometrical strength that it provides to the structure (Nathan 2015) while giving it a pleasant aesthetic look.

If the intent to making skyscrapers even taller continues, then the necessity for new research and constant testing will be required. This kind of time and investment can, in part, also be put into the research and development of new designs, such as earthscrapers, which if given the time can be of great benefit for the structural industry in general.

## **Earthscrapers**

It has to be understood that even though earthscrapers are structures with the same intent that skyscrapers provide, they react to many of the structural factors in very different ways.

Earthscrapers, being underground, deal with a very different series of internal and external loads.

A major factor that plays an important role is that of an earthquake. Since the structure is underground, forces such as the frequency created acts differently as these go to the bedrock depth, which reduces the amplification of such force. An underground structure also reacts along with the soil, loading and wave motion is more or less uniform and in sync with the exterior of the structure.

The design proposed for the earthscraper located in Mexico City is that of an inverted pyramid. This is because triangles, being the strongest geometric shape, are very hard to distort because of their fixed angles and ability to distribute force evenly to its sides as well as adjacent triangle shapes.

In earthscrapers, the pressure caused by the soil around the structure is a very impactful factor that magnifies as depth increases, which is a concern to take into account for both design

and constructability. These kind of pressures will vary and increase with further depths. This may require detailed testing and investigation of the soil properties in the location where the project will be located.

## **Chapter 6 - Safety and Special Systems**

Whether the project constitutes a new design idea or the design process that has been used for nearly a century, the main focus of assuring structural and occupant safety is priority to its overall success. As discussed in the introduction of this report, a series of codes and standards have been created between the early skyscraper era and post-World War II. Even though a lot of these codes' priorities initially focused on the safety and stability of the structure, many, if not most, codes and standards have been modified and updated to assure the safety of the occupants as well. These codes continue to be updated and changed as new concepts and improvements come about.

A major factor in the modification of codes has been the experience to new threats to both structures and occupants. Drastic climate changes, the study of frequency for natural disasters and the threat of domestic or foreign terrorism have been crucial in the implementation of new measures, designs and techniques. An example is that of the events of September 11, 2001, after that many of the structural and safety codes and standards, such as the IBC, NFPA, NEC, AISC Manual and others, were strictly looked at in order to make the necessary additions or modifications. This is all done in order to strive for better, safer systems and structure designs that focus in the safety of the occupants.

The big scope of safety and special systems covers from anything dealing with communications to anything dealing with safety, security and emergency response systems. Each one dealing with its own sublevels of different and complicated designs. Every structure, as similar as it might be to others, is unique in certain aspects of its design and therefore the codes and standards of safety and special systems are applied in many different ways. Several things need to be taken into account when thinking of the design of these systems. Factors, such

as the purpose of every space within the structure, the type of equipment within the space, the materials use for construction, paths of evacuation, and more have to be all taken into consideration.

The design of this system is significantly affected by the type of structural design and space constraints that the project may have. Nevertheless, these safety systems also play a huge factor in the way many of the other systems may be designed, such as mechanical, plumbing and electrical, mainly based on the amount of additional air exhaustion, water flow or energy demand that safety systems may inflict on them.

Like many of the other systems, the cost of safety and special systems can drastically fluctuate depending on the complexity of it and the purpose that is intended to serve. As already mentioned, the design and parameters of others components of the project will help determine the complexity and therefore the cost of it. However, is crucial to discuss these factors and the desired design possibilities with everybody that is involved or may have an input, including but not limited to the owner(s)/investors, architects, engineers, and contractors. All with the intent to provide the safest and most efficient project that can be afforded.

## **Skyscrapers**

As discussed in the introduction of this report and the initial section of this chapter, many of the code and standard changes that have been made in the past century, have been due to the effect that disasters have had on skyscrapers. These type of experiences have allowed for the research and development of ways in which the systems can avoid, prevent or minimize undesired outcomes. Through research, testing, and unfortunately disastrous experiences, these systems have been able to be designed more rigorously while still being applicable to the necessities of each space.

Considering that the priority is the safety of the occupants, is also important to not lose sight of the other components that are also important to the owners of the structure. Due to the introduction of expensive equipment in structures, such as computers and data centers, and the necessity to protect them as well as the structure itself, there have been developments in the quality and types of materials or methods that are being implemented within safety and special systems. The lessons learned from different disasters such as domestic and foreign terrorism to exposed structures, such as skyscrapers, have also allowed for similar developments of both methods and materials. At the same time it has put in perspective the way that design is perceived and what future threats could arise that different structure should account and be prepared for.

Escape routes in a skyscraper, for example, are a very important and complicated component of these systems. The design of a proper escape route has to take different things in consideration, such as paths of egress for both occupants and emergency response teams, structural stability points of the structure, fire rated components, and many more.

Communication systems have also made big improvements in the past decades, assuring that the proper personnel and occupants are informed of different situations, as well as aware in how to evacuate. It is important to know how these systems are being operated and maintained in order to avoid failures of it. It is also crucial to know what factors surrounding the structure could possibly interfere with the performance of such systems in case of an emergency.

An efficient design of safety and special systems will also incorporate components from other engineering disciplines such as emergency lighting, magnetic locks, mechanical smoke detection and ventilation, among other things.

## **Earthscrapers**

When discussing the safety and special systems within an earthscrapers, the focus of structural and occupant safety remains. However, the process of designing an appropriate system changes in several ways, as many other factors have to be taken into account.

Earthscrapers due to their recent introduction, provide us with a lot of questions and concerns in regards the ability to provide the adequate safety for the occupants. There are many doubts about the efficient ways in which escape routes can function and be designed. However, with this being a big challenge, it is also a great opportunity for the industry, and its subdivisions of engineering, to make major advances and developments in the products and designs that are being implemented when talking about safety and communication systems.

