LIVING THE HIGH LIFE

Potential and Problems of Buildings Taller than 2400 Meters

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"Works of architecture can never be too large, but they can easily be too small. In fact, ceteris paribus, the aesthetic effect is in direct proportion to the size of the buildings, because only great masses make the effectiveness of gravitation apparent and impressive in a high degree."

-Arthur Schopenhauer

"You could conceivably build higher than the highest mountain"

-William F. Baker



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ABSTRACT

Since the Tower of Babel, the Gothic cathedrals, the Skyscrapers of Chicago to the Towers of Dubai, humanity have strived for the sky, often using architecture as a tool. Motives have varied, but the limit for what is possible have been rising over and over again. And if this trend continues, buildings are soon to grow out of the typology of the skyscraper, and into something new; enormous in size and facing environmental conditions we are not used designing for.

Through the design of an 8849 meter tall skyscraper, one meter higher than Mt. Everest; the aim of this thesis is to develop an understanding of a new typology; ultratalls, buildings taller than 2400 meters. Investigating the demands, possibilities and consequences of high-rises that grow into a new scale and into new parts of the atmosphere. Creating a comprehensive understanding of some of the most unique challenges when building this tall.

Based on informed design, the unique conditions of the different altitudes are studied and used in the design by either embracing or resolving them. The contemporary skyscraper has been used as a benchmark, to build upon, but also learning from the criticism.

The proposal is a conceptual skyscraper, a vertical city by size and population, 8849 meters tall. Showcasing the challenges and possibilities of the new environment, thereby having a variation in design across altitudes; at high altitudes designed to withstand the low air pressure, while at lower parts designed to gather water from clouds. The interior is designed inspired by a city rather than a building; divided into boroughs, with vertical trains to solve the infrastructure, huge greenhouses to feed the population and parks to compensate for a life 6000 meters above the surface of the earth.

If humanity choses to continue going higher, there are certainly challenges, but with careful studies of the new conditions, many of them could be solved, or even used to our advantage if embracing them correctly. It might seem farfetched, but it is not as distant as it seems. And since there are architects today designing for Mars, we should be able to design for our own atmosphere, right?

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1.1 PURPOSE

Looking back of the history of architecture, the maximum height of buildings have continuously increased. And while the debate is still going on if this is good or not, there are economic power, technical innovations and even more importantly groups interested in building higher, this combined with a fast development in the field that seems to allow increase in building height unseen to humanity today. And if this development is going to continue, the height will soon reach levels where the rules start to change.

The purpose of this thesis is to investigate the effect this would have, being a part of a debate in the future of high rises, and the possible continued growth. By presenting some of the most unique factors, in a design proposal, relating to the change in height and scale, the idea is to nuance the debate and find important design rules related to these future projects. But not only try to provide insight in how to solve new problems, but also old problems, since skyscrapers is a typology exposed to criticism, critiscism important to meet and discuss if the typology should have a future.

The thesis will investigate the new skyscraper typology of Ultratalls, building taller than 2400 meters, an important limit, since many changes of natural conditions occur at approximately this altitude. The name Ultratalls referring to current naming of Supertalls being skyscrapers taller than 300 meters and Megatalls being buildings taller than 600 meters.

1.2 METHOD

By studying current high-rise design through references and literature the important aspects and problems of high rise design is used as a foundation for further research.

Through studies of the environmental conditions on high altitude, among them temperature, air pressure, wind and prediciting how these would affect habitability and the structure. Aspects considering scale was discussed, since most of the systems known from current highrise design isn't scaleable, and new versions has to be proposed.

From these studies a design proposal was developed, with focus on certain details with high demands and a need for completely new solutions in these structures, and further focus on the systems, details and spaces that is most affected by this development.



figure 1. Diagram showing which year the every 100 meter mark was beaten

1.3.1 History of Skyscrapers

Tall building was in its early days a typology related to defense and increased sightlines, but did soon turn to be a typology of might, wealth and power, as with the Pyramids of Giza, the towers of Bologna and the Gothic chatedrals. But as the urbanization increased during the industrial revolution - cities grew denser - land got more expensive, and floor count increased as a mean to maximize income per property, resulting in the skyscraper.

The skyscrapers was introduced in Chicago in the 1880's when the Home Insurance Building was constructed; ten stories and 42 m tall. The introduction of the skyscraper was tightly linked to the invention of the elevator and the invention of the steel-frame, allowing a possibility to achieve the height the developers and land owners asked for.

High-rises have become an important part of our cities, as a mean of increased density. Making it possible to reside more people in cities than ever before.

Today the skyscraper is all of this, it is still a typology built for economic reasons, but in many cases it is once again a symbol for wealth and power, a monument for people, cities or companies. Easy to conclude is that the development to higher altitudes goes fast, figure 1 showing milestones in high buildings, and how the pace increases.



figure 2. Number of skyscrapers above 200m completed each year

1.3.2 Problems of Skyscrapers

In the book *S*, *M*, *X*, *XL* Rem Koolhaas writes about bigness, the scale where architecture goes into a sort of "just because" where quantity is more important than quality (Koolhaas, 1995). And he criticizes the fact how something in the scale of bigness can not be a part of a city, it can merely co-exist with a city.

But more than anything the skyscraper receives criticism for three reasons, the ecological, the infrastructural and the social aspects.

The skyscrapers, when placed in a city, creates a bottle neck for the infrastructure (Arup, 2013). In a residential skyscraper all inhabitants want to get out in the morning, embark the same bus or train and return home at the same time at night, creating a bottle neck not only in the door of the building itself, but in the infrastructure of the city, especially when these projects are parts of a fill-in project. The same happens with office high-rises, where people enter in the morning leaves at lunch, going to the same restaurants and leaves in the afternoon.

The ecological aspect reminds of the infrastructural (Arup, 2013), being that these buildings are usually just black holes of resources, using a lot of resources and energy, but provides nothing but space, an urgent problem for these kinds of structures.

The social aspects relates to the tendency that high-rises usually don't have social spaces, and the interaction with other people being sparse. Despite this, as can be seen in figure 2, the interest in building high increases by the year.



figure 3. Some of the important tallest structures in the world throughout time, clearly showing the increase of height.

1.3.3 Limits of Skyscrapers

Through history, new inventions have allowed us to build taller (see figure 3), among the most important among them is the invention of the steel-skeleton, tower cranes, the elevator and the the tubullar structure invented by Fazlur Khan. But each time when obstacle is surpassed, another one becomes governing, so what's the most urgent obstacle today?

In a interview performed by the Council of Tall Buildings and Urban Habitat in 2012 (CTBUH, 2012), ten experts in skyscrapers - architects, engineers ands developers - were asked "what is the main limiting factor on building the mile high building, or higher". Three answers occurred more than once, *economics* were answered two times, *vertical transportation*, was answered four times and *nothing* and was answered two times.

In an interview performed by Justin Davidson (Davdison, 2015) William Baker, structural Engineer at Skimore, Owings and Merrill claims that structurally 2 mile would be a feasible limit today, but says that theoretically there aren't really any structural or physical limit "you could conceivably build higher than the highest mountain..." he claims (Berg, 2012). And in an interview Tim Johnson (Berg, 2012), chairman at Council of Tall Buildings and Urban Habitat claims that programatically and physically, 2 miles shouldn't be any concern today.

Traditionally the structure and the vertical transportation has been the biggest limitations, and the economy, but as will be discussed in the next chapter, there are reasons to reconsider these limitations due to new research and development of technology,



figure 4. Ratio between live-load and dead-weight per square meter in traditional high-rises (left) and lightweight high-rise (right)



figure 5. Ratio between live-load and dead-weight in traditional high-rises (left) and lightweight high-rise (right)

1.3.4 Why higher now?

So after this short retrospect of the skyscraper, the question is, what reason is there to believe that the height might increase?

As discussed in the last chapter, vertical transportation have been a bottle-neck in design of skyscrapers. Elevators haven't been able to travel distances that are long enough and the space that they occupy is too big. But with recently presented technology, several elevators can be fitted to the same shaft, improving the capacity drastically, as well as removing the maximum distance (ThyssenKrupp, 2015).

Another aspect is the material aspect, where new materials are introduced to the market aside from the traditional steel and concrete. Among them are several kinds of composites, materials lighter and stronger than the materials used today. And with buildings of big scales, the massive loads from the structures have been an economical and structural problem, but if the mass from materials are decreased while strength is not, this would be put in a completely different perspective (see figure 4 and figure 5 and chapter 7.2), bridge construction already using these materials a lot, due to their strength to weight ratio, durability and low need of maintenance (Andersson, Good, 2017).

Building with light materials have several implications, to quote Greg Lynn in an interview with Geoff Manaugh (2016) "If you can take 30 per cent of the weight out of the upper section of a building by using lightweight composite materials, you could end up saving between 70 and 80 per cent of the material in the entire structure", making it not only cheaper to buy, but also easier to construct, and with materials being pre-fabricated also quicker.



figure 6. Diagram of the context and conditions of different altitudes.

2. NEW CONDITIONS

The following pages presents important aspects of increased building height and scales, new conditions that will be important to consider in design.

With the assumption that architecture grows out the scales known today, it's important to have insight in what will change, summarized in figure 6. With change in scale comes a change in how the life is lived in these buildings. But the building will also be exposed to new and different conditions than we see and design for today. The following pages are a presentation of some of the aspects one should consider when working in this new scale.

2.1 Distance - Noun - One of the most obvious aspects of building higher is the increased distance to the ground. And this is what will affect the citizens the most during life. With increased distance comes increased need of transportation and increased need of alternative safety measures.

With increased distance comes an decreased possibility or will to travel to the ground. This decreases the possibility to visit nature, and it affects the possibility to travel to a store, or other commerce. So increased distance will create another need for what functions one brings into the building.

Important to note is that the distance is vertical, going exactly opposite to the direction of gravity. This means that functions we take for granted today, will be complicated, like access to water, every liter of water needs to be transported to the top of the building, which would mean an advanced system of pumps, or another solution. **2.2 Light - Noun -** The horizon is the limit of perceivable space, you can never see longer, even if the actual space is bigger the part of it you can perceive is limited by the horizon.

This is an not an important consideration today, But will be apparent as height increases. The view from higher altitude will be longer, and so will the days. At higher altitudes, the sun sets later, with approximately 2 min per 1.5 km, meaning that a the top of a really tall building, the days are longer. This also creates the possibility to relive the sunset, watching it at ground level first, then relive it 10 minutes later at the roof (the principle of this seen in figure 7).

This is mostly a novelty effect, that can be utilized for experience.

A building of this height will also cast very long shadows, although most of the shadows will, at least on a cloudy day, not reach the surface of the earth but be projected on the clouds.





figure 8. Length of shadows at different times of year, in Swedish conditions

2.3 Pressure - Noun - At higher altitude, the air gets thinner and air pressure decreases. The rate of the decrease is approximately 10% of the pressure at sea level every 1000 m. Meaning that at 8000 m, the pressure is only 20 % of the pressure on the surface.

This change of pressure affects people, altitude sickness is an effect experienced by people moving between pressure zones to quickly, if traveling from the surface of the earth, symptoms starting to show at only 2500 m (Khan, Yu, 2017). While at 8000 m the low amount of oxygen is lifethreatening. Major settlements can be found up to 5000 m, meaning that with time to get adjusted, it's possible to survive at these altitudes.

The conclusion is, that if the intention are that people should be able to leave these buildings and not be permanently resided there, the buildings needs to be pressurized, not to experience illness

2.4 Population - Noun - The massive height and size of these buildings will mean a need of massive population to fill them. Looking at Elia Zenghelis' discussion on the *House for a Million People* for inspiration.

To create reasonableness in these projects, and make them possible to defend these buildings needs to seek inspiration in Soleri's ideas of Arcologies. Today skyscrapers could be described as a black hole for resources and energy, where massive amounts are fed in, but providing nothing but space, which would be an increasing problem with the increase of the number of citizens. A high degree of self-supply needs to be achieved for these projects to be realized.



figure 9. Diagram of effects on how air pressure is affected by altitude.

2.5 Temperature - Noun - There is a temperature-gradient affected by altitude. As altitude increases, the temperature decreases. A rule of thumb of the decrease is 6°c per 1000 m. Meaning that the temperature outside on the top of the proposed building could easily reach -50°c.

The low temperatures do create huge demands on the structure, to create suitable comfort inside. But the temperature is comparable to what the polar-researchfacilities and airplanes are exposed to, and knowledge should be taken from this field.

2.6 *Population - Verb -* As the size and population of these building increasing, the question of which functions and use to include rises.

The presented project are big enough for approximately 1 million people to reside making a reference and seeking inspiration in the challenge posted by Elia Zenghelis in his studio in the Architectural Assosciation, London: *The builiding for 1 million people.*

This means that a building as the proposed is a city by size and population. But a building with 1 million people residing there need supporting functions and can't be purely a residential building, and the pressure on the infrastructure would make it impossible to place in a city-grid. The probable solution would be to make cities of these buildings, including not only work and living as in todays mix-use skyscrapers, but all functions one expects to find in a city, recreational areas, commercial areas and social but also areas for food production and industries needs to be included.

This could be seen as an alternative to respond to the needs of the increased urbanization, decreasing the need for an area-based infrastructure and instead creating a onedirectional infrastructure. This would save land for other things, like agriculture to feed an increasing population, or if land gets crowded as the sea rises. **2.7 Weather - Noun -** Weather changes with altitude. The normal blanket-like rain clouds that we perceive from earth is usually located on an altitude from 500-2500 m. Above that, rain is as good as non-existing. But being above the clouds, also means that there is constant sunlight during the day, and constant star-gazing possibilities during the night. Something that could be utilized for energy, both for gardening and PV-cells.

One drawback of the lack of clouds on these high altitudes, are the lack of water in the air. As the temperature goes down, so does humidity, making it hard to harvest water from the air at high altitudes - creating a need to transport water to the top.

2.8 Wind - Noun - In high-rise construction wind is considered a governing factor. The higher a building is, the more vulnerable the structure is to wind. Wind increases with height, to very high wind speeds at the altitudes discussed. Although, according to calculations this phenomenon is compensated by the decrease of air pressure, to a level where wind pressure is almost constant at high altitudes, reducing the problem of wind.

But still, despite this phenomenon, wind is the single most important load in the design of skyscrapers.



figure 10. Diagram of the altitude of clouds

Conclusion - This study was meant as a contextual study for the project, a site analysis. In the environment architecture is usually found today, although diverse, some things are taken for granted, access to air, a possibility to simply leave the building and conditions that are constant across the whole building.

This study shows that the context when designing a 8849 m tall building is facing slightly different conditions, some are similar to what can be learn from current high-rise design, some are completely new.

The first conclusion to learn is that the building needs to be divided into zones, treated differently and with different methods. Much like Rem Koolhaas writes in *Bigness* (1995):

"Beyond a certain critical mass, a building becomes a Big Building. Such a mass can no longer be controlled by a single architectural gesture..."

This holds true, for both pragmatical and ideological reasons, due to changes in condition over altitude; the building is exposed to completely different demands, which should be treated as different solutions and different gestures. Cause while the lower 500 meters of the building is exposed to the same environment as nearby buildings, the top 500 meters is in several aspects more comparable to the Mars Projects. Many of these aspects can't be foreseen and will leave important traces in design.

Secondly, the altitude will change design in both the exterior; how to treat the strong winds, and make sure that the air is contained. But also internally, like how to treat the amount of people, and create the qualities of life people are used to, for example in greenery and mobility.

3. THE PROPOSAL

To illustrate the new conditions faced when building this tall, a proposal was developed, demonstrating and benchmarking the aspects. In figure 11 the full section is presented and in figure 12 to figure 15 the section is presented in parts, from bottom to top.



figure 11. Section of the proposal., with Empire State Building and Burj Khalifa in the background for scale.