The design of safety and communication systems in an earthscraper will include the concerns that are already taken into account with skyscrapers, however, some of them at a different level of concern. For example, when talking about providing escape routes, besides the common consideration of paths of egress, structural stability points, fire rated components and other things, the thought process has to go a little bit more in depth as to how to make these things more efficient. This is due to the fact that earthscrapers will bring some additional complications, as for example, it takes longer and more physical effort to exit a structure going up, than going down.

In case of a fire, research and testing will have to be conducted in order to determine the direction and rate at which it spreads based on location, as well as if there are additional different ways to suppress it now that the structure is located underground. On the other hand, it also has to be considered whether being underground also limits other existing possibilities of preventing and containing fires, or if it makes them less feasible and more expensive. The current

assumption is that the cost and design of a typically used fire protection system would be the same as in a skyscraper as most of the equipment is routed within the structure.

Considering other natural disasters such as floods, it is crucial to determine what the outcomes and possible solutions are for this specific design concept so that consequently the outcome of the project can be a successful one. Further research needs to be conducted in order to determine whether or not there are ways to prevent or limit these specific concerns in underground structures, as well as to evaluate whether or not there are some geographical areas that are better suited for this design application. Regardless of location, it is important to have the structure be designed to prevent as many problems as possible. The addition of drainage tunnels and drainage systems directed towards the adjacent body of soil, has been discussed as a possible solution, as long as this is distributed appropriately in order to not put at risk the surrounding structural support of the structure.

Other threats to the structure that need to be taken into account for the future of design as previously discussed, are those of domestic and foreign terrorism. A terrorist attack, a bombing for example, within an earthscraper will not behave the same way as it would in a skyscraper, and thus will not have the same effect on the structure. That being said, the possibility of having a structure underground may limit a lot of other terrorist attacks, however, is also important to keep in mind that it might create some concerns in whether or not new kinds of terrorist attacks will be created. Therefore is essential that some of this project and further research is conducted and directed with the assistance and interest of federal organizations.

As mentioned before, the fact that this design concept is new and innovative gives the opportunity for new solution concepts to rise not just within this design, but within the industry in general. Some of the new concepts that have also been recently introduced are those of



implementing an ant algorithm escape route method, which is the concept of creating a series of numerous underground escapes, with the intent of maximizing the amount of escape routes available without jeopardizing the aesthetical design or stability of the structure. The idea of creating as many escape routes as possible, multiple accessible from all different levels of the structure and others accessible from only certain levels, is to minimize the amount of risk that it would create if some of these routes are blocked or inaccessible in case of a certain emergency (Yan, 2013). Thus creating a more secure and flexible safety system, however, this will most likely bring several concerns in regards the overall cost and future expansion of the project.

## Chapter 7 - Engineering Systems

One of the most important aspects of a structure to take into account when designing is that of the engineering systems, such as mechanical, electrical, plumbing and lighting, that are being implemented. These systems are the ones that help establish the functionality of the different spaces within a project. The design and routing of the engineering systems revolve around everything else in the project and vice versa. Designating what type of resources will be used for certain systems will be based upon the surroundings, what is easily accessible and the space constraints as discussed previously in chapter 4. The proper and adequate design of these systems is crucial for the positive and efficient performance of the structure, which is further discussed in this chapter, as well as for the flexibility and lasting life of each system.

The performance of a system has to be considered for both present and possible future functionality. A system can be designed to perform at a very high level for a specific task, but if it is only considered for one specific task, then it may not be as flexible in terms of design in case the space changes. This will cause several problems in the future, not just within that system itself but also with those systems around it.

The efficiency and performance of a system is primordially affected by its surroundings and the task that it is supposed to serve. The better the systems are designed to be able to adapt to its surroundings and use the appropriate resources to run, as well as to interact with other systems, the better it would be for the overall performance of the project.

One big factor to consider when discussing the different engineering systems that will be implemented is their integrated functionality and how each will be affecting the other based on their design and performance. Discussions with all the members that play a role in the development of these systems, as well as with the owner, should be occurring in order to

determine which systems will be the ones that require the most focus. These conversations will also help decide as well which ones will end up being the most complex designs.

Another thing to take into account is the type of materials and components that are being utilized within the entirety of the engineering systems, as well as how long or sustainable these system are expected to be. Materials and components consideration do not just deal with the way each system will affect the other and the conditioning of the space, but also on how it will be affecting the project overall, based on its aesthetical presentation and how some designs may be better suited for certain materials and components of equipment.

These factors and more are just some of the things that will help better establish the parameters of designing the engineering systems. By doing so, aiming to assure that the legacy of the structure will be a positive and long lasting one.

## **Skyscrapers**

Whether it has been by placing tons of ice in a building or by using nearby ponds or lakes with innovative cooling systems, the goal has always been to provide structures with a conditioned environment that is comfortable or acceptable to most occupants. From the first design of mechanical, electrical and plumbing systems, since their implementation in skyscraper in the early 1900's, to today's complex designs, the constant development and improvement has been the focus to any challenge that has come up. With the application of each new system that is designed, new complications appear.

The desired to continue building higher structures has also encouraged the research of systems that would provide a more efficient performance, without jeopardizing the other aspects of the structure. One of the main focuses for the application of new systems is that of obtaining more cost efficiency that will help with the long term savings and investments in a project.

Therefore, the decision of which systems need to be implemented is something that needs to be discussed with all those involved in the project, including the investors. This, with the purpose to determine what the overall desires of the projects are, as well as if initial or long term savings are more important. In ideal situations, both would be implemented, however, long term cost saving systems tend to be such a sophisticated and expensive design that initial high costs cannot be avoided.

In each project there are a series of different complications that come up as the construction process continues. Constant coordination among the designers and contractors is crucial for the proper execution and functionality of all the systems as well as how much demand will be expected from each.

When it comes to skyscrapers, as mentioned before, there is always the desired to create higher structures. A factor that is affected by this, is the amount of load and energy demand that the building is expected to experience. Even though the purpose of the spaces within a skyscraper can be changed and thus increase or decrease such demand of the different engineering systems, skyscrapers cannot easily just change or add height to the entirety of the structure itself. A structure that is designed as a skyscraper can have expansions of adjacent buildings attached to it, but typically these expansions require the addition of separate systems that would run independently from those already set in such structure.