3.1 THE PARTS OF THE BUILDING

The following pages are a short summary on the different parts of the building, and the way they're named in the text, thereby working as a quick walk-trough of the project and an explanation of the naming of the parts and how they're refereed in the report.

Podium - The podium is what one meets when approaching the building. Having the expression, together with the wings and the supporting tower, of a small skyline, showing a familiar typology as one approaches.

The podium is wide 450 meter in diameter, a width needed in order for the building to be stable, creating a vast and rather dark floorplan. The podium is therefore filled with industry, warehouses, logistics and parking. Functions needed to create a city, but as with the case of Ringön in Göteborg, usually occupying valuable space. In this building its hidden and used to make the building stable, lowering the center of gravity and be a part of a self-supply approach. *Wings -* Inspired by the design of Burj Khalifa, using the buttressed core as a mean of creating torsional stiffness, enough light and a big enough footprint, the tapering part in the bottom of the structure is called the wings.

The wings are mainly residential. With high access to water, due to the relatively low altitude, the facades are green and the apartments have terraces, to be extroverted, since the climate allows it at these altitudes.

Greenhouse - As mentioned before in *Problems of the Skyscraper* the modern skyscraper is consuming a lot of resources, but providing few. Therefore, with the assumption of aeroponic agriculture, a needed floor area was calculated, how much greenhouse is needed to feed one million people, 23km² equivalent to 500 floors of plants, really demonstrating what needs to be incorporated in order to make these projects sustainability feasible.

The placement of the greenhouse is made partly due to the closeness to the distribution center in the podium, but mainly due to the access of water. Since it's extremely energy-consuming to transport water to the top of the building, the main water-source for thirsty functions like industry and agriculture is through the harvest of rainwater and clouds. $\frac{1}{2}$

Tower - To create a lighting situation habitable inside the skyscraper the tower is divided into three parts. A parts of the buildings filled with residences, offices, schools and stores.

Center Platforms - The center platforms are part of several systems. They work as train stations between the different elevator-systems. They're filled with commerce, sport halls and other functions needing bigger floor-plans than the tower allows.

The platforms are also functioning as parks, on top of each platform there is a park/greenhouse in order to provide social spaces and greenery.

The platforms are city centers, located in the center of each borough. Including stores, restaurants, doctors office and fire department.

In the center of the building there is a bigger platform, this includes global functions, such as museums, concert halls, governmental functions and serves all citizens in the building.

Borough - The borough is the bigger subdivision of the building. Centered around a platform, spanning around all three towers, 800 meters high, it's the home of approximately 75000 people.

Helix - The helix might look odd, but is an important feature in several aspects.

It works as a structural bracing between the towers, in order to activate the group effect. It also works as an opportunity to move between the towers, and thereby activate the group effect also in infrastructure.

The helix is an important feature aerodynamically, decreasing the turbulence around the building (see chapter *Aerodynamics*).

The helix also works as the location for goodstransportation in one of its arms and five of them being terrace-like agriculture, being an important part in cleaning air and water, since air from the residential parts are circulated between the towers through these arms.

Block - The block is the smaller subdivision in the building, consisting of 20 floors, including residential space and possibilities for professional functions. Each also including a lobby, a separate elevator, machinery and a few spaces for smaller workshops or stores.

3.2 THE JOURNEY THROUGH THE BUILDING

When designing today, one can be fairly certain that the environment around the building is fairly similar, across the full altitude. But when building ultra-tall like in this proposal, the environment and climate changes, and this needs to be embraced in the design. On the following pages is a walk through of important locations in the building and what makes them unique.

3.1.1 - The Entrance - Being conceptual there is no given site to the project.

A project of this site can't be fitted into a city, the demands on the infrastructure in the city would be too massive, adding a million people on a small area.

The approach to the building is made either by train, accessing the underground train station, by car, accessing just below ground or by plane, on the runways at approximately 3000 m altitude.

To work with the design on a scale possible to grasp, the entrance is worked with as motives, where the wings works as a mountain. And the flying buttress-like system at the ground creating a scale of architecture that is possible to read as a skyline.



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figure 16. Perspective approaching the building. 24

3.1.2-+300 meter - The extroverted apartment

Site: At 300 meters, air and temperature conditions are the same as the conditions on the surface of the earth. The climate is still well adjusted for plants to grow. The sight line goes above the tree tops and most of the built environment, but details in the built environment is still visible.

Description: To maximize and adjust the apartment and spaces to the environmental conditions, all apartments in this part of the building are extroverted, with a terrace and greenery, allowed by the climate and the high access to water. The structure is heavy, to stabilize the taller parts of the structure and to accommodate heavy functions as industry and infrastructure. The travel time to the surface is short and it's easy to get there.

Travel time: 1 min



3.1.3 - +1500 meter - The greenhouse

Site: At 1500 meters the temperature have decreased by approximately 10°c. The air is still breathable, but humid and the view is at times obstructed by heavy rainclouds

Description: This part off the building consists mainly of a greenhouse of hydroponic agriculture, taking advantage of the clouds as a source of water. Due to the sometimes obstructed sight, there are also functions like offices and hospitals placed here, where light is more important than view. The tower is still a single volume and the core of the building consists largely of storage and factories.

Travel time: 2 min





figure 18. View of the greenhouse, with the automated aeroponic agriculture, and a chance for recreation. The space is full of pipe transporting water collected from clouds and rain through the facade.

3.1.4-+3200 meter - A square

Site: Going out at this altitude would cause slight dizziness and nausea, an uncomfortable feeling. The temperature reaches 0°c or below during the majority of the year.

Surrounding: This is one of the hearts of the vertical city, the platform spanning between the towers, allowing transportation between the towers without going to the ground, but also being the city center of each borough. The interior of the platform contains the station where you change from the vertical express train to the local line (see chapter 4). It also contains a domed square, a place for recreation, gatherings and street life.

Travel time: 3 min



figure 19. View from the Express Train onto one of the platforms, showing a boulevard and the recreational areas. One can see the Express Trains on the facades on the other towers, as well as an airplane landing on the runway below.

3.1.5- +3400 meter - The introverted apartment

Site: The temperature have decreased further, to approximately 18°c lower than at the surface. The air pressure have decreased to a point where it would cause altitude sickness to leave the building, and therefore this part of the building is pressurized. Looking out of the windows, one does either meet a blanket of clouds below you, or the topography of the land, with individual buildings distinguishable. Since one lives above the clouds, there is as good as constant sun at this altitude.

Description: In this apartment we encounter the highaltitude facade (see chapter 4), a facade that is a necessity, and only possible due to the pressurization (otherwise it would buckle), designed to contain the pressure. Due to the relative closeness to the surface, and the greenhouse, the apartment lacks direct access to green areas. The water used here is recycled from the inhabitants above.

Materials will be dominated by lightweight and flexible materials, such as polymers, timber and sheet metal.

Travel time: 4 min 30s



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figure 20. View from an apartment higher in the building, where the atmosphere is starting to get inhospitable, the apartment is introverted, but the facade is thin and relatively flat, since the difference in air pressure is small. Size of structural members is big.

3.1.7- +4700 meter - Introverted apartment 2 Site: The temperature have decreased further, to approximately 24°c lower than at the surface.

Description: The swaying and vibration from wind is noticeable here. But through a liquid-damper system and through stabilizing fans, the displacement and vibrations are heavily reduced. The light at this level is very sharp and strong, with constant sunlight and few objects to reflect on, there is nothing diffusing the light creating very directional light.

Travel time: 6 min 30s



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figure 21. View from an apartment higher in the building, with view of one of the wind turbines.

3.1.6 - +6400 meter - A station

Site: At this altitude one can't leave the building without having acclimatized to the pressure for several days. The temperature outside is 40°c degrees lower than at the surface making it very cold all year round.

Surrounding: This is the interior of the platform, the location of one of the main stations, where one switches from the express train, stopping in every borough. This is also a space for services, stores and social interaction.