A main thing to consider when the planning and design of a system is occurring is the way that these systems will be laid out and introduced to the structure. For example, when designing a plumbing system, calculations need to be computed in order to help establish the best way to route main, water, sewer and ventilation lines in the building. At the same time determining the necessary amounts of domestic water pressure to maintain within the system, as

in higher levels more pressure is needed, in order to provide a well performing system at all levels of the structure.

Regardless of what the decisions are of the systems being selected, whether it is based off money, efficiency or feasibility, it is good to know that currently there are several different options available and the development for more system designs continues due to the high demand and continuing expansion of this urban space scarcity solution.

### **Earthscrapers**

While the implementation of engineering systems within an earthscraper are as much needed as in a skyscraper, the methods and designs of them might differ in several ways. Many current engineering system designs are solely based on the skyscraper concept that has been used for nearly a century. Thus, making a lot of its improvements and methods of application a little more difficult to incorporate in recently introduced concepts, such as is earthscrapers. While some might be more complicated to implement, there are other systems that could gain a lot more benefit from this design concept.

For example, components of some of the systems, such as sewer lines, depend on basic design aspects such as the use of gravity as a natural flow influence that eases the complication of design in that system. The idea of having a sewer system that will have to actually work against gravity in an earthscraper design, only seems to complicate and challenge things more. However, these challenges already exist in different current projects, simply at a different scale. Therefore, since it is known that there are ways to deal with these kinds of complications, new ideas and better components will have to be developed if the cost of the system wants to be kept low. There is also the constant thought of a system being problematic, not because of the cost or

complexity of design, but simply because the possibility of having some of these piping lines running as such depths could be detrimental to the system itself as well as its components.

As previously discussed in different chapters of this report, many challenges always rise with the introduction of new ideas and concepts. However, these complications are also counterbalanced with the many benefits that these new concepts offer. While some components of plumbing, mechanical ventilation and even emergency power systems may need a more complex design, other aspects of complex engineering systems may become less of a complication or be more efficiently implemented. For example, bringing in and distributing ventilation into depth of this magnitude and being able to circulate fresh air, could cause an increase in the size of units and system components being used. However, one thing to consider is the application of a geothermal system that would greatly benefit the structure in its entirety, as further discussed and explained in the energy efficiency section of this chapter. Since the structure will be within the soil, not only will it help the system perform better, but it could also ease the way the system enters the structure.

Even though this could be seen as an advantage, it is also important to take into account the constant development of engineering systems, which could affect many other things. Test and further research will need to be done in order to determine different design factors that can have a negative or possibly positive effect on projects overall. The structural stability of the project, for example, needs to be crucially considered when determining the location, length and separation of a geothermal system in correlation with the structure. Geothermal systems can potentially be designed within soils at depths of 50-400 feet, which is about 15-120 meters. These depths, in comparison to the proposed initial design of an earthscraper of 300 meters, do not seem like much. The reality is that in order to dig the holes at that depth to be able to route

the necessary piping is very costly and complicated. However, earthscrapers might allow for the implementation of this system to be more feasible, and possibly more efficient, if the construction process of the system occurs from within a sector of the structure. Something else to think about is the new methods or additional equipment needed, as well as the different ways in which it may need to be laid out in order to provide the necessary ventilation and fresh air into lower levels.

Implementing this and other known engineering systems to a new design concept, such as is earthscrapers, will open up new perspectives on how to deal with different issues or complications that arise. As with any engineering system, it will come down to a lot of testing, research and life-cycle cost analyses in order to help determine how well balanced and beneficial to its surroundings a structure designed based on this innovative design concept can be.

### **Energy Efficiency**

When it comes to such big structures, energy is a big focus point related to the feasibility to accomplish a project. Even though we are trying to create very large structures with minimal use of surface area, we are also trying to create the most efficient buildings. Modern structures and construction processes within the industry have a major focus in energy efficiency and the positive outcomes of it. Nowadays we are trying to design and construct structures that efficiently utilize renewable resources, as well as having the least amount of energy consumption while still providing the desirable and most ideal interior conditions. Even though these expectations may seem unrealistic, with the help of organizations such as the United States Green Building Council (USGBC), they are being met and exceeded.

It is important to invest and maintain an energy efficient structure, as it correlates to the architectural design and all engineering systems including electrical, mechanical, lighting and

even plumbing. At the same time this sets us up for new and better standards that will shape the direction in which the design of our urban areas continues to go (Yun, 2011). There are many different factors that play a role into how efficient a system can become, and the best that can be done is to keep finding ways in which to minimize those that have a negative effect. One of the main systems that utilize a lot of energy and that regularly fluctuates throughout the year, is that of a mechanical system. When it comes to meeting the code requirements, is hard to achieve the desired building air qualities and pressures without using the high needed energy demands (van Dronkelaar, 2014). This is why, for the USGBC, this system among others is a main focus to maximizing energy efficiency. In this section of the report I will briefly compare and evaluate the energy efficiency for both concepts of construction, along with some of the main factors that point out their advantages and disadvantages.

## **Skyscrapers**

As mentioned before in chapter 4, due to the fact that high structures are fully exposed to environment conditions, skyscrapers are more directly affected by the climate factors that cause changes within the systems. This type of exposure takes into account several different factors, such as the change in weather, which can be harsh winters or summers, as well as the constant exposure to sunlight.