Travel time: 7 min



figure 22. The cylindrical installation in the foreground is the platforms for the vertical express trains, in th background is the transition to the local line, an elevator on the inside of the building. To the right is stores and services and behind the elevators is the view to one of the other towers.
3.1.7 - +6800 meter - Balcony apartment

Site: At this point the day is 10 minutes longer than on the surface, due to curvature of the earth, meaning that you will experience the sunset later than the people living underneath you. The temperature is practically always under freezing point.

Description: At this point the distance to the surface is long, the trip taking 9 minutes including transfer. This creates a demand for artificial greenery at the residence, using a system of small spiraling sky gardens, common for the block. The sky gardens are open to one side, 5 floors high; inspired by Commerzbank Tower by Foster+Partners.

The demands on the insulation is bigger, but the structural members are smaller, since the building start to top out. The air pressure gets very visible on the inflation of the facade.

Travel time: 9 min



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figure 23. View from one of the extroverted-introverted apartment. View through on of the gardens, then through the exterior envelope. The envelope is visibly under higher pressure.

3.1.8 - +8800 meter - Mountain park

Site: The building is topping out, the temperature is extremely low, and the air pressure outside is lethal to almost every human.

Description: To celebrate the altitude, the top part of the building contains a mountain-inspired park, where the elevators stops and one needs to climb the last 400m yourself. The climate is slightly colder.

Travel time: 11 min

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Conclusion - Starting with the information and conditions found in the initial chapter, including the *New Conditions* and the retrospect of the history of tall buildings, the organizations tried to embrace the new conditions, while trying to solve some of the critical aspects of today.

The geometry of the building is very much given by external condition, creating the subdivided volume, the podium and the helix, the geometry and volume starting out very much as a pragmatic concept. This should be translated to organization of the building.

By exploring the different parts of the building, together with the functions and needs that should be incorporated, an idea of the organization was crystallized. Some functions needs horizontal spaces, some need vertical spaces, some parts needs water, many parts need light. Seeking inspiration in ideas used in city-planning for subdivision of big populations, and adding spaces for social interaction close to the residence. The idea is to find sustainable ways to increase the scale of the structure, without meeting the same problems of social interaction, as is usually experienced in contemporary skyscrapers. The increase of scale seems extremely favorable in these aspects since it allows the additions of spaces impossible to fit in smaller structures.

As concluded in the last chapter, the different parts vary very much in conditions, beneath and inside the clouds, the access to water is high, and transporting water is expensive, thereby should thirsty functions be placed at low altitude.

To design different apartments, with difference assets across altitude came naturally, allowing for unique situations, embracing the actual conditions. The biggest difference comes between the lower, extroverted apartments, to the middle-altitude introverted apartments with relatively close access to the ground, to the extroverted-introverted apartment with access to its own yard.

4. BUILDING SYSTEMS

The following chapter is a walk through by the systems of the building, and their effect on how the building is planned and designed.

4.1 Shape - Noun - An important feature in skyscraperdesign is the overall shape. And when designing them, one of the most important structural aspects is the aspect ratio, the ratio between height and width for the building to be stable. Looking at figure 24, it's clear that high buildings, in different times and different materials have had a fairly consistent ratio between height and width, between 6 and 10, today approaching 20.

This also applies at ultratalls. But applying these rules to a building 8849 m tall, would mean a width of almost 1000 m, this is problematic since most of the area in the building would be too dark to use. And as Junya Ishigami writes in *Another scale of Architecture* "the view is only impressive from a window" after all (Ishigami, 2010)

To develop the geometry of the project, several concepts of solving the wide-enough-to-be-stable-butsmall-enough-to-be-used problem, some of the ideas can be seen in figure 25.

The design that was chosen was *The Truss* in figure 25 with several towers built in tandem, structurally and infrastructural linked together with a system reminding of a truss beam.

The shape of the tapering towards the ground is another solution to this, providing enough base. The degree of the taper was calculated to correspond to the stability for wind, which showed to coincide with the optimal shape for tall buildings according to buckling quite well (figure 27) (Naicu, Williams, 2015).

A summary of the generation of the shape is shown in figure 28.



The Pyramide

figure 25. Sketches for how to make the building stable, but maximize usable area.



figure 24. Aspect ratio of existing buildings, showing a clear relation between height and width.

figure 27. The optimal shape of a very tall building, as calculated by Chris Williams, compared with the shape of the proposal.

figure 26. Final Geometry of the tower, with three individual towers, connected by bracing.



- 1. A normal width-to-height ratio is 1:10
- 2. Just elongating a normal floor plan will make a too slender building to be stable.
- 3. Making a building that is wide enough will create a big, dark unusable area in the middle.
- 4. Instead three normal floor plans is used, making three separate towers.

5. Since the towers are placed in an environment of thin air it want to expand, so a sheet is introduced to contain the air and an exoskeleton is introduced to contain the sheets

6. The three towers are connected structurally and infrastructurally with a bracing, making a vertical truss-beam.

7. The geometry of the truss is optimized through iterations based on topology optimization and aerodynamics, to a helix-structure based on six branches.

8. The elevator core takes much of the compressive forces, while tension is takn by sheets and exoskeleton in facade

figure 28. A summary of the generation of the final geometry



11. Platforms are introduced between the towers at regular distances throughout the height. To create public spaces, and a connection between the towers.

12. The helix and the widening foundation together with the infill platforms creates a cross section that is changing throughout altitude, this is favorable since serious turbulence isn't happenign at all parts of the building at the same time. At extreme winds are the wind turbines there to counteract the wind, by blowing it in place.

13. Parts of the building are extruded, to fit bigger functions.

14. The final geometry is highly informed by the different structural and functional demands.9. Between the tower and the helix, a new semi-core is created, just for bigger functions and transportation

10. To avoid crushing of the structure and the ground underneath, the structure widens to the bottom, following the change in bending-moment. Creating a footprint similar to the torsionally strong buttressed core of Burj Khalifa (10 a).

8.

4.2 *Air - Noun -* To make the atmosphere in the building habitable, it needs to have a artificial atmosphere, due to the low air pressure at high altitudes. This is done by moving air from the surface into the structure vertically, and making sure to have a facade that is airtight to contain it.

To contain the air, a special facade is applied to the building at facades above 2500 m, where the pressurization is needed. It's designed to be airtight. Allowed by an exoskeleton where sheets of fiber-reinforced plastic are glued on to, creating an airtight facade. The facade consisting of two airtight sheets for safety reasons, with insulation in between (see separate chapter *High Altitude Facade*) (figure 30).

The transport of air is done by adding another shaft in the elevator core, for vertical transport of air, letting it out for circulation in every block of the building (figure 29). To get the air flow, stack effect is used. This is usually an unwanted effect in skyscraper, but in a separate shaft this can be utilized. In the proposed design, a break is included in all the other shafts, allowing air flow in just this one. Calculations shows (Chapter 7.1) that the natural draft due to the height and temperature difference is more than enough to provide for the air needed in the building.



figure 31. Through the circulating systems of yards, the apartments and spaces are ventilated in the local scale.



figure 30. High-altitude facade, designed to be airtight. Carbon fiber sheets adhesively joined to an exoskeleton.

figure 29. Visualization on air transportation due to tack effect

4.3.1 Vertical Transportation for People - Noun - With increased altitude and increased population comes and increased need of efficient vertical transportation. The system needs to be based on several system, so that the residents don't need to stop at every level.

The vertical transportation system in the building is based on three system: the Vertical Express, taking you to the right borough, corresponding to a train in the city-scale. The Local line, taking you to the right building, corresponding to the bus or the walk from the station and the Building elevator, taking you to the right floor, corresponding to the elevator in your building (figure 33).

To provide for an effective space:capacity-ratio, the systems are each based on two shaft, one going upwards and one going downwards with several cars per shaft, much like a pater-noster-elevator system. Based on an electro-magnetic system.

The layout was chosen with aspect to keep the number of station per line to a modest level, and to be adjusted to the number of trips one has to make to different places, one elevator to the neighbor, two systems to the city center. Three systems out of the city. Inspired by the life in a city of comparable scale.