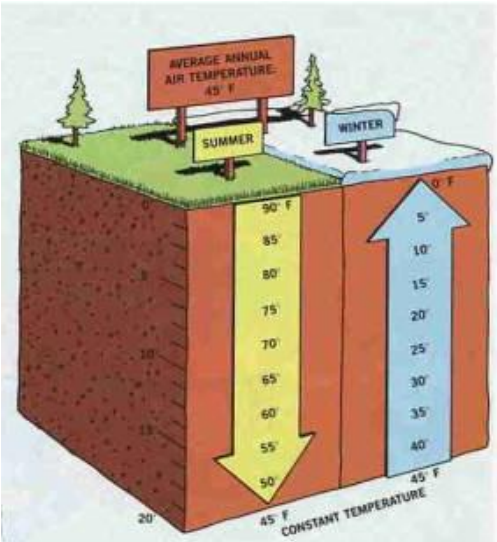
All these variations provoke fluctuations within the systems, mainly the mechanical, which causes high demands of energy (Nathan, 2015). The use of high energy demand is needed to adjust the interior condition to counteract the effect caused by the exterior thermal loads. A way to minimize the effect that external thermal loads have on the structure is to increase the type and rate of insulation. However, in big structures such as skyscrapers this can be a major budget hit.



Sunlight, as also discussed in previous chapters, is a big contributor to the way some of the engineering systems behave and perform, and regardless of the way some solution methods may be implemented it would not eradicate all the effects of exterior thermal loads.

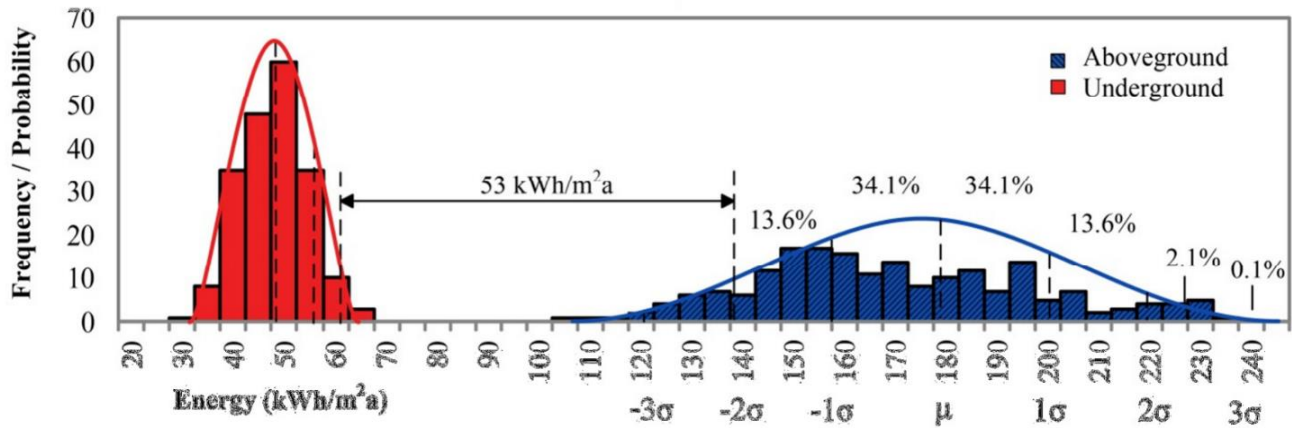
### Earthscrapers

Earthscrapers can help reduce the energy demand by using the large amounts of soil covering the building as insulation, while also using the beneficial earth constant temperatures (van Dronkelaar, 2014). This is further illustrated throughout Figure 7-1, Figure 7-2 and Figure 7-3. Even though the magnitude of the factors affecting loads, such as radiant heat from the sun, vary with the climate of the surroundings, it is shown that the total energy reduction is achievable for all climates and functions (Anselm, 2008). However, as discussed previously in this report, there is a concern as to how much natural light will be able to get into the building in order to have a positive effect, both physically and psychologically, within the inhabitants.



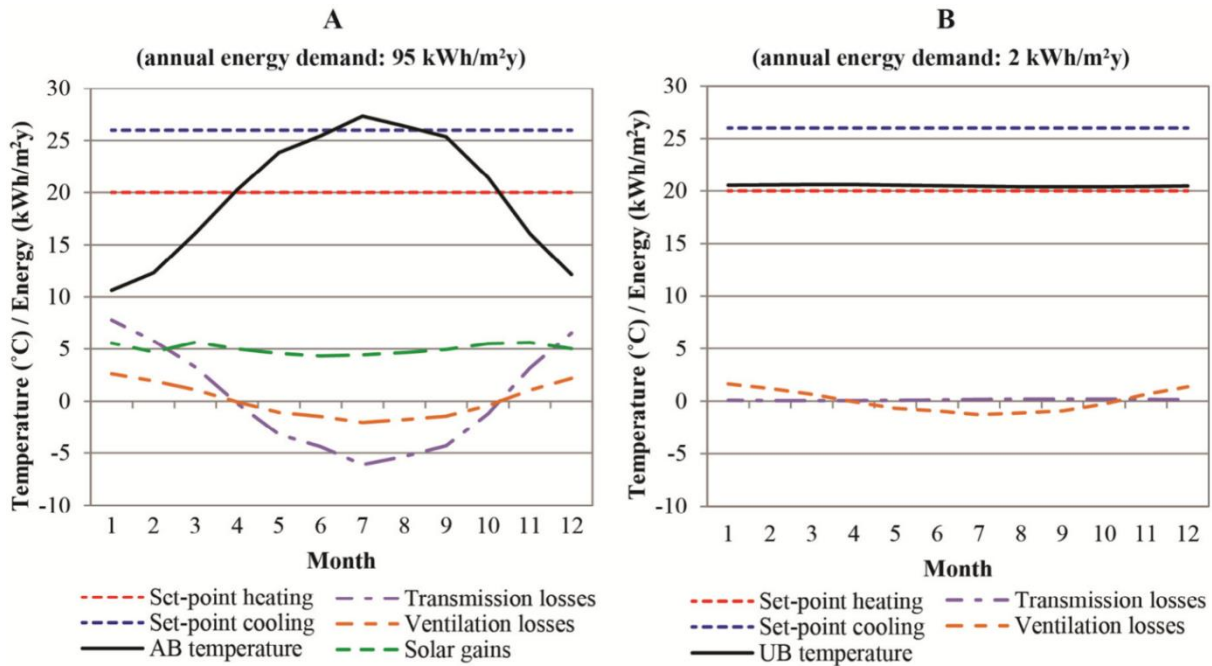
**Figure 7-1 Diagram of Underground Constant Temperature (Reproduced from Anselm, 2008).**

As shown in Figure 7-1, twenty feet under the surface, the soil temperature reflects the average ambient air temperature during the year.



**Figure 7-2 Distribution of the Annual Energy Demand Graph  
(Reproduced from van Dronkelaar, 2014)**

As shown in Figure 7-2, the mean values of annual energy demand (kWh/m<sup>2</sup>a) and its frequency (%) of aboveground buildings in comparison to underground buildings are illustrated in a column chart. The data shows a great range of energy demand for aboveground buildings, varying from 105kWh/m<sup>2</sup>a to 240kWh/m<sup>2</sup>a. On the other hand the data also shows that for underground buildings the energy demand range is much narrower, varying from 30kWh/m<sup>2</sup>a to 65kWh/m<sup>2</sup>a, and that the frequency at which this occurs is much higher and consistent. The chart also illustrates the percentages of probability that certain energy annual demands would occur. This demonstrates how, for aboveground buildings, in big differences of energy demand, such as between 205kWh/m<sup>2</sup>a and 140kWh/m<sup>2</sup>a, the probability can be similar and therefore inconsistent. It also goes to show, that for aboveground buildings, the probability is never high enough to have the certainty that maximum efficiency is achievable regardless of the energy system applied to this building. Figure 7-2 also illustrates that when comparing the best case (lowest energy demand) of the aboveground building with the worst case (highest energy demand) of the underground building, at their higher probability, the difference is a significant 53 kWh/m<sup>2</sup>a.



**Figure 7-3 Energy Balance of an Aboveground (A) and Underground (B) Building (Reproduced from van Dronkelaar, 2014)**

As shown in Figure 7-3, an example of balancing energy flows is given for a domestic building in moderate mid-latitude climate. The figure shows the difference in the variables that play a role in achieving temperature comfort in a building and their effect on energy demand in a period of 12 months. Figure 7-3A shows the data for an aboveground building and the fluctuation of certain variables that determine the temperature comfort within the building. Both heating and cooling set-points remain constant at 20°C and 26°C respectively. However the big fluctuation of the outside air temperature (AB temperature) throughout the year, ranging from 11°C to 28°C, along with the effect of solar gains creates much higher transmission losses. On the other hand, Figure 7-3B shows the same sort of information for the underground building. In this case the heating set-point and the ground temperature (UB temperature) are almost identical, around 20°C. Therefore, temperature variations in the underground building are minimal, transmission losses are insignificant and the building requires a relatively low annual energy

demand of 2kWh/m<sup>2</sup>a in comparison to that of 95kWh/m<sup>2</sup>a in the aboveground building for an ideal space conditioning.

The application of artificial natural lighting as an alternate solution, which uses hundreds of LED displays, could mean an increase in the overall energy demand of the building.

However, since these are LEDs, they have several advantages as in comparison to conventional incandescent and fluorescent light sources typically used in large structures. LEDs have a “lower energy consumption, longer lifetime, improved physical robustness, smaller size, and faster switching” (Hansen, 2014). Therefore, even though the overall demand of energy in an earthscraper might be higher than that of a skyscraper, it might not be by much. At the same time, the utilization of this type of lighting will push the project in the right direction and make its components to be less prone to become obsolete. This makes having the exposure or appearance of natural light within an underground structure much more feasible.

## Chapter 8 - Prospects of Daylight Harvesting

One main component that has really stood out in the research done throughout this report, is that of daylight introduction, as well as its interaction with structures and its effects on both the occupants and the project in general. Daylight introduction is known to make an impact in every project, and it has to always be kept in consideration, as it affects all aesthetical, engineering and comfort aspects of every space.

While daylight, and harvesting of it, does have many benefits to every design it is also important to acknowledge the challenges that it brings, and how these are counteracted by innovative new design applications that improve with every new project. Some of these challenges deal with being able to properly use, locate and route the lighting and daylight harvesting systems that are being implemented. Many solutions come across by simply having a better knowledge of what equipment and design concepts are available out there to ease the amount of complications that come up.

Daylight in general has been implemented in many different ways to benefit people, even before it was purposely introduced within structures. In 400 BC Hippocrates, a Greek philosopher and physician, was a big advocate for heliotherapy, a series of sunlight treatments that would help stimulate body healing properties ("Science Museum ", 2017). During the 14<sup>th</sup> through the 16<sup>th</sup> century, there were several recordings of diseases caused by the lack of sunlight exposure. Also in the mid 1800's, observations were made in hospitals and recovery centers, that showed that direct sunlight promoted a speedy recovery ("Philips", 2017).

Although heliotherapy is directly related to the effects of natural sunlight on the body, it has also become applicable to the effects that alternative artificial sources of ultraviolet, visible and infrared light radiation may have. Is also important to remember that just like many other

things, knowing how to be able to incorporate and possibly repurpose the appropriate amounts of daylight is crucial in order to not have negative effects.

By being able to better manage the quantities and even the times at which occupants are exposed to different wavelengths of sunlight, or therefore a form of it, we can create a system that will bring many more benefits. This would affect the overall project in ways that are not usually as noticeable in cost or building performance data. Health benefits and the overall comfort of the occupants, as previously discussed, are things that should be the primary focuses of the outcomes in a project. Also, it is important to remember to not take away from other focuses of the project, such as how too much exposure may affect the internal thermal loads of a structure and the performance of its engineering systems.

Retinal ganglion cells that are within the eyes, have no direct function in the visual system, but do serve directly to the body clock in order to help synchronize internal and environmental time awareness. This provides the body with the ability to know how much time has passed, as well as when it is time to get the needed rest to recover.