The station platform was an addition made for several reasons, the first concept was fitting all transport in the internal core, like a traditional skyscraper. But due to the space this requires, the space in-between the towers were turned to a semi-core, where the express system and goods transport is located, as well as the horizontal transportation between the buildings (figure 32).



figure 32. Diagram of the idea of the traditional internal core (left) and the system of an semi-internal core (right)



figure 33. Left: Vertical Express Train, on the exterior of the building, with stops at every 800 m. Middle: Local Line, with stops every 80 m Right: Building elevator, stopping every floor

4.3.2 Vertical Transportation for Goods - Noun -

Transportation of goods happens mainly through the train system in one arm of the helix . The train is powered by a vacuum-system. Having distribution-centers in every platform, where goods are transported to stores and post offices. Separating the system for goods and people will decrease bottle necks and allows for longer loading and unloading times for goods.

Furthermore goods and postal service can be done by drones in an assigned shaft in the elevator core.



figure 34. Diagram of the goods-train including the stations.

4.4 Structure - Noun - When constructing high-rises there are two types of loads that is important, gravitational loads, consisting of dead-weight and live load among other and lateral loads, that is mostly wind.

The gravitational loads are rather easy to handle, with a pillar system and a load bearing core. Especially if using lightweight materials, where the size of these members can be reduced due to the reduced dead-weight.

To handle lateral forces, the structural cross section needs to be expanded, utilizing the facade and perimeter. The compressice forces are handled in the elevator core and exoskeleton, while tensile forces can be handled by the facades carbon-fiber sheets.



figure 36. Left: Outrigger are used to structurally activate the facade Right: The pressurized interior helps the facade to be stable against buckling



figure 35. Principle of splitting the volume to increase the structural base.



figure 37. The redesign from truss to helix included topology optimization which was then remodeled to a helix.

4.5 Aerodynamics - Noun - One part of handling the wind is to create a structure able to withstand the loads, but one should also work with an aerodynamic approach to minimize the loads.

By varying the cross section over the height (as shown in figure 38), problems related to vortex shedding, a turbulence-phenomenon that puts high pressure on the structure, is minimized (Feblowitz, 2010). This is due to that the different cross sections activates turbulence at different wind speeds, thus will the whole building not be affected by vortex shedding at the same time. The helix, platform and podium has an important parts in this.

Due to the high net pressure on the high-level facades (see chapter *High Altitude Facade*) a facade with bumps is created (figure 39), this will create an effect similar to what happens with the dimples on golf balls, creating a thin layer of turbulence on the surface, reducing drag.



figure 39. Horizontal cut through building-facade +2500m, showing the dimpled facade, that provides reduced drag

figure 38. Diagram of the cross section of different parts of the proposal, showing the variation of cross section, and important part of the aerodynamic approach of the building.



4.6 - Vibrations - Noun - In tall structures, vibrations and movements are a big issue, mainly for comfort.

In order to decrease the movements, and thereby increase the comfort, the water reservoirs for drinking water in the structure works as slush-tanks (figure 41). A system based on the inertia of matter, utilizing that the mass of the water moves independently from the structure and will thereby counteract vibrations.

To further decrease lateral movements there are fans, in normal conditions used as wind turbines, but at high wind speeds used to counteract movements by blowing the structure into place (figure 40).



figure 40. The design of one of the stabilizing fans. Able to rotate, to always be in the right direction.



figure 41. Liquid dampers, so called slush tanks are placed throughout the building, counteracting lateral movements.

4.7.1 High Altitude Facade (2500-8849m) - Noun - The high altitude facade are designed to contain the higher air pressure on the inside of the building. Consisting of sheets of carbon reinforced polymers, filled with an insulation material.

To avoid excessive expansion of the facade, the sheets are tied to an exoskeleton using an adhesive joint. The exoskeleton also working as structural tubing according to Fazlur Kahn's principles.

The bubbles seen on the facade is not manufactured, but rather a demonstration of the pressure difference.

The temperature at high altitudes are surely extremely low, but heat is mainly transported through air, and vacuum is considered the best insulator there is, this means that the need of insulation is moderate since the building is actually insulated by the lack of air.

Lightweight composites such as carbon fibers will be important in the development to these typologies, being extremely light strong and durable (Andersson, Good, 2017). But furthermore they're materials with large possibilities in shape and form, being possible to vacuumform and heat form (Kreysler, 2017).

The elasticity of the composite materials are important, due to big movements in the structure, where a glass facade would crack and the use of adhesive joints is also important, keeping the tightness of the facade.





figure 42. 1. Sheets of carbon fiber. 2. Exoskeleton of carbon fiber beams. 3. Maintenance performed by robots, since the exterior is unhabitable for human cleaning and maintenance.

4.7.2 *Rain Colleting Greenhouse Facade (500-2500m)* - *Noun* - The greenhouse facade is made to collect water from rain and humid air. By making the wind force humid air through a tight mesh, similar to the fog fences of Chungungo in Chile. the water condensates and is collected, providing water for greenhouse and industry.



figure 43. Since placed inside the clouds, the air being very humid, pressed through a small mesh by the wind. 2. The air is pressed onto and flows down the window to a canal. 3. The water is lead away in pipes into the building.

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4.7.3 Low Altitude Green Facade (0-2000 m) - Noun - These facades are placed underneath the clouds, mainly on the wings. Displaying the habitable surrounding and the potential of an extroverted building at these altitudes. Forming terraces with vegetation for the apartments. The structure is rather heavy, to create a solid foundation for the rest of the tower.

The greenery and the heavy structure also helps to dampen and heat the air transported up the building.

house have





4.7.4 Platform Algae Facade (2500-8849)- Noun -This facade is placed on the sides of the platform, made up of panels filled with algae, utilizing the almost constant sunlight. The algae is fermented and used as nutrients for the trees on the platform. On the platform there is a geodesic dome structure of carbon fiber, creating a greenhouse like structure containing the square.





figure 45. The algae facade on the platform

4.8 Safety - Noun - Safety is a pressing matter in skyscrapers, and ultratalls is not an exception. Evacuation is complicated, both considering distance and the amount of people.

The first important measure is preventive design, using materials and structures that can handle the most common accidents. But this is a general measure for all kind of construction.

Secondly, evacuation in these structures are not done to the ground, but away from the fire/accident by a number of floors, so called phased evacuation. And as in Burj Khalifa (Naffco, 2015) there are evacuation rooms, fire proof spaces located in the elevator core, so rather than evacuating the building, one evacuates to the elevator core. These do also have a reserve system for air supply, in case of pressure drop in the building.

Thirdly, one problematic aspect of high-rises is the response time for emergency personnel. In a building of this size, fire departments and medical emergency needs to be located throughout the tower, so a fire department and medical staff islocated in each borough.

This might be one of the biggest challenges there is to build tall. (CTBUH, 2012). And probably the single factors that will keep us from building this tall longer than any other factor, since accidents are hard to predict, hard to account for everything, and the stakes are high. **4.9 Energy - Noun -** The opportunities to produce energy in an ultratalls are many.

Since the buildings is unshaded at most times, being above the clouds, it's a perfect opportunity to use different kinds of solar-energy. PV-solar cells are included in big parts of the facades, as well as algae-panels, allowing for bio-energy to be produced in-house

Due to the high wind speeds at the higher altitudes, it's possible to incorporate wind-turbines in order to produce energy.

And since the idea is to incorporate a chimney-like system in the building, as a part of the natural ventilation, this can also be used as a wind turbine, utilizing the airflow in the chimney, a technique used in so called solar-updrafttowers.

4.10 Water - Noun

The supply of water is complicated in high buildings, since water is a rather heavy substance, and is also in need of vertical transportation to be provided to the people living on the highest floors. It's extremely difficult to pump water to these heights.

But as was mentioned before in chapter *pressurization*, air can be transported using the stack effect. If making sure that the air transported vertically is humid, 14600 m³ of water can be extracted from the air for ventilation (calculations in chapter 7.1) (figure 46, left).

This amount is not enough for the consumption of the building, but for the of one consumption of the borough. So the system is based on that on top of each borough is a water reservoir, also working as an active part in vibration dampening. The water is consumed in the borough, flowing down through the building where it is cleaned and stored again in the reservoir for use in the next borough (figure 46, middle).

The thirstier functions are placed in the bottom of the building (up to 2500 m) on these altitudes water is extracted from rain clouds through the *Rain Collecting Greenhouse Facade* (see separate chapter). This is a measure to provide more water to thirstier functions.

figure 46. Left: Sources of water is from the moist air transported through the building and from rain and clouds - providing water for the lower levels. Middle: The water flows down the building, where it is cleaned and used again in the next borough. Right: Locations of the water reservoirs.

4.11 Food - Noun

A common opinion against high-rises is their use of resources, consuming massive amounts of resources, but providing nothing but space. This being one of the main points in why the contemporary skyscraper never can be sustainable.

To decrease the need for the building to be a served space, relying on other systems and structures and important feature was to incorporate ideas of the archology, the self-supplying building. A first step to do this is to add agricultural spaces in order to supply food for the population.

In the podium, between 500-2500m altitude a greenhouse, filled with aeroponic cultivation is located. The size might seem massive, but according to calculations (chapter 7.1) this is the size it would take to feed a population the size of this one.

The location of agricultural spaces can be seen in figure 47. The locations for the main greenhouse, in the podium is chosen due to the access to water, which is higher in and below the altitude of rain clouds (see Chapter *Water*).



Conclusion - These studies, aiming to solve many of the problems of the *New Conditions* by creating conceptual solutions to predict the design of the typology.

Firstly, the conclusion is that the shape we're used to when designing towers won't do. Looking at ratios possible structurally, using the same shape will result in a building consisting mainly of unusable space, by subdividing the tower into three parts, interlinking them, a structure with less wasted space is created, while still being stable.

Secondly, much happens at the envelop of the building, at the border between environment and building. Which means that the facade became extremely important, and all of them were fulfilling different tasks.

The high altitude-facade being the most important, a facade that wouldn't have been possible to construct until very recently, with the flexibility and air-tightness of fiber reinforced plastics and adhesive joints.

Much work was needed to create a concept for the vertical transportation. During iterations, it turned out that the most reasonable solution from an infrastructure point-of-view as well as to save space, is to create a second, figurative, core in between the three divided towers and place some functions there. Thereby returning from three separate towers, to three towers sharing so much infrastructure it almost becomes one tower.

Thirdly, it's possible to transfer many effects from problems to solutions by embracing them. For example the stack effect, usually seen as a problem and designed around in high-rise design, but can be utilized to work in our favor, as a mean of pressurization, if kept under control. And if using slightly more humid air, by leading it through a green-house, this can provide water for the whole building. And there are also many possibilities to combine functions, like using the water reservoirs as liquid vibration dampers. **5. DESIGN ITERATIONS**

Important sketch #1 - Early sketches, working with a basic concept of communication, organization and structure. Combined with a study of traditional solution. The monocoque solution to the top left is similar to the final solution, although an exoskeleton was added.



Important sketch #2 - Page from notebook, trying to find ways to utilize and solve the introduction of pressurization. This particular one was also concerned about the different zones and what different altitudes means in different graspable scales, like mountains, cities and forests Imporatnt sketch #3 - Imagined perspective of an early greenhouse, where it mainly consisted of a bubble-like structure and with a spiraling walkway upwards where arms with agriculture where floating around almost freely in the space.

Another idea in this sketch was the cloud-like mesh of cable on top of the building, a parts of the structure, but also meant as a way to produce artificial clouds and artificial weater in the space.



Important sketch #4 - Early sketch describing the idea of the separate towers connected by a truss, inspired by a bird-skeleton structures. In this sketch bubbles were introduced in the opening, as greenhouses and as supporting balloons.



The focus in this early sketch was on composite materials, rather than height, and the height was much lower. As the height grew higher, the ideas was scrapped due to the problems regarding the footprint size.

Several ideas of material treatment and the studies regarding material tectonics was brought into the next iterations.



An iteration based on model sketches, where one investigated the potential of a beads-on-a-string like structure that is hanged from above, and the performance of such a structure.

The other of the models showing an early version of organization and the structural principle of monocoque construction.





This was a study with focus on discussing and showing a wide range of structural concept that isn't used very often in construction today, and discover their possibilities. Among them can be seen the topology-optimization of the interlinking between the towers and the cable stabilizing between the higher and lower parts of the tower.

This was an important iteration, and one of the aspects that remained to the end is the group effect of several building supporting each other and topology optimization.



The iteration presented on the midterm critics was more clearly divided, both as functions and as geometry, where the different parts were more distinguishable from on another.

The structure suspended in balloons were still present at this stage. What was taken from this iteration was the three towers, and the bracing and the podium, although all of them was drastically remodeled.



The following pictures are of the model used in the final presentations. Showing the overall geometry of the tower. One of the buildings are shown in full height, another is shown at approximately half the height, to demonstrate the airport runway between the buildings and the third is outlined as a hole in the ground, to demonstrate the train station and the foundation of the towers.

The models show the relation of the different parts, as well as some details, one of the platform squares are shown as well as the wind turbines.

The size of the models is 0.5x0.5x1.9 m.













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6. GENERAL CONCLUSION

It might seem like, and it probably is, a crazy idea to construct a building so tall that it needs an artificial atmosphere to be habitable. But the truth is that, if the construction of high rises follows the same trend as today, these will soon have to be questions we need to consider.

To demonstrate which pace the height increase is happening it's worth mentioning that when the Jeddah Tower is completed in 2020, it's expected to be 1000 m tall. 1000 m talls means 310 % taller than the tallest building 100 years ago, 120 % taller than 25 years ago and 96 % taller than 10 years ago. And that the environment changes by altitude is a fact that can't be ignored if this is to continues higher.

My aim with this thesis was to start with the assumption that this was possible, and working from that assumption, investigating the needs, how these buildings might look and function. And I think, given this investigation that these buildings are far more possible than it seems at first glance, at least I've been convinced that many of the challenges seems to have a solution, maybe not possible today, but in a rather close future.

But then again the future of these structure will not lie within what is possible, but rather what is feasible. One question is however people would like to live like this, far away from the ground, in an insulated bubble. But I think that the main reasons of what will keep us from building these structures is firstly safety and secondly economics, who will pay for such a building? and how, since it will be expensive? But in a future where the land might be sparse to due the seas rising from global warming, there might be a need of building again, not just a desire. One important conclusion from this investigation is that many of the unique challenges, cause some of them are certainly challenges, posted by altitude can be solved, or even used to our advantage if studied and considered thoroughly. As an example, stack effect is to be mentioned, this is considered a problem today, creating draft in shafts where draft is unwanted, but proving the existence of a stack effect, but this can also be used to transport the so needed air to the top of the building in this new typology.

Even though this study touches upon many of the aspects related to the problem, it's merely a starting point of the subject, there are still many blank pages, open for further research. A more thorough investigation of how the social and everyday life in the top of the building would be is an interesting study and is important to consider.

This investigation also poses a contribution in a debate of general skyscraper design, not only of heights higher than the highest mountain. With ideas of what could be introduced to make a more sustainable and functional typology.

My aim was to develop an understanding of the unique challenges in the construction of ultratalls, and investigate the possibility to solve them. Conceptual solutions are presented, together with a design, an building that poses as a prediction of how these building might look, since these complicated structures will need a great deal of design informed by its demands. The design proposal is not the only way but includes some design rules important for the typology and points to consider when humanity wants to reach even further into the sky, with architecture as its tool. 7. STUDIES
7.1 Calculations

Agricultural Area - The calculations used to establish the needed Greenhouse-area, with respect to food. Using high-density-nutrients and considering aeroponics, a highly efficient and lightweight agricultural system based on freestanding plants, which roots are sprayed with water and nutrients. With the designed greenhouse layout, it would be possible to feed 1.1 million people, which is enough for the population. This only includes the greenhouse, if the terraced faming in the helix is also taken into accounts, this could be increased, allowing for more variation among the cultivated plants.