Daylight has all sorts of positive effects on the body as it helps with a variety of mental health concerns, such as depression, stress and general daily performance. At the same time it also gives the body several physical benefits, by providing it with much needed amounts of vitamin D and by helping the body be in a better overall condition in order to prevent diseases. However, there is more to daylight than just light, façade openings also provide us with a combination of views. These views also contribute to the positive effect that daylight has on the occupants. Therefore, it is crucial to keep daylight harvesting in mind as a priority when it comes to discussing the overall desired outcomes of a design, as well as what challenges need to be overcome in order to assure proper implementation.

## Skyscrapers

One of the advantages that skyscrapers has provided is that of being clearly exposed to large amounts of daylight from all angles at different times of the day, as long as weather allows. That has at the same time allowed for the development of new design methods and concepts in which to interact and implement lighting and daylight harvesting systems in general within structures. Ideas that started as simple as the creation of blinds and curtains for windows, have now developed into more complex systems involving things such smart glass, whose light transmission properties change when voltage, light or heat is applied. Another example is that of the application of more complex construction/design processes and lighting systems that interact with other engineering system components in order to minimize unnecessary energy use and maximize efficiency. Astronomical clock or solar positioning control systems is another coordination method that can currently be implemented in order to provide a more efficient and integrated function of those other systems connected to it.

Many more solutions are currently being researched and developed, and one of the main reasons is that the control of daylight and the efforts to focus its purpose is complicated and problematic due to the high levels of exposure. While several regulations have been put in place, future development of higher structures will not only keep bringing bigger issues with urban design and thermal internal loads, but at the same time it could start jeopardizing the available amounts of daylight exposure to other structures in the surroundings. Thus, putting at risk the performance and efficiency of any daylight harvesting methods that neighboring structures might be implementing.

Being able to control and manage daylight has become more expensive and complicated as new methods, software and devices are created. While these challenges are good for the

development of new solutions, it is complicated to find an ultimate solution to something that is such a variant factor as is daylight. Another advantage that skyscrapers have been able to provide, along with exposure to daylight is that of great views of the environment, which depending on the location and height may be highly costly for some. These views are a big influence in the way occupants perceive their environment, and even though some of these highly praised skyline views do have their benefits, they are also a very variant and hard to manage variable.

## **Earthscrapers**

One of the main reasons, besides the fact that it helps the body, for why the development of daylight harvesting has been a big focus of design in structures over the past century is that people already spend most of the day inside of them and typically not all of it in well-lit parts. While daylight harvesting methods have been and continue to be well developed for current typical structure designs, such as skyscrapers, it is not always with the main focus to provide occupants with the appropriate exposure of daylight. Many of these systems tend to focus on improving its efficiency to mainly maximize money savings within the system.

Due to current complications with daylight harvesting and its exposure, most structural designs focus on typically having offices on the façade of buildings. Even though a lot of new aesthetic designs try to implement new methods in which to direct natural daylight within the structure, is hard to make them effective. The design concept of an earthscraper has several concerns in regards to being able to provide the necessary amounts of daylight to its occupants, but the implementation of new daylight harvesting concepts gives it the means to do so.

As previously mentioned in chapter 4 of this report, the application of glass flooring panels at the surface of the structure, along with the use of glass channels and fiber optics, can



help provide some of the needed natural daylight. However, these concepts also have their limitations as natural daylight can only be transferred down so far, about a maximum of 50 meters down, and bounced across channels before it becomes impractical and ineffective. New design concepts, such as using dynamic and artificial natural lighting systems, would allow for the development of new architectural design styles. Architectural designs will have many more design possibilities, than just being constrained to typical elongated designs due to daylight exposure being a façade factor.

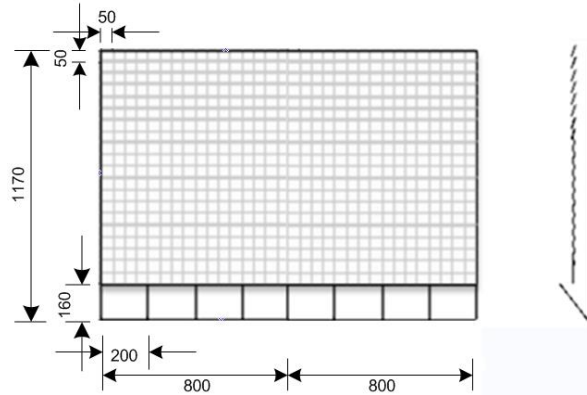
An artificial natural lighting system that is dynamic with its environment can provide many opportunities not just for aesthetic design but for the benefits of occupants' health as well. Artificial natural lighting systems, composed of many light emitting components, are mainly Light Emitting Diode (LED) matrices that attempt to replicate the lighting characteristics and visual perception of natural light (Yun, 2011) as shown in Figure 8-1. The continuing work on this lighting concept focuses on the ability to fully provide not just a perception but also a feeling for authentic natural light. Along with this, the main purpose is to be able to offer the same benefits, in a more controlled method, that daylight has on the body.

Testing and research done with what has currently been developed as artificial natural lighting options have shown many similar effect to those seen when exposure to natural daylight. In the tests people were falling asleep faster, sleeping longer and showing to be less depressed when exposed to the artificial natural lighting than when not, as shown in Figure 8-2.