Outer Radius Greenhouse -	R	= 175 m
Inner Radius Greenhouse -	r	= 125 m
Number of people possible		
to feed with aeroponics per square-kilometer -	е	= 49000 people/km ²
Height Greenhouse	Н	= 2000 m
Height single floor	h	=4 m
Number of Floors	$n_{_{floors}}$	= H / h=2000 m / 4 m = 500 floors
Area per floors	A _{floor}	$= \pi (R^2 - r^2) = \pi (175^2 - 125^2) = 47124 m^2$
Total Area	A_{tot}	$= n_{floors} * A_{floor} = 500 * 47124 = 23\ 000\ 000\ m^2 = 23\ km^2$
Number of people possible to feed	$n_{_{people}}$	$= A_{tot} * e = 49000 \text{ people/km}^2 * 23 \text{ km}^2 = 1 100 000 \text{ people}$

Pressurization - The calculations used to verify that enough air and water can be provided in the building. The air can be well provided, from a breathing point of view.

Air flow natural draft		
Temperature outside top of building	T_{o}	= -50°c
Temperature inside bottom of the building	T_{i}	= 20°c
Height air canal	Н	= 8800 m
Air canal diameter	D	= 8 m
Minor loss coefficient	$\Sigma \xi$	= 1
Density outdoor air	ρ_o	$= 1.58 \text{ kg/m}^3$
Density indoor air	ρ_i	$= 1.20 \text{ kg/m}^3$
Darcy-Weisbach friction coefficient	λ	= 0.019
Gravitation coefficient	g	= 9.81m/s
Air flow velocity	v	$= [(2 * g (\rho_o - \rho_i) * h) / (\lambda * H * \rho_i / D + \Sigma \xi * \rho_i)]^{1/2} = 51 m/s$
Air Supply		
Side length air shaft	l	= 8 m
Area air shaft	Α	$= 64 m^2$
Number of towers	n	= 3
Velocity air (from above)	v	= 51 m/s
Volume air transported per second	V_{second}	$= A * v * n = 64 m^2 * 51 m/s * 3 = 9792 m^3/s$
Seconds per day	t _{dav}	= 86400 s
Volume air transported per day	$V_{_{dav}}$	$= V_{second} * t_{day} = 9792 \ m^3/s * 86400 \ s = 846028800 \ m^3$
Volume air needed per person per day	$V_{_{person}}$	$= 11 m^3$
Number of people possible to provide with air	n people	= V _{day} / V _{person} = 76 000 000 people
Water supply		
Density Water	$ ho_w$	$= 1000 \ kg \ /m^3$
Vapor density (RH100%, 20°c)	и	$= 0.01728 \ kg/m^3$
Water transported per day	$V_{_{water}}$	$= V_{day}^{*} u / \rho_{w} = 14600 \ m^{3}$
Water used per person per day	V _{w-person}	$= 0.15 m^3$
Number of people possible to provide with water	n _{pers}	$= V_{water} / V_{w-person} = 97\ 000$



figure 48. Collection of the findings of the findings in "Extreme structures of the history" and "Extreme structures of the future" - to be able to compare the results.

7.2. STUDY - MATERIALS OF TODAY AND YESTERDAY

The purpose of this investigation is to perform a brief historic study of superlative structures, trying to find patterns in function, performance and tectonics based on the used materials. The idea is also to by doing this, position this project in an environment.

By looking into different materials, what they've performed and how they've performed one might learn a lot about how materials have been treated and what kind of structures and scales might work, results collected in figure 48.

The historical studies are then followed by a similar experiment, using modern techniques and materials, looking into what could be achieved and how.

The terminology on structural systems refers to the division suggested by Heino Engels. Engels used vector-active systems, such as bars and cables; cross section-active structures; like beams; surface active systems like plates and shells and form-active systems including arches, membranes and inflatables (Engels, 1997).



figure 49. High - Pagoda at Hōryū-ji - 7th century - symbolic Section active structure



figure 50. Long - Bridge Switzerland - 18th century - Utility timber - vector active



figure 51. Big - Tillamook air museum - 1942 - storage timber - vector active

7.2.1 TIMBER

Introduction: Timber is one of the classic materials that have been used in architecture since the dawn of architecture. While timber have seen a renaissance during the last decades, this is mainly different kinds of glued timber, while this study mainly focuses on the pre-industrial revolution timber structures. Examples of timber projects, in categories tall, big and long can be seen in figure 49, figure 50 and figure 51.

Timber have gotten its popularity mainly due its easiness to work with, and the accessibility.

Period: Stone-age - industrial revolution

Behavior: Timber is strong in bending, and is relatively strong, while still being light-weight. The softness of the material result in big deflections. But timber is, even tough behaving different in different directions, a material that is strong in tension, compression and bending.

Timber is also highly dependent on the moisture-levels, and have a swelling behavior, making it somewhat unpredictable.

Density: 500-700 kg/m³

Scale of applications: Most of the projects we can see from this age is either on the scale of the individual, or the scale of the village. One of the reasons for this is the scale of the society during this age, one is the fact that trees only comes in certain sizes, and splicing was complicated.

Strength: Varies a lot, but in the span of 8-25 MPa in tension, 16-26 in compression and 14-40 MPa in bending.

Form- Structure: Due to the nature of timber, it's shape and its length, that is one important influence on the form and shape, suitable in vector and section-active structures, like post and beams systems.

Why stop at this size?: Once again, the shape and size of the raw material is pretty decisive on the size, also the relative softness of the material.



figure 52. Tall - Lighthouse on Île Vierge - early 20th century - lighthouse Surface active + height active



figure 54. Big - Santa Maria del Fiore - early 15th century church masonry - surface active



figure 53. Long - Masonry bridge - late 19th century masonry - surface active

7.2.2 MASONRY

Introduction: Masonry and stone structures is also one of the classic building materials. Common in great parts of the world. Have been used in everything from small structures to monumental buildings, the durability of the material have granted it a long-lasting status, literally. Examples of masonry projects, in categories tall, big and long can be seen in figure 52, figure 53 and figure 54.

Period: Stone-age - industrial revolution

Behavior: Masonry is a material that is only effective in compression, and that's governed by the size of component, or the stone itself, since historically there is no effective way to join the stones. Mortar have been used, but until recently more as a matter of tightening the structure and transferring loads, not strengthen.

Density: 2500 kg/m³

Scale of applications: Most of the superlative projects we can see in this material is in the scale of the borough, or the horse carriage.

Strength: Varies a lot, but in the span of 50-130 MPa in compression.

Form - structure: Due to the fact that stone is a compression-material, the shape of the structures are rather significant, so called gravity-structures. Either as vertical walls, allowing the loads direct contact to the ground, or as arches and dome, allowing forces a to travel in a slightly angled manner downwards. Relying on its massive weight as a mean to handle other forces, by making sure to, at all times be the biggest load.

Why stop at this size?: One of the main reasons to why you would stop at these sizes, is the fact that stones can only get so big, and still be able to handle.



figure 56. Big - Singapore National Stadium - 2014 - sport arena steel - cross section active



figure 55. Big - Centre Pompidou - 1977 - exhibition hall steel - vector active



figure 57. Tall - Willis Tower - 1973 - office Section active + height active



figure 58. Long - Akashi Kaikyō Bridge - 1998 steel - form active/vector active

7.2.3 STEEL

Introduction: When metals were introduced in the building industry, first as cast-iron and later as steel, there were a lot of possibilities opening up. With steel came a material, not only stronger but also with better possibilities of joining, first with bolts and then with welds. And the possibility of customized sizes. Examples of steel projects, in categories tall, big and long can be seen in figure 55, figure 56, figure 57 and figure 58.

Period: Industrial revolution - today. Completely dominant until 1980's

Behavior: Steel is a uniform material, as strong in tension as in compression. Rather flexible makes buckling and deflection a possibility, also the concept of frames and stiff connections is problematic.

Density: 2400 kg/m³

Scale of applications: The superlative structures in the category of tall could be considered borough-scaled. The structures in the categories big and long is more to be considered to be city-scale, or even region-scaled.