The design concept of earthscrapers, gives the opportunity to implement these systems and create a more controlled environment that can provide and ease the perception for the occupants as they desire and therefore avoid discomfort. If bad weather outside does not allow for appropriate amounts of daylight then artificial lighting can be properly used in order to

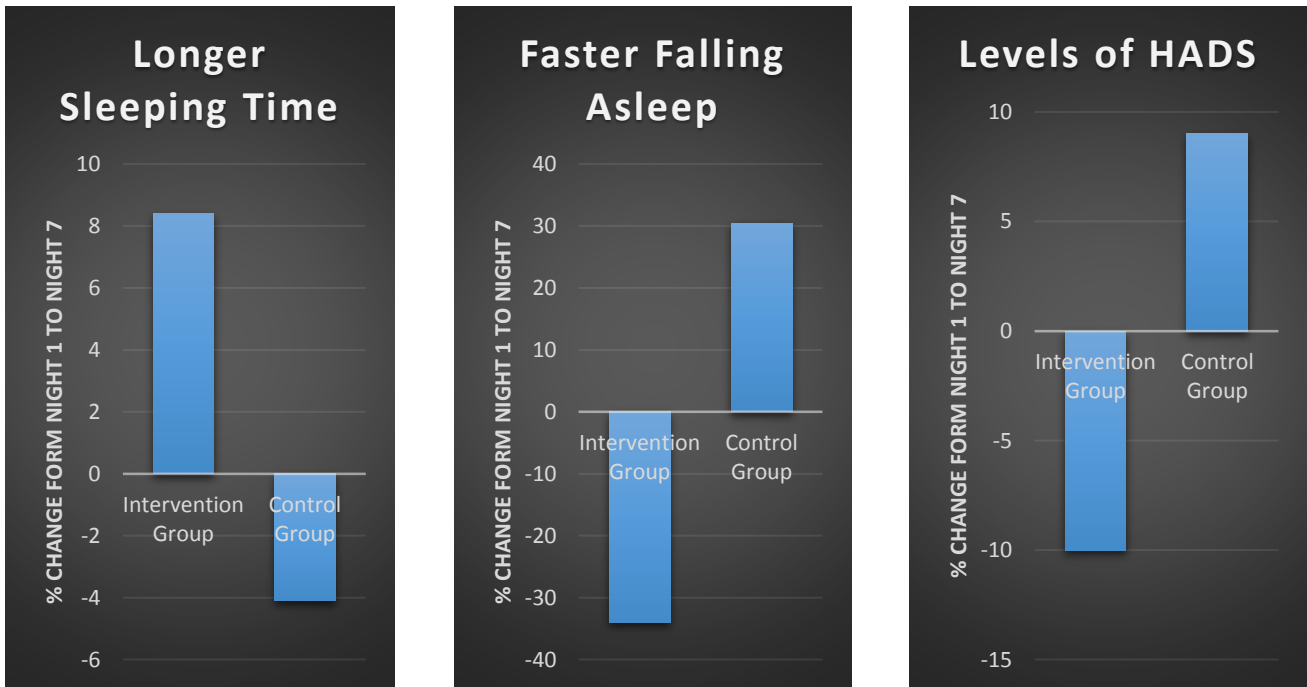
positively impact the occupants. However, it is also important to consider the possible negative effects that this could have in the general perception of the occupants between indoors and reality outside. It is crucial to keep a balance, realistic and proper coordination between outdoor and indoor exposure, whether that is day in contrast to night or rainy versus sunny, in order to not create an environment in which some occupants never feel the need to go outside. These will be discussions that need to occur between all those involved with the project, in order to determine the general purpose of the building and its spaces, as not every occupant may need or want to be affected the same way.

Currently there are no artificial natural lighting systems that fully satisfy all the characteristics of realistic daylight and its views. However, new methods are currently being created in order to deliver a more realistic perception. Some of the main factors that further development will be dealing with both lighting and visual quality are intensity, distribution, spectrum, dynamic, heat, control of information, complexity, coherence and depth of perception. This with the purpose to overcome some other complications such as, being able to project white light while providing blue sky views among other combinations. Further research needs to be conducted to determine how other design factors such as economic value, building performance, balance of energy consumption and reality perception will be affecting the project in general and what will be the next steps in order to be able to create a more desired environment.



**Figure 8-1 Typical Artificial Natural Lighting Matrix Configuration (Recreated from Mangkuto, 2014)**

Figure 8-1 shows the front (right) and side (left) views of an artificial natural lighting system matrix.



**Figure 8-2 Effects of Artificial Lighting (Recreated from Philips, 2017)**

Figure 8-2 shows the different test results of the effects on a group of patients at a hospital that are (intervention group) or are not (control group) exposed to artificial natural lighting. Every chart shows how the group exposed to current artificial natural lighting systems experienced much positive effects than the group that did not.

## Chapter 9 - Conclusion

The progress in the design of future urban areas is crucial in order to maintain and continue to develop the sustainability of cities and its structures. Finding new innovative concepts, such as earthscrapers, to improve or change our current methods of construction are needed. This will challenge and help us make a difference in the things that need improvement within the industry, including design concepts and code basis. Research proves that there are means to develop new ideas and to validate them through testing in order to continue our “thinking outside the box” mentality that will help us reach new heights, and depths (Nathan, 2015).

Space constraint is a big factor when it comes to the development of these ideas and designs. Space constraints consist of more than just physical limitations, it also involves the considerations of every aspect in the surrounding environments and how these affect the overall design of the structure and its systems. Skyscrapers present the biggest range of limitations as they are constantly exposed to the varying environment conditions, as well as the constant parameters set by codes (Anselm, 2008). Earthscrapers, on the other hand, will not have that big of a range of constraints. This is due to the recent introduction of the concept, reducing the amount of code regulations while still keeping crucial ones, as well as eliminating the factor of major exposure to environmental conditions. Thus, making the Earthscraper, the easier option when it comes to design parameters, as long as the new conditions are taken into account, tested and researched more in detail.

Structural stability is one of the main aspect, if not the major, to take into account when developing the design of a structure. In order to make a structure stable, there are many loads and factors to take into consideration. With the proper knowledge of these factors and codes

guidance, calculations and determinations can be made on the sizes and materials that need to be selected for the structural members. Skyscrapers, due to being above the ground surface, are constantly exposed to a wide range of types and magnitudes of loads (Miller, 2002). In order to make higher structures more stable, the use of wider bases is necessary. This demands for more surface area to be occupied and is counterproductive to the initial purpose of the design. On the other hand, earthscrapers will not have such a wide range of loads, making it a more stable structure. However, earthscrapers will be exposed to loads that are still being tested, causing some skeptic views. These unfamiliar loads will require much more temporary structural support, which could cause an increase in the initial cost.