Strength: 250-500 MPa in both tension and compression.

Form - structure: The usual steel structure is post and beam, meaning a strict vertical and horizontal system. With introduction of steel came the popularity of the truss. Steel is an excellent material working with axial forces, and with the truss there is no real need for stiff joints. But also all kinds of frame-structure based on trusses or not.

Why stop at this size?: Going vertically there comes a point where the feasibility the material is flexible enough and starts swaying. Depending on the circumstances at the site, it could be worth more to divide the bridge into more spans, instead of longer ones.





figure 61. Big - Norfolk scope - 1971 - exhibition hall concrete - surface active



figure 62. Big - Palazzo de lavoro - 1961 - exhibition hall concrete - section active





figure 60. Long - Qinglong Railway Bridge - 2016 concrete - surface active

7.2.4 REINFORCED CONCRETE

Introduction: When talking about concrete today, one means the mixture of Portland cement, aggregate and water, reinforced with steel. Examples of concrete projects, in categories tall, big and long can be seen in figure 59, figure 60, figure 61 and figure 62

Period: Mid 20th century - today.

Behavior: Reinforced concrete is a material working in compression. The porosity and material structure makes it very weak in tension. By strengthening the material with steel-bars or meshes, it compensates, and these materials works together.

Density: 7800 kg/m³

Scale of applications: The superlative structures in the category of big and long could be considered borough-scaled. But the structures in the tall category could surely be considered city-scaled. Possible to fit all the offices and resident you could imagine

Strength: 20-100 MPa in compression, negligible in tension.

Form - structure: As with masonry, the most efficient structures are based on the shapes of the hanging chain, allowing the material to work in compression. But with the introduction of reinforcement, the concrete is a material performing well in terms of bending as well, making it a material suitable for post and beam structures.

Why stop at this size?: There is really no reason to stop at this size, materialvise, the only thing that needs to be done is adding more material at the base, going wider and wider. But the main reasons to why not anything bigger is built is the price, and the fact that with the bigger footprint, the darker the bottom floors.



figure 63. Diagram of the composition of reinforced concrete.

CONCLUSION

This investigation was performed to find and evaluate extreme structures throughout the history. By use and the structural concept.

What becomes clear from the examples in masonry and timber is that until the industrial revolution the size of the material was governing. And the size of the structures usually stopped around 100 m, no matter if it regarded height or spans.

Traditionally timber have been use as vector-active structure and section active-structure, mainly due to the physical shape of the raw material. Its flexibility have made it successful to last over time, and to resist big temporary forces.

Masonry structures is mainly based on stereotomy and will create a surface-like structure. The shapes of the structures are usually similar to the form-active structures, but with the difference that masonry relies on its weight to achieve stability, independent from exterior forces, thus they've the optimal shape for its own weight, and relies on the weight being big enough.

With the introduction of steel and concrete the biggest improvement was a possibility to create members of wanted dimensions and an effective way of joining.

The most important finding of this experiment was the trend in effective structures, and what seems to be efficient for different types of typologies. For buildings relying on long spans, form active structures are clearly the one performing the best.

It's worth noticing the difference in the "big" category between the systems based on domes and shapes and the systems based on the straight geometry. Where the domes performed much better.

While, on the other hand high buildings seems to be performing best using systems based on either vector- or section-active systems, this probably due to the problem of building formactive tall structures.

7.3 STUDY - MATERIALS OF TOMORROW

With the industrial revolution came a way to produce materials, and thereby started a way of customizing materials to new properties. Carbon was added to iron, creating a material much stiffer, and stronger than the two original materials. With reinforcement concrete was customized to a much more useful material, by introducing a possibility to handle tension as well.

The next material revolution is a continuation of this, but on a much smaller scale, down to atomic scale. A lot of research today is being performed on materials where the atomic lattice are customized to perform optimally, thereby creating a material without flaws when scaled up. Today many of these materials are still in extremely small scale, but many of the projects are beginning to emerge to usable scales.

But there are materials in this new generation of materials on the market already, one of them being carbon fiber.

"If you can take 30 per cent of the weight out of the upper section of a building by using lightweight composite materials, you could end up saving between 70 and 80 per cent of the material in the entire structure"

-Greg Lynn

6.3.1 Carbon fiber

Introduction: When saying carbon fiber one usually mean one out of two things, either the actual carbon fiber, or the fibers cured in a plastic resin, the matrix, which actual name is carbon reinforced polymer. These materials are widely used in bridge-building, aviation and naval engineering.

Period: Mid 20th century - today.

Behavior: Carbon fibers are comparable to high-strength steel in compression, but several times higher in compression and bending, rather stiff. But in weight comparable to plastics. They're also air and water-tight, due to the plastic matrix.

Density: 1600 kg/m^{3.}

Scale of applications: The potential scale of these structures are big. The question is, if these structure should increase the size of structures.

Strength: As fibers 1200 MPa in tension, as composites comparable, slightly higher, than to steel. The main strength is in-plane, but with the introduction of graphene, one might expect the stiffness out of plane to increase as well, being an reinforcement of the matrix.



figure 64. Diagram of the composition carbon fiber sheets

6.3.1.1 Carbon fiber - tectonics

Inflatables

Inflatables structures are structures stabilized by the high air pressure inside them. Usually constructed of ETFE-foil, reinforced by carbon fibers. Popular during the era of high-tech architecture. Such as the Eden project By Grimshaw architects.

Fibers

The fibers in carbon fibers are the strongest parts, being thin fibers with high tensile strength and low weight. These are woven into fabrics or strings, usually then introduced in a matrix of resin, binding them together, forming sheets. But can also be used as cables, without the matrix.

Shells

When the fibers are cured in plastic resin, it forms sheets of carbon-reinforced polymers, that can be used as shell structure. Today the resin is the weaker part, but recently graphene has been introduced between the layers of fibers, as reinforcement of the matrix radically increasing the strength (LIGHTer, 2016). Further increasing the possibilities.

Beams

Carbon fiber is also used to produce beams, creating stiff, lightweight beams.

Adhesives

Constructing with polymers, plastic and carbon fiber, the common material for construction is glue (Manaugh, 2016). Creating quickly assembled structure, with tight

6.3.2 Other materials

Nanotube-refinforced concrete.

Carbon can form strong bonds on an atomic-scale, forming nano-tubes. Nano-tubes are expected to be able to replace steel in reinforced concrete in a near future, creating a material with improved strength in tension and compression and without the durability problems of reinforced concrete, also reducing the weight and construction time (Garkavenko, 2017).

Self Healing

With the new generation of materials comes other properties beyond strength. For example researchers expect self healing materials (Garkavenko, 2017). Thereby reducing the need for accessibility for maintenance.

Aerogel

Aerogel is an the common name for a number of highly-porous materials made from different materials. Due to the extreme porosity they've densities close or lighter to the density of air, but are solids, and although brittle, rather strong. The main use for these materials are expected to be as thermal insulation and gas-filtering.

Vacuum Panels

Vacuum panels are a material, or rather a lack of material. Hollow panels where all air is sucked out, creating panels with exceptional isolation-qualities. Since heat is is transferred in three ways, radiation, convection and conduction, where convection and conduction needs matter to transfer heat, vacuum panels effectively eliminates parts of the heat-transfer. This is a material already in commercial use. **7.4 Balloon** - In an attempt to reference Buckminster Fuller's Cloud 9 experiment, several experiment on the themes of balloons where executed. One quantitative, trying to reproduce his calculations, which seemed successful and showed great lifting force until the change of airpressure over altitude was considered, giving negative lifting forces. Another ideas was the use of vacuum, with an idea of construction method is shown in figure 67.

A performative test on how a structure behaves when hanged from buoyancy float was made, and the result is presented in figure 66 and alternative ways to incorporate the volume of a balloon in a structure is shown in figure 65.



figure 65. Volume studies, testing different solutions of balloon-attachment



figure 66. Demonstration of stability by hanging. Each picture taken 0.2s apart, from unloaded to loaded and released. Showing that the building goes back to it's straight state.



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