Special systems are crucial in order to obtain a successful project, regardless of the design concept being implemented. Skyscrapers have and continue to help with the development of codes and standards that assure the protection of the structure, but more importantly the occupants. New systems and concepts are being created around these regulations in order to improve the overall safety of structures. Earthscrapers, since there is not as much experience with the design, certainly present several different challenges and uncertainties in regards to safety, communication and response. Understanding these challenges and providing different solutions will require much research and testing, which will eventually lead to some methods that can be effectively implemented. However, just as happened with skyscraper development, further development and drastic advances will just come as time passes and actual application occurs.

Energy efficiency is a main focus point as to how feasible it is to construct a structure in a big urban area. There are many factors that determine the usage of energy within a structure as well as its efficiency. However, mechanical systems are considered the main factors that affect

these components. Therefore, in order to obtain the most energy efficient systems, organizations have set a series of regulations and standards to be met. Skyscrapers, as mentioned before, are constantly exposed to varying exterior conditions and experience very high energy demands. A way to minimize these effects is to provide more and better insulation; however, this will cause a much higher initial cost and some possible counter effects. In the case of earthscrapers, the fact that the structure is underground helps with reducing the energy demands as the surrounding soil acts as a natural thermal insulator. There is a significant difference in energy usage, of 53 kWh/m<sup>2</sup>a, in comparison to skyscrapers (van Dronkelaar, 2014). However, the possible prevention of obtaining the needed amounts of natural light may require alternate solutions to be used, such as artificial natural light systems, which will present an additional cost and energy consumption (Yun, 2011).

Current daylight harvesting solutions for skyscrapers continue to create more and more challenges due to the constant and inconsistent exposure to sunlight. These solutions also do not maximize benefits to the health and performance of the occupants, which should be the main focus, but rather focus on saving money across all the engineering systems. Earthscrapers will allow the focus to shift into other engineering systems in order for them to be more efficient and provide major savings in that aspect. The design concept would also give more purpose to the way that daylight is being utilized as a whole. At the same time this design concept will give a new perspective to the way problems are being approached and therefore create a new series of innovative solutions, such as alternate natural light systems, and their development. As for future design of structures, the expectation is not to fully replace all windows and openings with artificial natural lighting, but instead acknowledge that this is an innovative and exciting solution

for spaces that may need it. Whether it is for simple applications as basements, or for more complex and aspiring concepts such as earthscrapers.

Both concepts of construction present a great solution to the scarcity of space problem that urban areas face. However, each has its own advantages and disadvantages to take into consideration. Skyscrapers have a reliable and acceptable design, for urban areas, that continue their development through research and testing. However, it is important to realize that many of the solutions that are being found, are starting to cause a regress effect as to the initial purpose, by having to occupy or disrupt more surface area as structures go higher. Earthscrapers, on the other hand, provide a lot of benefits that skyscrapers are still researching for in order to find alternate solutions. These benefits, however, come at the cost of inexperience and uncertainty with a lot of them being the construction and durability factors. In order to eliminate these main concerns more research and testing needs to be set in place in all aspects of design and system development.

### **Recommendation**

As of today, the earthscraper concept is perceived as more of an idea, but if proper research and testing is done, this concept can be more of a possible reality for many urban areas that suffer from space scarcity issues.

Based on the research completed and the information provided throughout this report, it is found suitable to make the following recommendations to the industry:

1. Encourage different organizations and companies from all aspects of design to appoint members, old and new, to begin focusing on solutions and design concepts such as earthscrapers.

2. Aim to create an entity or organization, composed of all disciplines of design that would meet regularly (at least two times yearly) to review and discuss the technical literature on underground construction and its feasibility.
3. Begin committing a fraction of research, possible intern programs, and development resources to exploring the implementation of earthscrapers.
4. Provide more incentives for companies, organizations or even academia, for the further involvement and investment into research that revolves around earthscrapers.

As one of the biggest and most innovative industries in the world, the design and construction industry has the talent, experience and resources to further advance the earthscraper design concept. In addition, the earthscraper is an integral component in the next generation of improvements and developments within the design and construction industry. With the current pace of innovation, the limits of an underground feasible solution may be broken within 15 years. Allowing the industry and everyone in it to be able to aspire for bigger goals, bigger heights and bigger depths.



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- Hi Chris, I cannot thank you enough for your willingness to help me and provide me with some very interesting points of discussion. It was and still is my intention to try and cover as many of the topics that you mentioned throughout my report. I would like to add you to my list of references, if that is alright with you. Finally, I was wondering, since your document is copyrighted, if I could get your permission to use some of the data used in your report in order to support some of my arguments. I would provide the required reference in my report, but I wanted to ask for your permission too. Again thank you very much, and once I am done with my report, I would be more than happy to provide you with a copy. Please let me know what you think. Sincerely, Carlos
- No problem, please go ahead. What kind of data are you looking for?
- I would like to see if I can use some of the energy demand graphs and data that you obtained, that are within the report, to support some of my points.
- Yeah, I suppose you could refer to them. I think most of the information is there in the paper. Are you looking at this paper:  
<http://www.sciencedirect.com/science/article/pii/S0378778813008104>
- Hi Chris,  
Yes that is actually the one that I would like to reference and possibly use some of your figures (mostly a couple of the graphs). However, if you would feel more comfortable with me remaking them I could do that too, I just wanted to check with you. Again, thank you very much for getting back to me and for all of your very helpful insight and willingness to help, it is truly appreciated it. Sincerely, Carlos
- Yes, that's totally fine with me. No problem at all, and best of luck with finishing up!
- Thank you Chris I appreciate your help a lot. Good luck with your work as well!